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ASSESSMENT OF ARTIFICIAL ACCELERATION TIME HISTORY GUIDANCE IN STANDARD REVIEW PLAN SECTION 3.7.1, “SEISMIC DESIGN PARAMETERS”

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Research Information Letter
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ABSTRACT

This research information letter (RIL) documents the results of research conducted by the U.S. Nuclear Regulatory Commission's Office of Nuclear Regulatory Research (RES) to address technical issues that the program offices experienced when using the guidance in NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" (SRP), Section 3.7.1, "Seismic Design Parameters," Acceptance Criterion II.1.B, "Design Time Histories." The staff uses this guidance during its review of licensing applications that involve time history analyses of safety-related structures, systems, and components (SSCs) or equipment qualifications using shaking table tests.

The resolution of the eight specific issues addressed in this RIL could enhance the clarity of the SRP guidance on the acceptance criteria for artificial acceleration time histories used in seismic analyses of safety-related SSCs. Use of an inappropriate time history in seismic analysis could significantly underpredict seismic demands on SSCs, which could lead to an unsatisfactory design of the SSCs. Better SRP guidance in this area could reduce the possibility of using unacceptable time histories in seismic analysis. Research results associated with this effort can also help the staff and the industry align better on certain critical aspects in the development of artificial acceleration time histories.

The eight technical issues cover a range of topics, such as the necessity of target power spectral density (PSD) functions; the effect of power deficiency in very low or high frequencies; criteria for recorded seed time histories and randomly generated seed time histories; different definitions of strong motion duration; differences in the number of frequencies, damping ratios, and frequency range between approaches; time increment and total duration of time histories; and multiple sets of time histories.

The RES work described in this RIL identifies opportunities to enhance several technical areas in the current SRP guidance and provides the necessary technical bases. The proposed resolution of the technical issues addressed in this RIL include the following four major technical conclusions and some minor ones:

(1) Power-deficient design time histories can lead to significant underprediction of in-structure response spectra (RS) and other frequency-sensitive structural responses.

(2) RS enveloping alone does not ensure power sufficiency, and a PSD assessment without a comparison to a target PSD function is not conclusive.

(3) The PSD check should cover a frequency range that is consistent with the shape of the input RS.

(4) A new frequency series developed in this study can enhance and unify the frequency points used for RS calculations and comparisons.

For the time history analysis method to be an adequate tool for estimating the seismic demands on SSCs, the artificial time histories should be treated as part of that tool. In general, seismologists have developed the input RS by condensing many parameters in the field of seismology and geophysics. Accordingly, structural engineers should effectively unpack those key seismological parameters when developing time histories from the input RS. Input RS by itself is not an adequate descriptor of the power distribution required for design seismic ground

motion specification. Without careful consideration of those parameters, the input RS can be overly simplistic and may not serve well as the interface between seismologists and structural engineers. The resolution of the issues in this RIL helps ensure that the same seismic hazards characterized by seismologists are mitigated adequately by structural engineers.

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES) staff conducted targeted research to clarify several technical issues in NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" (SRP), Section 3.7.1, "Seismic Design Parameters," Acceptance Criterion II.1.B, "Design Time Histories." SRP Section 3.7.1 provides options and approaches in the guidance for determining the acceptance of artificial acceleration time histories, which are used as input earthquake ground motions in seismic response analyses of nuclear power plant (NPP) structures. The program office staff has encountered difficulties in applying this guidance during its review of reactor licensing applications and has identified eight specific issues to be addressed by RES. The goal of this research was to evaluate these issues related to the acceptance criteria for the artificial acceleration time histories of ground motions for seismic-resistant designs of structures, systems, and components (SSCs) in NPPs. An inappropriate time history used in a seismic analysis could significantly underpredict seismic demands on the SSCs and therefore potentially lead to the unsatisfactory design of the SSCs. The resolution of the technical issues addressed in this Research Information Letter (RIL) can be used to establish new guidance or enhance the clarity of the existing guidance in SRP Section 3.7.1 concerning the acceptance criteria for artificial acceleration time histories. The staff uses this guidance during its review of licensing applications that involve time history analyses of safety-related SSCs or equipment qualifications using shaking table tests.

The Office of New Reactors initially identified eight technical issues, which were refined after further discussion with staff from that office:

(1) whether it is necessary to demonstrate power sufficiency of artificial acceleration time histories by a comparison to target PSD functions for both approaches in Option 1, "Single Set of Time Histories," of SRP Section 3.7.1

(2) appropriate acceptance criteria for recorded seed time histories that are used to generate the artificial acceleration time histories

(3) guidance and technical bases for determining which of the two different definitions of the strong motion duration in the current SRP guidance should be used

(4) appropriate acceptance criteria for randomly generated seed time histories that are used to generate the artificial acceleration time histories

(5) the differing guidance between the two approaches in Option 1 with regard to the number of frequencies for response spectrum calculation, specified damping ratios, and frequency range for the PSD check and the bases for such differences

(6) whether the guidance in Option 1, Approach 2, on the minimum Nyquist frequency, time increment, and total duration of time histories also applies to Approach 1

(7) whether the same response spectra matching and PSD criteria in Option 1, Approach 2, should be used for Option 2, "Multiple Sets of Time Histories"

(8) the significance to the structural responses of a power deficiency at very low frequencies or high frequencies

To address these issues, RES reviewed relevant NUREGs and other NRC references to identify the technical bases and develop a further rationale for resolving these issues. In most cases, a literature review could not identify sufficient information to address the issue, and RES performed limited and targeted analytical work to demonstrate and develop the bases for technical recommendations.

The work described in this RIL has identified opportunities for enhancement in several technical areas in the current SRP guidance and provides the necessary technical bases. The recommended SRP enhancement can reduce the possibility of using inappropriate time histories in seismic analysis of safety-related SSCs. Research results associated with this effort can also help the staff and the industry align better on certain critical aspects in the development of acceleration time histories. The research efforts led to the four major conclusions summarized below:

(1) The current criterion of demonstrating the power sufficiency of artificial acceleration time histories by a comparison to target power spectral density (PSD) functions, as provided in Option 1, Approach 1, of SRP Section 3.7.1, should remain. Guidance provided for Option 1, Approach 2, should be enhanced to require such a demonstration by a comparison to target PSD functions. The RES review and analytical work showed that response spectra (RS) enveloping alone does not ensure power sufficiency and that a PSD assessment without a comparison to a target PSD function is not conclusive.

(2) Power deficiency at very low frequencies or high frequencies can be significant to structures and components with important modes in those frequency ranges. Both a literature review and a RES analysis showed that a power-deficient time history could lead to significant underprediction of in-structure response spectra (ISRS). Houston et al. (2010) found that power deficiencies could underpredict the peak spectral accelerations in ISRS by as much as 70 percent. Similarly, this study found that a broadband acceleration time history and an acceleration time history with 15 major frequencies, both satisfying the same RS enveloping criteria, led to about a 90-percent difference (broadband compared to 15 major frequencies) in the peak spectral accelerations of the 5-percent damped ISRS. Therefore, power-deficient time histories should not be accepted unless an adequate technical justification is provided to show that the power deficiencies are not important to the affected structures and components for the particular application.

(3) The PSD check should cover a frequency range that is consistent with the shape of the input RS.

(4) The use of a new frequency series developed in this study can enhance and unify the frequency points used for RS calculations and comparisons. For RS enveloping, acceptance criteria should include criteria that no more than 6 percent of the total number of frequency points are allowed to be lower than the design RS and that the cluster of these points should not exceed a frequency window of ±10 percent.

ISSUE-BY-ISSUE SUMMARY AND CONCLUSIONS

For each technical issue described above, the following sections provide more comprehensive issue descriptions and the issue resolution summaries. The text describes Issue 3 after Issue 4 because Issues 2 and 4 are closely related and are addressed together.

Issue 1—Necessity of Target Power Spectral Density Functions

Issue Description:

The SRP Section 3.7.1 guidance provides two options for the use of acceleration time histories in seismic analysis of safety-related SSCs:

(1) Option 1—analysis using a single set of time histories
(2) Option 2—analysis using multiple sets of time histories

In Option 1, to demonstrate that the acceleration time history (each of the three components of the ground motion) is compatible with the design ground-motion spectra, the SRP gives two approaches. The key difference between these two approaches is that in Approach 1, there is a need to demonstrate the power sufficiency of the time history, by comparing the time history PSD function to a target PSD function defined using associated rules in the guidance. Approach 2 does not require the demonstration of power sufficiency using a target PSD function. The issue is whether it is necessary to demonstrate power sufficiency by a comparison to a target PSD function in both approaches and the technical basis for such a determination.

Summary of Research Results and Conclusions:

In addition to ensuring that the estimated RS enveloping the design response spectra (DRS), SRP Section 3.7.1, Revision 2, issued August 1989, introduced the PSD check as a secondary yet necessary check to ensure power sufficiency of the acceleration time history. Based on a recommendation in NUREG/CR-6728, "Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines," issued October 2001, SRP Section 3.7.1, Revision 3, issued March 2007, adopted Option 1, Approach 2, which requires the computed RS to be below 130 percent of the DRS as a substitute for a PSD check. However, NUREG/CR-6728 did not provide a technical basis for such a substitution. SRP Section 3.7.1, Revision 4, issued December 2014, makes the PSD assessment in Option 1, Approach 2, unconditional on the result of RS enveloping, but it does not explicitly require a comparison to a target PSD function. Section 2.1 of this RIL provides the results of RES's literature review, technical discussion, and examples, which together led to four conclusions:

(1) RS enveloping alone does not ensure power sufficiency.

(2) A PSD assessment without a comparison to a target PSD function is not conclusive.

(3) The PSD check should also include a check of the raw PSD curve to determine whether the ±20-percent frequency window for smoothing adequately produces a mean PSD curve following the trend of the raw PSD curve.

(4) For practical purposes, a target PSD function can be developed for a given practical DRS, and methods currently exist for developing such target PSD functions.

Therefore, the RES staff recommends that Option 1, Approach 2, should include the criterion that the estimated PSD function of the acceleration time history should be computed and shown to be higher than the minimum target PSD function to ensure that there are no significant gaps in power at any frequency over the frequency range of interest, as described in Step (a) of Approach 2.

Alternatively, Approach 1 and Approach 2 may be combined to simplify the SRP guidance on the acceptance of acceleration time histories based on the resolutions of all technical issues in this RIL. With the newly proposed frequency series and newly recommended RS enveloping criteria (see Issue 5) and the need for a comparison to target PSD functions in Approach 2, these two approaches differ only in the number of DRS curves. The combined approach can easily accommodate this difference.

Issue 2—Criteria for Recorded Seed Time Histories

Issue Description:

The SRP guidance recommends the use of recorded time histories as seed for the generation of artificial time histories. The staff review guidance lacks detailed acceptance criteria for the seed time history records. The issue is to develop or clarify the appropriate acceptance criteria for recorded seed time histories.

Summary of Research Results and Conclusions:

Because Issue 2 closely relates to Issue 4, this RIL addresses these two issues together under Issue 4 below.

Issue 4—Criteria for Randomly Generated Seed Time Histories

Issue Description:

The SRP guidance allows the use of randomly generated seed time histories for the generation of artificial time histories but provides no detailed acceptance criteria for randomly generated seed time histories. The issue is to develop or clarify appropriate acceptance criteria for randomly generated seed time histories.

Summary of Research Results and Conclusions:

Because Issues 2 and 4 are closely related, this RIL addresses them together. Revisions 0, 1, and 2 of SRP Section 3.7.1 do not have provisions for seed time histories. SRP Section 3.7.1, Revision 3, states that artificial time histories that are not based on recorded seed time histories should not be used. SRP Section 3.7.1, Revision 4, allows both recorded and artificial seed time histories.

Based on its literature review, RES recommends the following:

- The SRP guidance on the spectral shape of the recorded seed time histories should remain as is (i.e., the RS corresponding to the seed record should be similar in shape to the target spectra across the frequency range of interest to the analysis). The intent of this guidance is to encourage minimal modification to the seed time histories so that the resultant artificial time histories are more like real earthquake ground motions.

- The SRP guidance should not include the criterion “phasing characteristics of the earthquake records should not change significantly.”

- Fourier phase spectra of the final artificial time history, based on either recorded or random seed time histories, should be demonstrated to have a uniform distribution over 0 to 2π. This recommendation was based on both empirical and theoretical research results in the literature.

Issue 3—Strong Motion Durations

Issue Description:

The SRP has two definitions for strong motion duration: (1) the time for the cumulative Arias Intensity to rise from 5 percent to 75 percent ($T_{5\text{–}75}$) and (2) the duration of near maximum and nearly stationary power in the time history (T_D). These two definitions may lead to somewhat different durations in the time histories. The issue is to clarify the guidance and technical bases for which should be used and, if both are to be used, to provide a condition for when to use which definition.

Summary of Research Results and Conclusions:

RES recommends using the strong motion duration T_D, as defined in Appendices A and B to SRP Section 3.7.1. In particular, the use of $T_{5\text{–}75}$ in the current SRP Section 3.7.1, Acceptance Criterion II.1.B, requires a check of the uniformity of the growth of the cumulative Arias Intensity, which is often overlooked in practice. Even when checked, the determination of uniformity can be subjectively biased because of the predetermined $T_{5\text{–}75}$. In addition, when the uniformity of the growth of the cumulative Arias Intensity is checked, T_D becomes readily available; therefore, $T_{5\text{–}75}$ would not need to be computed.

Issue 5—Number of Frequencies, Damping Ratios, and Frequency Range

Issue Description:

The SRP provides different guidance for DRS and PSD matching, including the number of frequencies for response spectra calculation, specified damping ratios, and frequency range for PSD check. The issue is to clarify or develop guidance explaining the reason for this difference and which guidance to follow.

Summary of Research Results and Conclusions:

This issue consists of three items:

(1) Option 1, Approach 1, uses fewer frequency points than Approach 2 does in RS calculations and comparisons.

(2) Option 1, Approach 1, uses more damping ratios than Approach 2 does in RS enveloping.

(3) For a PSD check, SRP Section 3.7.1, Appendix A, requires a frequency range of 0.3 hertz (Hz) to 24 Hz, whereas SRP Section 3.7.1, Appendix B, requires a frequency range of 0.3 Hz to an unspecified upper bound frequency that is required to be consistent with the RS shape.

Of these three items, Item 1 concerns RS enveloping, Item 3 concerns PSD check, and Item 2 concerns both.

For Item 1, an assessment of the frequency points currently used in Option 1, Approach 1, and in Approach 2 indicated that the two frequency series can be unified and replaced by a newly proposed series, log_power (*p* = 0.6 and *n* = 151):

$$\log F_i = 3\left(\frac{i}{n-1}\right)^p - 1, \qquad i = 0, 1, \cdots, n-1$$

where *n* is the total number of frequency points and *p* is the power that controls how the frequency points are distributed. This new frequency series is similar to Approach 2 at high frequencies (greater than 10 Hz) and similar to Approach 1 at midfrequencies (1 through 10 Hz). In the low-frequency range (0.1 Hz to 1 Hz), the new frequency series has 25 frequency points and is close to the Fourier spectrum of a typical time history (dt = 0.005 seconds, N = 4,096), as compared to 8 frequency points for Approach 1 and 100 frequency points for Approach 2. The assessment concluded that the log_power frequency series is flexible, convenient, and sufficient.

The RES assessment of the Option 1, Approach 2, RS enveloping criteria showed that these criteria could allow unconservative RS enveloping situations. Therefore, the RS enveloping criteria in Approach 2 can be enhanced to put a limit on the total number of spectral points that are allowed to be lower than the DRS. RES proposes that no more than 6 percent of total frequency points in the frequency range of interest should be allowed, which translates to 16 points up to 50 Hz using the current Approach 2 minimum frequency series (i.e., 100 points per frequency decade). For Option 1, Approach 1, if the allowable 5 points occur in the same frequency range, they can cover a frequency window larger than the ±10-percent frequency window allowed in Approach 2. Therefore, RES recommends that Approach 1 be enhanced to require that the points below the DRS should not fall in frequency windows larger than ±10 percent. Note that these conclusions and recommendations only indicate the potential deficiencies in the current criteria but do not suggest that these situations often occur in practice. The goal of the proposed enhancement is to improve regulatory efficiency by avoiding potentially unfavorable cases in the future.

For Item 2 on RS enveloping, the RES assessment reaffirmed that the use of multiple DRS in RS enveloping is more conservative than use of a single DRS (even at a damping ratio as low as 2 percent). DRS curves tend to govern at different frequency ranges, although DRS at lower damping generally govern more often than do DRS at higher damping. However, in situations where only the 5-percent damped DRS is available (e.g., as a result of the probabilistic seismic hazard assessment), instead of generating and using DRS at other damping ratios, RES considers the use of the DRS at a 5-percent damping ratio acceptable. This conclusion is based on (1) the degree to which the RS enveloping criteria are exceeded at other damping ratios is considered somewhat insignificant in an engineering sense, (2) other DRS can be generated consistently, and (3) the PSD check against the target PSD function helps identify the unsatisfactory frequency ranges in RS enveloping at lower damping values.

For Item 2 on the PSD check, if the DRS are consistent with each other (i.e., they can be generated from the same set of time histories), the use of the 5-percent damped DRS is sufficient for developing the target PSD function. Otherwise, the target PSD function should take the envelope of the target PSD functions developed for the DRS at all damping ratios.

For Item 3 on the upper bound frequency for the PSD check, RES recommends that the current guidance in SRP Section 3.7.1, Appendix B, remain as is because the upper bound frequency for the PSD check depends on the shape of the DRS. As demonstrated in Section 2.3 of this RIL, the development of a criterion based on the cumulative PSD function is not feasible as it becomes flat at high frequencies.

The lower bound frequency for the PSD check, which is currently set at 0.3 Hz, may need to be removed from both Appendices A and B to SRP Section 3.7.1, because low frequencies close to this frequency can be important for the soil-structure interaction (SSI) phenomenon at some deep soil sites and for sloshing in large tanks. As a replacement, the lower bound frequency for the PSD check should also be consistent with the DRS, similar to the case of the upper bound frequency in the PSD check. It should be emphasized that the same single set of time histories is often used in different analyses, such as the SSI analysis of major buildings that may not be sensitive to low-frequency motions and the analysis of large storage tanks installed on the ground surface that can be sensitive to these same low-frequency motions.

The upper bound frequency of 24 Hz in SRP Section 3.7.1, Appendix A, can remain; this study demonstrated that the power above this frequency has minimal effect on RS. However, it can be removed from Appendix A for consistency with Appendix B with regard to the upper bound frequency for the PSD check. RES considers the practical impact of such a revision to be minimal.

Issue 6—Time Increment and Total Duration of Time Histories

Issue Description:

Approach 2 provides guidance on minimum Nyquist frequency, time increment, and total duration of time histories. However, Approach 1 does not explicitly include this guidance. The issue is to assess whether this Approach 2 guidance also applies to Approach 1.

Summary of Research Results and Conclusions:

The SRP acceptance criteria for minimum Nyquist frequency, time increment, and total duration of time histories currently provided in Option 1, Approach 2, are commonly met in practice regardless of which approach has been used. The RES staff's experience indicates that achieving these technical aspects in synthetic acceleration time histories is not difficult. Therefore, because imposing these criteria on Option 1, Approach 1, raises no practical problem, the provisions in Step (a) of Option 1, Approach 2, can be relocated to the general criterion of Option 1, thus making such provisions applicable to both approaches.

Issue 7—Multiple Sets of Time Histories

Issue Description:

In Option 2, to demonstrate the adequacy of a set of multiple time histories, in terms of enveloping criteria and having sufficient power, the procedures described for Option 1, Approach 2, are applied. The issue is to clarify whether the same RS matching criteria and PSD check criteria (i.e., the current criteria in SRP Section 3.7.1, Revision 4, or the proposed criteria in this RIL) in Option 1, Approach 2, should be used for Option 2.

Summary of Research Results and Conclusions:

To demonstrate the adequacy of multiple sets of time histories, Option 2 indicates that the average RS and average PSD function should meet the Option 1, Approach 2, criteria, whereas each individual time history does not need to satisfy these criteria. The goal of such a criterion is to prevent situations where systematic biases may occur in the multiple sets of design time histories. Systematic biases may arise from using the same RS matching program or procedure, using seeds recorded at seismometers with similar applicable frequency range, filtering records, and other practices.

The intent of this issue was to check whether the Option 2 guidance still applies if a change is made to Option 1, Approach 2, because of the resolution of other issues in this RIL. RES concludes that Option 2 does not need a revision in this area because of the recommended revisions of Option 1 (except for probably minor editorial changes to ensure consistency).

Issue 8—Effect of Power Deficiency in Very Low or High Frequencies

Issue Description:

This issue is to assess the significance to the structural responses of a power deficiency at very low frequencies or high frequencies. The assessment is necessary to allow a reasonable assurance of safety determination.

Summary of Research Results and Conclusions:

Power deficiency at very low frequencies or high frequencies may be significant to structures and components with important modes in those frequency ranges. Both a literature review and RES targeted analyses showed that a power-deficient time history could lead to a significant underprediction of ISRS. These analyses showed that, except for zero-period acceleration, ISRS reflects the power distribution of the input time history more than the input RS does. RES expects that other structural responses sensitive to frequency content, such as fatigue, can be similarly affected. Because Option 1 uses a single set of time histories as a surrogate for DRS, which is the current practical way to specify the input ground motion, power-deficient time histories are not able to authentically represent the DRS. Therefore, power-deficient time histories should not be accepted unless an adequate technical justification is provided to show that the power deficiencies are not important to the affected structures and components for the particular application. The applicant may use other methods (e.g., methods based on response spectrum analysis or random vibration theory) or time histories without power deficiencies to justify its use of power-deficient time histories in its application.

RECOMMENDATIONS FOR FUTURE RESEARCH

The RES work described in this RIL also identified the following six technical areas for future research. Studies in these areas can offer further technical insights to enhance technical positions in the SRP guidance related to the proposed resolution of the issues identified for the generation of ground motion acceleration time histories for seismic design. Such work would address, for example, issues that might arise in implementation of the proposed resolutions.

1. Development of an Automated Method To Determine the Strong Motion Duration

The cumulative Arias Intensity curve (also referred to as the Husid plot) is used to determine the strong motion duration, during which the acceleration time history reaches near maximum and nearly stationary power. The cumulative Arias Intensity curve usually shows a shape similar to a log-sigmoid function, with the strong motion portion nearly a straight-line segment. Therefore, a log-sigmoid function or other similar functions can be used to determine a best fit to the cumulative Arias Intensity curve, and the parameters of the fitted curve can then be used to calculate the strong motion duration. This process can be implemented as an automated procedure and consequently can be standardized to avoid ambiguity. The relationship between T_D and the parameters of the fitted curve needs to be determined based on the analysis of many real and synthesized acceleration time histories.

2. Study of Power Spectral Density Effects Using Realistic Models

The study by House et al. (2010) is the only example found by the RES staff that uses realistic models to show that power deficiencies in time histories can have a significant effect on structural responses (ISRS in particular). That study compared the results of SSI analyses using hundreds of artificial time histories that were developed based on recorded seed time histories to meet the Option 1, Approach 2, criteria in SRP Section 3.7.1. Analysis of a variety of other realistic structural and component models would provide further insights for real SSCs and other response parameters (such as fatigue). The analyses would consider different methods, such as response spectrum analysis and random vibration analysis, and time histories that adequately envelop the DRS but may or may not envelop the minimum target PSD functions. One of the technical difficulties is to develop time histories with power deficiencies in specific frequency ranges that affect the adequacy of the calculated response of the models. The results of this effort would provide further insights into the development of target PSD functions and related PSD checks based on the effects of power deficiency on realistic SSCs.

3. Spectral Shape and Phase Spectrum of Recorded Seed Time Histories

A future effort would investigate the feasibility of establishing quantitative criteria for adequate similarity between the spectrum shape of the seed record and that of the DRS. Many real earthquake records would be examined to determine the metrics of the significance of the shape similarity between the RS of the seed records and DRS in predicting structural responses. The RES staff did not find such studies in the literature.

A related effort would study the significance of the phase spectra, in particular their uniformity, for structural response and confirm the view in the literature that phase spectra do not have a significant impact on structural responses (beyond the known variation that has been accounted for in practice by meeting the RS enveloping criteria, PSD check, ground motion specification, and factors in design equations). This would also involve development of a procedure or numerical criteria to determine the uniformity of the phase angle distribution.

4. Single Set versus Multiple Sets of Time Histories

There is general concern whether a single set of time histories should be allowed in seismic analysis and design of NPP SSCs, because a single set of time histories enveloping the DRS may not represent the potential seismic scenarios based on the findings from the deaggregation procedure in Regulatory Guide (RG) 1.208, “A Performance-Based Approach To Define the Site-Specific Earthquake Ground Motion,” issued March 2007. A single set of time histories enveloping a broadband DRS may be overly conservative as the DRS consists of both low spectral frequency events and high spectral frequency events. On the other hand, a single set may be less conservative than multiple sets as it includes only a single set of phase sequences. From a historical perspective, the practice of using a single set of time histories has been in place since the initial release of SRP Section 3.7.1 in 1975, and this method apparently was widely accepted before that time. Revision 2 of SRP Section 3.7.1 introduced the use of multiple time histories in 1989.

This research would involve a working group of staff from various offices and specialties to establish whether the use of a single set of time histories continues to be justified or adequate, or if future guidance should concentrate on the use of multiple sets of time histories. The work would account for the added clarity associated with the use of multiple sets of time histories, the improvements in computational power and the complexity of methods of seismic response analysis, and new design refinements and criteria that may be more sensitive to the randomness in the time histories.

5. Development of a Regulatory Guide for Acceptable Criteria and Methods for Generating Acceleration Time History

As Section 1.2.1 of this RIL indicates, the content of SRP Section 3.7.1 has grown significantly, and much of that growth relates to the acceptance criteria for artificial time histories. The discussion of time histories and the associated acceptance criteria in the main text of SRP Section 3.7.1 and its two appendices has reached a level of technical detail that is far greater than that in other typical technical areas in SRP Sections 3.7 and 3.8. This imparity with other SRP sections by itself would warrant the development of a standalone technical report (NUREG) or RG that can be referred to in SRP Section 3.7.1. The simplified SRP Section 3.7.1 would then require less revision and focus on guidance that is more specific to the NRC review processes.

This standalone document would allow more technical discussion to be included as needed. For example, it could include a critical appraisal of common methods for generation of time histories to identify issues that may be important to the safety of NPP SSCs but do not need to be included in the SRP guidance. The literature and practice offer many methods for generating artificial time histories. The resulting artificial time histories may have characteristics that can differ significantly from method to method.

To achieve a broader, more stable review practice in the program offices, this work would preferably be integrated with activities in the current Structural, Geotechnical, and Seismic Research Plan. These are the plans for the joint review of the updated consensus standard for seismic analysis of nuclear facilities. This review can integrate with the update of a set of existing NRC guidance documents for seismic analysis currently dispersed over various parts of SRP Sections 3.7 and 3.8, RGs, and interim staff guidance (ISG) documents in a risk-informed manner. The consensus standard of interest is the American Society of Civil Engineers/Structural Engineering Institute standard ASCE/SEI 4-16, “Seismic Analysis of Safety-Related Nuclear Structures.” Examples of relevant NRC guidance documents are RG 1.92, “Combining Modal Responses and Spatial Components in Seismic Response Analysis”; RG 1.122, “Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components”; RG 1.208, “A Performance-Based Approach To Define the Site-Specific Earthquake Ground Motion;” DC/COL-ISG-17, “Interim Staff Guidance on Ensuring Hazard-Consistent Seismic Input for Site Response and Soil Structure Interaction

Analyses"; and DC/COL-ISG-01, "Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications."

6. Development of Software Tools To Support Staff Review

To support technical reviewers in assessing the adequacy of artificial time histories, the development of computer tools for use in the review activities is recommended. These tools are expected to quickly and objectively determine the adequacy of the time histories. Since the acceleration time histories include thousands of data points and not all of their important technical aspects are observable directly from the data, the success of staff reviews without using computer tools would largely depend on what is described in the applications. The RES staff experience indicates that given the technical complexity of the issues related to acceleration time histories, application documents may not be able to effectively address these issues, and many requests for additional information and other costly regulatory actions such as audits are often needed. To this end, staff confirmatory analysis using computer tools can be much more efficient and effective. Even more effectively, these tools may be developed, validated, and maintained through a worldwide consortium drawn from academia, industry, and regulators.

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ABBREVIATIONS AND ACRONYMS

ACC	Accelerogram
ADAMS	Agencywide Documents Access and Management System
ASCE	American Society of Civil Engineers
CEUS	central and eastern United States
CFR	*Code of Federal Regulations*
COL	combined license
CSDRS	certified seismic design response spectrum (spectra)
DC	design certification
DRS	design response spectrum (spectra)
DTH	design time history
FFT	fast Fourier transform
FIRS	foundation input response spectrum (spectra)
g	acceleration due to gravity
Hz	hertz
ISG	interim staff guidance
ISRS	in-structure response spectrum (spectra)
km	kilometer
m	meter
M	moment magnitude of the earthquake
MSE	mean squared error
NIST	National Institute of Standards and Technology
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
P-CARES	Probabilistic Computer Analysis for Rapid Evaluation of Structures
PEER	Pacific Earthquake Engineering Research Center
PSA	peak spectral acceleration
PSD	power spectral density
PSHA	probabilistic seismic hazard assessment
RIL	research information letter
RES	Office of Nuclear Regulatory Research, NRC
RG	regulatory guide
RS	response spectrum (spectra, spectral)
RSA	response spectrum analysis
RVT	random vibration theory
s	second
SASSI	System for Analysis of Soil-Structure Interaction
SDOF	single degree of freedom
SEB	Structural Engineering Branch, NRO/DEI
SEI	Structural Engineering Institute
SGSEB	Structural, Geotechnical, and Seismic Engineering Branch
SRP	Standard Review Plan
SSC	structure, system, and component
SSI	soil-structure interaction
UH[R]S	uniform hazard response spectrum (spectra)
WUS	western United States
ZPA	zero-period acceleration

1 INTRODUCTION

1.1 Background

This research information letter (RIL) documents the results of work done by the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES) to develop or clarify guidance in NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" (the SRP), Section 3.7.1, "Seismic Design Parameters," Acceptance Criterion II.1.B, "Design Time Histories." SRP Section 3.7.1 provides options and approaches for the acceptance of acceleration time histories that the NRC staff considers appropriate for use as input ground motions in response analyses of nuclear power plant (NPP) structures. The program office staff has encountered difficulties in applying this guidance during its review of reactor licensing applications and has identified the eight technical issues addressed in this RIL. The goal of this work was to evaluate and resolve these technical issues. These issues relate to the acceptance criteria for the artificial acceleration time histories of ground motions for seismic-resistant designs of structures, systems, and components (SSCs) in NPPs.

RES has reviewed the relevant NUREGs and other NRC references to identify the technical basis and develop further rationales to resolve these issues. However, for some of these issues, RES's literature review could not identify sufficient information, and the staff performed targeted analytical work to demonstrate or develop the basis for the technical recommendation.

Section 1.2 briefly describes the revisions to SRP Section 3.7.1 to illustrate the evolving nature of the staff's guidance development in the area of acceptance criteria for time histories. Later sections of this RIL will describe in more detail the SRP acceptance criteria specific to each of the technical issues when they are addressed. Section 1.3 categorizes the eight issues into four groups to facilitate a coherent resolution to the issues. Section 1.4 describes the organization of this RIL.

1.2 SRP Section 3.7.1 Acceptance Criteria for Time Histories

1.2.1 A Brief History of SRP Section 3.7.1 Acceptance Criteria for Time Histories

SRP Section 3.7.1, Revision 4, issued December 2014, provides acceptance criteria for design ground motions for the seismic analysis and design of SSCs. Similar to other SRP sections, the NRC has revised SRP Section 3.7.1 to accommodate various enhancements and additions since its first release in November 1975. As shown in Figure 1-1, the content of SRP Section 3.7.1 has greatly expanded, from a mere 7 pages in Revision 0, issued November 1975, to 45 pages in Revision 4. This trend partly reflects the increase in the staff's experience resulting from its review of licensing applications and the overall advances in seismic analysis and design of SSCs, including the vastly improved access to highly capable computational technologies. Relevant to this RIL, much of the increase in information is devoted to the acceptance criteria for design input motion, including design time histories, showing the importance of time histories as upstream parameters in the whole process of seismic analysis and design. Today's advanced computational capability has renewed the staff's interest in exploring the practicality of using multiple time histories in seismic analysis in place of the legacy single time history approach, which was devised when computation was expensive and primitive decades ago. Seismic ground motions are random processes in nature and can be better characterized using multiple time histories.

To facilitate a history-informed clarification of existing guidance or development of technical bases for new guidance, the sections below summarize major technical positions and major changes in these revisions. Section 1.2.2 provides a summary of the structure and major components of the current acceptance criteria for the acceleration time histories in SRP Section 3.7.1, Revision 4.

1.2.1.1 Initial Release, November 1975

The title of the initial release of SRP Section 3.7.1, issued November 1975, was "Seismic Input," which was changed to "Seismic Design Parameters" with the issuance of Revision 1 (described below) in July 1981. As stated in the initial release, the time histories can be applied at the base of the idealized soil profile or at the foundation level of the Category I structures in the free field. The acceptance criteria for time histories to envelop response spectra (RS) require both a comparison of spectral values at all damping values and a review of the frequency intervals at which the RS values are calculated from the design time history (DTH). The frequency intervals must be small enough that any reduction in these intervals does not result in more than a 10-percent change in the computed RS. SRP Section 3.7.1, Table 3.7.1-1, which all revisions have retained without any changes, lists the acceptable frequencies. This version also indicates that an acceptable alternative method is to choose a set of frequencies such that each frequency is within 10 percent of the previous one. As for acceptance criteria for RS enveloping, the initial release states that no more than five points of the RS estimated from the time history should fall below the design response spectra (DRS) and that no point should fall below the DRS by more than 10 percent.

1.2.1.2 Revision 1, July 1981

SRP Section 3.7.1, Revision 1 (NUREG-0800, 1981), issued July 1981, indicates that the DTH used at various depths of the soil media in the free field shall be consistent with that developed or specified in SRP Section 2.5.2, "Vibratory Ground Motion." It further states that Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," to 10 CFR Part 100, "Reactor Site Criteria," specifies that, for soil-structure interaction (SSI) analysis or for the seismic design of structures, the design ground motion is applied at the foundation level of Category I structures in the free field. This revision specifically states that when recorded or specified time history is not available, an artificial time history may be generated from the DRS to carry out a time history analysis, and the RS obtained from such an artificial time history should generally envelop the DRS at all damping values to be used in the analysis. There is no difference in the criteria for RS enveloping compared to the criteria in Revision 0.

NUREG/CR-1161, "Recommended Revisions to Nuclear Regulatory Commission Seismic Design Criteria," issued May 1980, influenced this revision. NUREG/CR-1161 documents the results of the NRC-sponsored research programs under the NRC's Task Action Plan A-40 to identify and quantify the conservatism inherent in the seismic design sequence of the criteria in the SRP and regulatory guides. Technical areas covered in NUREG/CR-1161 include ground motion, SSI, structures, and equipment and components.

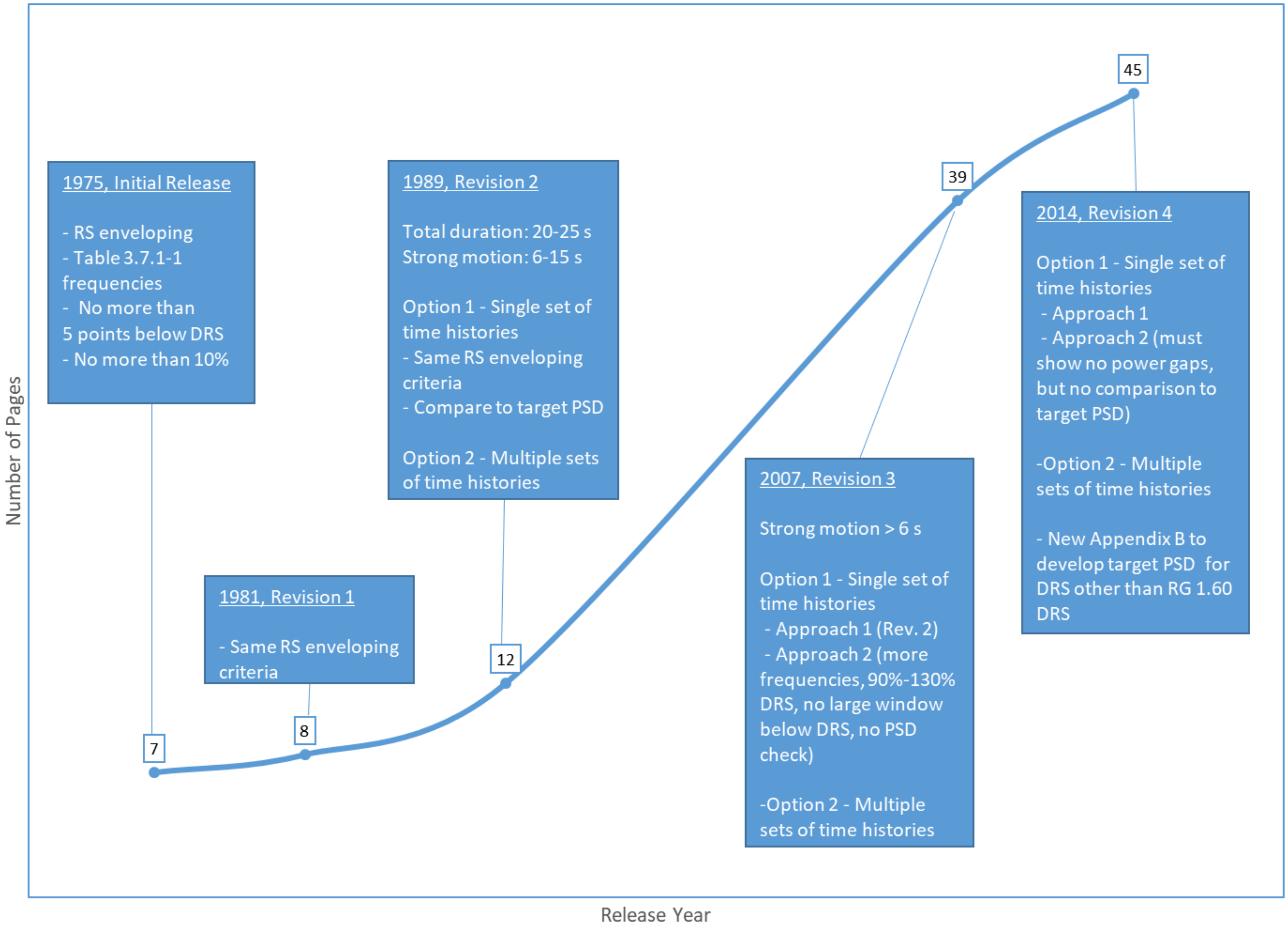


Figure 1-1 SRP Section 3.7.1 Revisions

1.2.1.3 Revision 2, August 1989

NUREG/CP-0054, “Proceedings of the Workshop on Soil-Structure Interaction,” held June 16–18, 1986; NUREG/CR-5347, “Recommendations for Resolution of Public Comments on USI A-40, ‘Seismic Design Criteria,’” issued June 1989; and NUREG/CR-3509, “Power Spectral Density Functions Compatible with NRC Regulatory Guide 1.60 Response Spectra,” issued June 1988, strongly influenced SRP Section 3.7.1, Revision 2, issued August 1989.

This revision states that the design ground motion can be specified at the top of the finished grade or at the top of the competent material, depending on data availability and soil profile conditions. This is the first revision to indicate clearly the use of “outcrop” in the specification of ground motions. This revision also distinguishes “free-field response spectrum,” which exhibits random peaks and valleys, from the “design response spectrum,” which generally is relatively smooth and is preferred in design. This revision clarifies that the DRS is defined as the mean plus one standard deviation (i.e., 84th percentile) RS, as defined in SRP Section 2.5.2. The provisions for the use of an appropriate recorded or specified time history or an artificial time history are the same as those in SRP Section 3.7.1, Revision 1.

This revision introduces two options for time history analysis using real or artificial time histories: Option 1 (single time history) or Option 2 (multiple time histories). It includes provisions for the total duration (10 to 25 seconds) and strong motion duration (6 to 15 seconds) of the time histories for linear analyses.

For Option 1, a target power spectral density (PSD) criterion must be satisfied in addition to the DRS enveloping criteria. The RS enveloping criteria and the frequency intervals at which the RS should be calculated from the time history have not changed from SRP Section 3.7.1, Revision 0 and Revision 1. Revision 2 recognizes that for the time histories enveloping the same DRS, their PSD functions can fluctuate significantly and randomly as a function of frequency; the more closely the time histories match the DRS, the more significantly and randomly the PSD functions fluctuate. More importantly, these fluctuations may lead to an unconservative estimate of responses of some SSCs. SRP Section 3.7.1, Appendix A, Revision 2, provides the target PSD function compatible with the DRS in Regulatory Guide (RG) 1.60, “Design Response Spectra for Seismic Design of Nuclear Power Plants,” Revision 1, issued December 1973, and describes how the one-side PSD function can be estimated from the time history and compared to the target PSD function.

For Option 2, a minimum of four time histories should be used for analysis; fewer time histories can be used but would be accepted on a case-by-case basis. Multiple time histories are acceptable if the average RS generated from these time histories envelop the DRS. Option 2 does not have PSD-related criteria. For nonlinear analyses, the time histories are reviewed on a case-by-case basis; these reviews consider the number of time histories, frequency content, amplitude, energy content, duration, number of strong motion cycles, and the basis for selection of time histories.

In summary, the major changes in this revision are the addition of the secondary PSD criteria to Option 1 and the addition of Option 2 for multiple time histories.

1.2.1.4 Revision 3, March 2007

SRP Section 3.7.1, Revision 3, issued March 2007, represents a major update 18 years after issuance of Revision 2. The new information in this revision appears to be consistent with NUREG/CR-6728, "Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines," issued October 2001. This revision states that the guidance in the following RGs can be used to develop seismic free-field ground motions:

- RG 1.60
- RG 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion" (withdrawn in 2010)
- RG 1.208, "A Performance-Based Approach To Define the Site-Specific Earthquake Ground Motion"

This revision also introduces several new terms to describe the ground motion: (1) ground motion response spectra for particular sites, (2) certified seismic design response spectra (CSDRS) for design certification (DC), and (3) foundation input response spectra (FIRS). This revision states that the requirements in Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," apply to applications for a DC or combined license under 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants," or a construction permit or operating license under 10 CFR Part 50.

SRP Section 3.7.1, Revision 3, has retained many aspects of Revision 2 concerning the acceptance criteria for time histories. The information below describes the changes and additions.

The statistical independence of the three components of ground motion needs to be demonstrated. Artificial time histories that are not based on recorded seed time histories should not be used. The time histories are also reviewed with regard to the strong motion duration based on the Arias Intensity and the ratios V/A and AD/V^2 (A, V, and D are the peak acceleration, peak velocity, and peak displacement, respectively). Nonlinear analysis should use multiple sets of real recorded ground motions appropriate for the characteristic low-frequency and high-frequency events, with the possible scaling of the amplitude while maintaining the phases.

Option 1 has two approaches: Option 1 in SRP Section 3.7.1, Revision 2, became Approach 1, and a new approach was added as Approach 2. For Approach 1, the frequency interval criterion for the RS calculation has been simplified to use only the acceptable frequencies in SRP Section 3.7.1, Table 3.7.1-1. The other two alternatives for frequency interval criterion, which were in Revision 0 through Revision 2 but were removed from Revision 3, require that (1) any reduction in frequency intervals does not result in more than a 10-percent change in the computed RS or (2) a set of frequencies can be chosen so that each frequency is within 10 percent of the previous one. As for the PSD check, the new Appendix B includes guidelines and procedures for DRS other than the RG 1.60 DRS.

The staff adopted Option 1, Approach 2, from NUREG/CR-6728. It includes provisions for the time histories to envelop only the 5-percent damped RS but requires the RS to be computed and compared at much denser frequency points than those of Approach 1. The computed RS shall not fall more than 10 percent below the DRS at any frequency and shall not fall below DRS in any consecutive frequency window that is larger than ±10 percent of any frequency. In addition, this approach also states that the computed RS should be below 130 percent of the DRS in lieu of the PSD criterion in Approach 1.

Option 2 is enhanced to provide more specific guidance on the number of time histories than included in the guidance of SRP Section 3.7.1, Revision 2. A minimum of four time histories should be used for linear analyses. For nonlinear analyses, the number of time histories must be greater than four, and the associated technical basis for the appropriate number of time histories is reviewed on a case-by-case basis. This revision also indicates that Option 1, Approach 2, is an acceptable method for meeting the Option 2 criteria, in terms of RS enveloping and power sufficiency, if it uses the averaged RS and averaged PSD of the suite of multiple time histories.

The major changes in this revision include the addition of Option 1, Approach 2, and the additions of Appendices B through D.

1.2.1.5 Revision 4, December 2014

The current revision of SRP Section 3.7.1 includes enhancements documented in the "Technical Rationale for Enhancements to Seismic and Structural Review Guidance," Revision 1, issued December 2014 (Xu et al., 2014). This revision more clearly introduces the various types of RS used in the seismic analysis of SSCs, such as performance-based surface RS, ground motion RS, FIRS, and CSDRS. The NRC significantly revised SRP Section 3.7.1, Appendix B, to introduce a new procedure to generate a target PSD function for any practical DRS other than the RG 1.60 horizontal DRS. Other enhancements include the selection of appropriate seed earthquake records, criteria for performing spectral matching, and criteria for the use of time histories for nonlinear analyses.

The NRC deleted SRP Section 3.7.1, Appendices C and D. Section 1.2.2 describes this revision in more detail.

1.2.2 The Current SRP Section 3.7.1 Acceptance Criteria for Time Histories

The eight specific issues in the Executive Summary cover only part of the acceptance criteria for acceleration time histories. To help appreciate how these issues fit in the entire set of acceptance criteria, this section summarizes the acceptance criteria in SRP Section 3.7.1, Revision 4.

The design time histories for the safe shutdown earthquake and operating basis earthquake can be either real time histories or artificial time histories, regardless of which option is used. The SRP guidance includes two options: Option 1 (single set of time histories) and Option 2 (multiple sets of time histories). Each set of time histories should consist of three mutually orthogonal components—two horizontal and one vertical. The three components should be shown to be statistically independent of each other by demonstrating that the absolute value of the correlation coefficient of each pair of time histories without shifting the starting time is smaller than 0.16. For generated time histories, the acceleration, velocity, and displacement should be compatible, and the displacement should have no baseline drift.

When developing artificial time histories, the seed time histories can be real recorded earthquake motions or, alternatively, can be generated using a random time history generator. The RS of recorded seed time histories should be similar in shape to the DRS across the frequency range of interest, and the phasing characteristics of the earthquake records should not change significantly. The acceptability of the artificial seed time histories is reviewed on a case-by-case basis.

For linear analysis, the ground motion time histories should be long enough to include an adequate representation of the Fourier components at low frequency. The stationary phase strong motion duration, defined as the time for Arias Intensity to rise from 5 percent to 75 percent, should be at least 6 seconds and should be consistent with the longest duration of strong motion from the earthquakes defined in SRP Section 2.5.2 at low and high frequencies and as presented in NUREG/CR-6728. The uniformity of the growth of Arias Intensity, which shows the degree of stationarity, should be reviewed. The ratios V/A and AD/V^2 should be consistent with the characteristic values for the magnitude and distance of the appropriate controlling events that define the uniform hazard RS and should be consistent with the values determined for the low- and high-frequency events in RG 1.208, Appendix D.

For nonlinear analysis, multiple sets of real or artificial ground motion time histories should be used. The amplitudes of these ground motions may be scaled, but phases of the Fourier components should be maintained. The adequacy of these ground motions is reviewed on a case-by-case basis.

For Option 1, Approach 1, the RS of the time histories calculated at the frequencies spaced with sufficient density or those listed in SRP Section 3.7.1, Table 3.7.1-1 (about 80 frequencies up to 50 hertz (Hz)) should envelop the DRS at all damping values used in the seismic analysis. The calculated RS should be no more than five points below the DRS at all frequencies and no more than 10 percent below the DRS at any frequency. Option 1, Approach 1, also requires, as a secondary check, the PSD function estimated from a DTH to envelop the minimum target PSD function compatible with the DRS. SRP Section 3.7.1, Appendix A, provides the target PSD function for the RG 1.60 horizontal DRS, and Appendix B provides a procedure for developing target PSD functions for other RS shapes.

Option 1, Approach 2 includes Steps (a) through (d) below:

(a) The time histories should have a sufficiently small time increment to achieve a Nyquist frequency of 50 Hz or higher if needed. The total duration of the time should be at least 20 seconds.

(b) Spectral accelerations at a 5-percent damping ratio should be computed for a minimum of 100 points per frequency decade, uniformly distributed on the log scale, from 0.1 Hz to the Nyquist frequency.

(c) The computed 5-percent damped RS should not fall more than 10 percent below the DRS at any frequency and should not fall below the DRS in a frequency window larger than ±10 percent centered at any frequency (e.g., a window of no more than 9 adjacent points for the case of 100 points per frequency decade in Step (b)).

(d) The computed 5-percent damped RS should not exceed the DRS by more than 30 percent at any frequency. In addition, the PSD function should be computed and shown to have no significant gaps in power over the frequency range of interest.

If the DRS are site-specific FIRS, the time histories developed following this approach should be consistent with characteristic values for the magnitude and distance of the appropriate controlling events, as defined for the corresponding uniform hazard RS. Option 1, Approach 2, currently does not explicitly require a comparison to a target PSD function when assessing power sufficiency.

For Option 2, an acceptable method used to demonstrate the adequacy of multiple time histories in terms of RS enveloping and power sufficiency is to follow Option 1, Approach 2, but replace the RS and PSD in Steps (c) and (d) with the average RS and average PSD of the suite of time histories.

For linear analyses, a minimum of four time histories should be used, and the average values of the responses may be used. For nonlinear analyses, more than four time histories should be used, and the maximum values of the responses should be used unless the number of time histories is at least seven when the average values of the responses can be used. Additional time histories should be considered if the extent of nonlinear responses is significant, or one or more time histories are found to be substantially different from the others.

1.3 Categorization of the Eight Issues

Some of the eight issues are related more closely than others, and they can be better addressed together. These issues are categorized below into four groups: (1) PSD functions, (2) seed time histories, (3) multiple time histories, and (4) others. Consultation with other staff members in the early stage of this project collected feedback that was instrumental in understanding these issues and in formulating the general approach to address them. The sections below also describe the affected SRP areas for each issue.

1.3.1 Issues Related to Power Spectral Density Functions

Issues 1, 3, and 8 and part of Issue 5 are related to PSD functions and target PSD functions. The information below summarizes these issues and the associated areas in the SRP guidance.

Issue 1: SRP Section 3.7.1, Option 1, Approach 1, explicitly requires a comparison of the PSD function of a DTH with a target PSD function that is compatible with the DRS to demonstrate sufficient power over the frequency range of interest. Option 1, Approach 2, does not explicitly require a comparison of the PSD function of the DTH with a target PSD function for the same purpose.

Guidance is needed on whether this demonstration is necessary for both approaches and the associated technical basis.

Issue 3: The SRP has two definitions for strong motion duration: (1) the time for the normalized cumulative Arias Intensity to rise from 5 percent to 75 percent and (2) the duration of near maximum and nearly stationary power in the time history. The evaluation identified additional definitions of strong motion duration. The strong motion duration in the SRP identifies the most damaging portion of a time history and is the normalization factor in the equation to estimate the PSD function of the time history. The SRP guidance states that the Fourier transform for the PSD estimation should use the strong motion portion of the time history, not the entire time history.

Guidance is needed on which of these two definitions should be used in the review, and if both are to be used, the basis for deciding which one to use and when.

Issue 5: The SRP has different guidance for the DRS enveloping criteria and the secondary PSD check, including the number of frequencies for RS calculation, specified damping ratios, and the frequency range for the PSD check. This issue includes the following three specific items:

(1) Option 1, Approach 1, uses fewer frequency points than does Approach 2 in RS enveloping.

(2) Option 1, Approach 1, uses more damping ratios (more RS curves) than does Approach 2 in RS enveloping.

(3) For the PSD check, SRP Section 3.7.1, Appendix A, requires a frequency range of 0.3 Hz to 24 Hz, whereas SRP Section 3.7.1, Appendix B, requires a frequency range of 0.3 Hz to an unspecified upper bound frequency that should be consistent with the RS shape.

Of these three items, Item 3 is related to PSD functions and is included in this group. Although Item 2 is related more to the RS enveloping criteria, it also requires some assessment of how to develop a target PSD function when multiple DRS at different damping ratios are specified. Therefore, Issue 5 will be addressed in this group and in the group for “Other Criteria.”

The issue is whether these differences are needed for the guidance and the basis for allowing such differences.

Issue 8: RES staff experience has shown that in some cases, the acceleration time histories developed following Option 1, Approach 2, can have power deficiencies in some frequency ranges, including low or high frequencies. Issue 8 focuses only on the effects on structural responses of power deficiencies at very low frequencies or high frequencies.

The following two general methods can be used to address the effect of power deficiency (this issue refers to the second method):

(1) Ensure that power is sufficient over the entire frequency range of interest during the development of input time histories.

(2) Assess the effect of power deficiencies on the structural responses.

The study documented in this RIL assesses the significance of a power deficiency at very low frequencies or high frequencies in the structural responses to allow a reasonable assurance of safety determination.

1.3.2 Issues Related to Seed Time Histories

Issues 2 and 4 are related to seed time histories that are used as the starting point to generate the artificial acceleration time histories.

Issue 2: The SRP recommends the use of recorded time histories as the seed for the generation of artificial time histories. This issue indicates a lack of specifics in the following guidance in the SRP:

> When the seed time histories are selected from earthquake records, the response spectra corresponding to the seed record should be similar in shape to the target spectra across the frequency range of interest to the analysis (e.g., Houston et al., 2010) and phasing characteristics of the earthquake records should not change significantly.

More specifically, this issue concerns the following two aspects:

(1) how to determine that a seed record is *similar* in shape to the DRS

(2) how to determine that the phasing characteristics are not changed *significantly*

The issue indicates a need for more specific acceptance criteria for seed time history records.

Issue 4: As an alternative, the SRP also allows the use of random generation routines to generate seed time histories. This issue concerns the artificially generated seed time histories but not the final artificial time histories used in seismic analysis. The SRP does not provide specific guidance but states that the staff will review the acceptability of the randomly generated seed time histories on a case-by-case basis.

The issue indicates a need for criteria for accepting artificial time histories as the seed.

1.3.3 Issue Related to Multiple Sets of Acceleration Time Histories

Issue 7: SRP Section 3.7.1, Option 2, provides acceptance criteria for the use of multiple sets of acceleration time histories in seismic analysis of SSCs. To demonstrate the adequacy of a set of multiple time histories, Option 2 indicates that the Option 1, Approach 2, procedure can be applied to enveloping DRS and demonstrating sufficient power. The existing guidance appears to be adequate because the Option 1, Approach 2, procedure is applied with the average RS and average PSD functions. In Option 2, an individual time history is not required to meet the Option 1, Approach 2, criteria.

This issue indicates a need to check whether the Option 2 guidance would still apply if Option 1, Approach 2, was changed based on the resolution of other issues.

1.3.4 Issues Related to Other Acceptance Criteria

Issue 5: As discussed in Section 1.3.1, Issue 5 covers three items related to PSD functions and others. This RIL addresses Item 3 and part of Item 2 in the context of a PSD check. In this category, this RIL addresses Item 1 and part of Item 2 of Issue 5 in the context of RS enveloping:

(1) Option 1, Approach 1, uses fewer frequency points than does Approach 2 in RS enveloping.

(2) Option 1, Approach 1, uses more damping ratios than does Approach 2 in RS enveloping.

The issue is whether these differences are needed and what is the basis for these differences.

Issue 6: SRP Section 3.7.1, Option 1, Approach 2, provides guidance on the minimum Nyquist frequency, time increment, and total duration of time histories, but Option 1, Approach 1, does not have similar criteria.

This issue indicates a need for clarification on the applicability (or lack of applicability) of these criteria to Approach 1.

1.4 Organization of the Research Information Letter

Section 2 documents the technical rationale and recommended guidance and clarification for Issues 1, 3, part of 5, and 8, which address technical areas related to PSD functions and target PSD functions. The topics covered in this section include the target PSD function criterion, strong motion duration, RS at multiple damping ratios, the frequency range used for PSD check, and the effect of power deficiencies on structural responses.

Section 3 presents the technical rationale and recommended guidance and clarification for Issues 2 and 4, which address areas related to recorded seed time histories and artificial seed time histories.

Section 4 addresses the technical rationale and recommended guidance and clarification for Issue 7. This issue relates to the Option 2 criteria for RS enveloping and PSD check for multiple sets of time histories. The specific task is to ensure that the acceptance criteria for Option 2 (multiple sets of time histories) continue to be adequate if Option 1, Approach 2, is revised because of changes made when addressing other issues.

Section 5 includes the technical rationale and recommended guidance and clarification for the remaining two issues (part of 5 and 6). These issues cover the number of frequencies in RS calculation, enveloping multiple RS at different damping ratios, the minimum Nyquist frequency, time increment, and total duration of time histories.

Section 6 summarizes the overall conclusions and recommends additional studies.

2 ISSUES RELATED TO POWER SPECTRAL DENSITY FUNCTIONS

As discussed in Section 1 of this RIL, SRP Section 3.7.1, Revision 2, was the first SRP revision to provide a PSD acceptance criterion to ensure an adequate power distribution in the design time history (DTH) throughout the frequency range of interest. Before this revision, the DTH was required only to envelop the DRS over the frequency range of interest at all damping values used in the analysis. NUREG/CR-5347 and NUREG/CP-0054 indicate that a DTH closely enveloping the DRS could have a significantly and randomly fluctuating PSD function that can lead to unconservative results for the responses of SSCs. NUREG/CR-5347 indicates that there are generally two methods for achieving the objective of preventing power deficiencies in the DTH. The first method is to assess the PSD functions, which NUREG/CR-5347 describes as a convenient approach. SRP Section 3.7.1, Revision 2, first implemented this PSD approach, and Revisions 3 and 4 later implemented the approach as Option 1, Approach 1. American Society of Civil Engineers (ASCE) 4-98, "Seismic Analysis of Safety-Related Nuclear Structures and Commentary," also adopted this approach.

As discussed in NUREG/CR-5347, the other method is to prevent potential power deficiency through stricter RS criteria, especially through those at a low damping level. Although this method was considered more practical, NUREG/CR-5347 recognized that RS do not provide a direct definition of input power because part of the power is dissipated in the form of viscous damping in the process of computing RS. In addition, specific criteria for this approach were not available at that time. NUREG/CR-5347 also identified two items that should be addressed to develop this approach: (1) the permissible frequency window for the damping considered in RS matching and (2) permissible amplitude difference in RS at this frequency window and in adjacent frequencies. NUREG/CR-5347 also provided preliminary recommendations on these two items: maximum 20 percent by average above the DRS within any ±20-percent frequency window centered at any spectral frequency, and 10-percent maximum dip below the DRS at any frequency. However, NUREG/CR-5347 indicated that further investigation of these recommendations was necessary. To this end, NUREG/CR-6728 proposed a set of criteria for RS enveloping to avoid the need for a direct assessment of power sufficiency. SRP Section 3.7.1, Revision 3, adopted those criteria as Option 1, Approach 2. Industry standards, such as ASCE/Structural Engineering Institute (SEI) 43-05, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities," and ASCE/SEI 4-16, "Seismic Analysis of Safety-Related Nuclear Structures," also adopted such criteria. However, recent applications of this approach (e.g., Houston et al., 2010) have shown that, in some cases, it can still lead to power deficiency and consequently to unconservative estimates of structural responses.

The above brief history shows the level of technical difficulty in developing methods to ensure power sufficiency. This section addresses those issues related to PSD functions. For each issue addressed in this section, the issue and excerpts of the affected SRP texts precede the technical discussion and recommendation.

2.1 Issue 1—Necessity of Target Power Spectral Density Functions

2.1.1 The Issue and Affected SRP Text

SRP Section 3.7.1, Option 1, Approach 1, explicitly requires a comparison of the estimated PSD function of a time history with a target PSD function compatible with the DRS to demonstrate the power sufficiency of the time history over the frequency range of interest. Option 1, Approach 2, does not explicitly require a comparison of the estimated PSD function of a time history with a target PSD function for the same purpose. Guidance is needed on whether this demonstration is necessary for both approaches and the associated technical basis.

The following two excerpts from the SRP show this difference. The first excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B.i, Option 1, Approach 1:

> Therefore, when a single design ground motion time history is used in the design of seismic Category I SSCs, it should satisfy criteria for both enveloping design response spectra as well as adequately matching a target PSD function compatible with the design response spectra. Therefore, in addition to the response spectra enveloping criterion, the use of a single time history should also be justified by demonstrating sufficient energy at the frequencies of interest through the generation of PSD function, which envelops the target PSD function throughout the frequency range of significance.
>
> …Regardless of the approach used, the development of the target PSD and the range of frequency for the PSD check are reviewed on a case-by-case basis. The PSD criteria are included as secondary check to prevent potential deficiency of power over the frequency range of interest.

The following excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B.ii, Option 1, Approach 2:

> The general objective is to generate a modified recorded or artificial accelerogram which achieves approximately mean based fit to the target response spectrum; that is, the average ratio of the spectral acceleration calculated from the accelerogram to the target, where the ratio is calculated frequency by frequency, is only slightly greater than “1.” The aim is to achieve an accelerogram that does not have significant gaps in the Fourier amplitude spectrum, but which is not biased high with respect to the target.
>
> …(d) The computed 5 percent damped response spectrum of the acceleration time history should not exceed the target response spectrum at any frequency by more than 30 percent (a factor of 1.3) in the frequency range of interest. In addition, the power spectrum density of the accelerogram should be computed and shown to not have significant gaps in energy at any frequency over this frequency range.

2.1.2 Technical Rationale and Basis

2.1.2.1 Literature Review

Since the release of Revision 2, SRP Section 3.7.1, Acceptance Criterion II.1.B.ii, Option 1, Approach 1, has provided the same rationale for the need to demonstrate sufficient power of acceleration at frequencies of interest. The estimated PSD functions should be greater than the minimum target PSD functions throughout the frequency range of significance. In particular, Option 1, Approach 1, indicates that studies had shown that time histories enveloping the same DRS can have quite different PSD functions, exhibiting significant and random fluctuations that may lead to unconservative results for the response of SSCs. In SRP Section 3.7.1, Revision 4, Appendices A and B provide target PSD functions and factors (less than 1) used to derive the minimum target PSD functions from the target PSD functions. SRP Section 3.7.1, Revision 4,

Appendix A, provides the target PSD function for the RG 1.60 horizontal DRS, and Appendix B provides a procedure for the development of target PSD functions for other DRS. Both appendices are consistent with NUREG/CR-5347, Appendix B. The staff has used the guidance and procedures for target PSD functions in multiple reviews of licensing applications.

NUREG/CR-5347 and NUREG/CR-3509, which were referenced in SRP Section 3.7.1, Revision 2, provide methods for the development of target PSD functions and artificial time histories for the RG 1.60 DRS, based on the Kanai-Tajimi PSD function. NUREG/CR-3509 indicates that artificial time histories should be developed using a PSD function without power deficiencies to dispel the concern that the generated time histories may be deficient in power over certain critical frequency windows. This report also recommends that an acceptable artificial acceleration time history should envelop both the DRS and a prescribed percentage of the target PSD function in the entire frequency range under consideration. NUREG/CR-5347, Appendix A, "Comments on Proposed Revisions to Standard Review Plan Seismic Provisions," provides an extreme example of a sinusoidal ground motion at 0.6 Hz to show that a time history enveloping the DRS can have severe power deficiencies (actually having power only at a single frequency of 0.6 Hz). Subjected to this sinusoidal ground motion at 0.6 Hz, NPP structures with a fundamental frequency of 2 Hz or higher would respond pseudo-statically and would have no resonant amplification because of the lack of power in the motion around their resonant frequencies. Equipment installed in such structures would experience only the same ground motion without the amplification effect of the supporting structures. In-structure response spectra (ISRS) for this case would be far less than those generated using a broadband ground motion at the structure's resonant frequencies. NUREG/CR-5347 also notes that although such an extreme case would not be accepted in practice, real design time histories, broadbanded but significantly deficient in power over large frequency windows (e.g., ±20 percent), would still lead to severe underestimates of ISRS even though the time histories have excessive power at other frequencies so that they meet the RS enveloping criteria. In NUREG/CR-5347, Appendix A, the late Dr. Robert Kennedy indicated that this situation had occurred in a few instances in the nuclear industry, but he did not elaborate on any particular analytical work that examined the effect of power deficiencies in time histories on structural responses.

In addition to supporting the SRP update to include a criterion for PSD functions, Dr. Kennedy mentioned an alternative approach to ensure adequate power distribution through closely matching a low-damped RS (such as 2-percent damping) over the entire frequency range. His reasoning was that time histories closely matched to low-damped DRS would not be able to have excess power over one frequency range masking a power deficiency in another frequency range. However, generally agreeable numerical acceptance criteria were not available at the time to determine how closely DTH should match the DRS. Note that the applications of Option 1, Approach 1, have often included the 2-percent damped DRS, but this approach was still determined to require the secondary PSD check. This observation casts doubt on the feasibility of this alternative approach.

An article in NUREG/CP-0054 briefly states that a time history generated to meet or exceed the DRS can have widely varying PSD functions, which can lead to both conservative and unconservative estimates of structural response. However, this article did not provide more technical details to support this claim.

The staff added Option 1, Approach 2, to SRP Section 3.7.1, Revision 3, based on the recommendations in NUREG/CR-6728, with minor adjustments. This approach represents a followup to the approach using RS to ensure power sufficiency, as envisioned in

NUREG/CR-5347. Section 5, “Criteria for Evaluation of Ground Motions for the Analysis of Nuclear Facilities,” of NUREG/CR-6728 recommends that, to avoid a check against a minimum target PSD function, the power sufficiency of a time history can be demonstrated if its 5-percent damped RS does not exceed the DRS by more than 30 percent at any frequency between 0.2 Hz and 25 Hz. It further states that, if all the recommended (Option 1, Approach 2) criteria are met, the time histories should be adequate to ensure that no gaps in the PSD functions or Fourier amplitude spectra will occur over a significant frequency range; therefore, there is no special need to compare the estimated PSD functions to minimum target PSD functions.

In addition, NUREG/CR-6728 used examples to demonstrate that gaps in Fourier amplitude spectra over a frequency window of ±20 percent led to reductions in RS at a similar level between 1 Hz and 10 Hz, at a half level at 0.5 Hz (low frequency) and at 15 Hz (a relatively high frequency), and at a significantly smaller reduction level at 25 Hz. In other words, this observation indicated that a smaller or significantly smaller reduction in the RS at low frequencies or at high frequencies could not reveal the large gap in the Fourier amplitude spectra, which translates to a gap in the PSD function at the same frequencies. Note that the frequencies for these correlations between the PSD and RS depend on the RS shape. As demonstrated later in this section, gaps in power distribution in a time history do not necessarily lead to a reduction in RS so as to violate the RS enveloping criteria. NUREG/CR-6728 also used sine waves to demonstrate the need to have a maximum allowable spectral exceedance criterion, but the report did not explain the basis for the choice of 130-percent DRS in the proposed method, which SRP Section 3.7.1, Revision 3, adopted.

If the 130-percent DRS upper bound criterion is not met, SRP Section 3.7.1, Revision 3, Option 1, Approach 2, states that the PSD function should be computed and shown to not have significant gaps in power at any frequencies over the frequency range of interest. However, it does not prescribe whether this demonstration should be based on a comparison to a target PSD function. The first clause in Step (d) in Revision 3 of this approach indicates that the 130-percent DRS criterion is intended to replace the PSD criterion in Approach 1 in which target PSD functions are required, as follows:

> …(d) *In lieu of the power spectrum density requirement of Approach 1*, the computed 5% damped response spectrum of the artificial ground motion time history shall not exceed the target response spectrum at any frequency by more than 30% (a factor of 1.3) in the frequency range of interest. If the response spectrum for the accelerogram exceeds the target response spectrum by more than 30% at any frequency range, the power spectrum density of the accelerogram needs to be computed and shown to not have significant gaps in energy at any frequency over this frequency range.

In practice, it is not difficult to develop an artificial time history whose RS is below 130-percent DRS; therefore, evaluating its PSD function is effectively not necessary in practice following the above guidance. In fact, NUREG/CR-6728 does not even mention the alternative of the PSD check for situations in which the 130-percent DRS criterion is not met.

However, based on the staff’s experience in reviewing several licensing applications and the experience of an industry expert who significantly contributed to Option 1, Approach 2, acceleration time histories developed using this approach can sometimes still have power deficiencies in some frequency ranges. Moreover, the study by Houston et al. (2010) used hundreds of time histories that met the Option 1, Approach 2, criteria and showed that meeting those criteria cannot prevent some time histories from having power deficiencies in large frequency windows. This study concluded that the power deficiencies could lead to an unconservative estimate of ISRS by as much as 70 percent (see a more detailed description in Section 2.4.2.1 of this RIL). These experiences reaffirm that RS enveloping criteria in Option 1, Approach 2, are not sufficient to ensure power sufficiency.

Revision 4 of SRP Section 3.7.1 has enhanced Step (d) in Option 1, Approach 2, to require both satisfying the 130-percent DRS upper bound criterion and showing that the PSD function does not have significant gaps in power. However, this revision does not specifically require a comparison to target PSD functions. Revision 4 has removed the beginning clause in Step (d): "In lieu of the power spectrum density requirement of Approach 1." It should be emphasized that the application of Option 1, Approach 2, is satisfactory in many cases where time histories meeting the RS enveloping criteria would also envelop the minimum target PSDs if a PSD assessment had been performed. The initial adoption of this approach in SRP Section 3.7.1, Revision 3, the later enhancements in Revision 4, and the current effort to address this issue (and other related issues) in this RIL merely demonstrate the new evidence in the application of this approach and the technical advances made possible by this evidence.

In both Approach 1 and Approach 2, the RS enveloping criteria serve largely the same role, whereas the current Approach 2 lacks the criterion of target PSD functions in evaluating the power sufficiency of the artificial acceleration time histories. Therefore, these two approaches are not functionally equivalent because the choice of an approach can lead to time histories that have different behavior in power adequacy.

As NUREG/CR-5347 similarly characterizes the PSD check as a convenient approach, the enhancement in the current SRP revision has made the PSD check against target PSD functions convenient, direct, and less problematic in practice. SRP Section 3.7.1, Revision 4, Appendix B, has provisions for standardized concepts and procedures to facilitate the PSD check, such as the definition of strong motion duration, standardized Fourier transform of the strong motions, application of tampering functions, PSD smoothing, and a procedure to generate target PSDs for practical DRS.

The above literature review indicates that Option 1, Approach 1, can avoid the problem of power deficiency by using target PSD functions, while Option 1, Approach 2, can result in time histories with power deficiencies. The following sections explain why RS enveloping alone is not adequate, give examples that show the need for target PSD functions for the assessment of power sufficiency, and clarify that a target PSD function can be "uniquely" developed for any given practical DRS. The last section provides the conclusions and recommendation.

2.1.2.2 Discussion of Response Spectra Enveloping and Power Sufficiency

In the current methodologies for seismic analysis and design of NPP SSCs, DRS (e.g., FIRS and CSDRS) are used to specify the ground motion. Response spectrum analysis (RSA), one of the widely applied methods for seismic analysis, uses DRS to estimate the structural responses with acceptable conservatism. Depending on the option chosen following the SRP guidance, either a single set of time histories or multiple but limited sets of time histories are also commonly required to generate some structural responses such as ISRS, which RSA cannot produce. Compared to DRS, acceleration time histories have more parameters and consequently more variabilities. At a high level, time histories can be considered as surrogates for the DRS in transferring the ground motion demand to the SSCs. However, because many time histories can be developed to represent the same DRS, some time histories may have features or defects that can lead to significant underestimation of structural responses, which is contrary to the common impression that the time history analysis method is more rigorous than other methods These features or defects are often very difficult to identify or detect. This issue is especially prominent when the number of time histories is small for a seismic analysis following the current SRP guidance. Recognizing the important role of the time histories as surrogates for the DRS, this section explains that RS enveloping criteria alone are not adequate to determine the power sufficiency of acceleration time histories.

NUREG/CR-5347 envisioned that an appropriate set of criteria for RS enveloping might be able to conveniently prevent power deficiency in time histories. Along the same line, the approach proposed in NUREG/CR-6728 and adopted in ASCE/SEI 43-05 and the SRP Section 3.7.1 guidance (since Revision 3) includes numerical criteria that require the estimated RS to fall between 90- and 130-percent DRS to ensure the power sufficiency of the time histories. However, as discussed above in Section 2.1.2.1, this approach, in practice, is incapable of ensuring that a time history is power sufficient over the frequency range of interest. The literature review described above indicates that such power-deficient time histories can underpredict the ISRS by as much as 70 percent. This section attempts to explore why RS enveloping criteria alone are not capable of ensuring power sufficiency.

By definition of an RS, the only assurance that RS-based criteria can provide is how close the maximum responses of the single-degree-of-freedom (SDOF) oscillators are to the DRS at their fundamental frequencies. They can neither (1) restrict the time when a maximum response occurs along the time history (e.g., a maximum response can occur inside or outside of the strong motion duration) nor (2) prescribe which frequency components in the time history contribute the most to a particular maximum response in the RS. Following these two thoughts, examples are given below to show that RS enveloping criteria are satisfied but that the time histories clearly are not acceptable in practice.

For the first thought, a time history can be constructed by concatenating many segments of miniature time histories, each of which is a sinusoid at a single frequency. Each miniature time history creates the maximum response of a particular oscillator in the series of oscillators in generating the RS. These miniature time histories may be separated in the final time history by zero padding so that the responses to these individual miniature time histories do not combine with each other. This time history can match the DRS exactly because each sinusoid can be scaled linearly and independently so that its maximum response equals the DRS at the frequency of this sinusoid. This is a much stricter match than the criteria of 90- to 130-percent DRS currently specified in Option 1, Approach 2. Figure 2-1 illustrates a train of 75 carefully constructed wavelets at frequencies from 0.2 Hz to 33 Hz, taking the SRP Option 1, Approach 1, frequencies tabulated in SRP Table 3.7.1-1. This time history is highly frequency nonstationary because the frequencies of the wavelets increase as a function of time. This figure also shows that the calculated RS of the wavelet train very closely matches the RG 1.60 DRS. The differences between the calculated RS and the RG 1.60 DRS result from the RS of the wavelet train being computed using 100 frequencies per frequency decade, which is much denser than the 75 frequencies associated with the wavelets. Another probable reason for the differences is that zero padding between the high-frequency wavelets is not sufficiently long.

Certainly, this time history is not acceptable in practice. However, without using other means to prevent the maximum responses from occurring anywhere in the time history, a time history constructed in this manner can perfectly meet the RS enveloping criteria to the strictest level. Although this unrealistic time history was constructed by concatenating miniature time histories, it exemplifies a typical problem of frequency nonstationarity by which two or more bands of frequency components do not occur in the same duration of the time history. The problem with frequency nonstationarity is that the structural responses to these frequency bands are not combined and the total responses are underpredicted. Unlike the extreme case shown in Figure 2-1, plots of these types of time histories often do not detect the problem of frequency nonstationarity because the clouds of many data points are not much different from time history to time history. However, a comparison of the PSD function estimated from the strong motion portion with the minimum target PSD function that is compatible with the DRS can identify this problem. For example, Figure 2-2 shows a PSD check of the train of wavelets, clearly identifying that this time history is power deficient by orders of magnitude compared to the minimum target PSD function described in Appendix A to SRP Section 3.7.1. Although the frequency nonstationarity is one of the issues that a comparison of a PSD check with minimum target PSDs can identify, the PSD check based on the strong motion alone cannot distinguish this issue from other issues. To identify the frequency nonstationarity issue, one needs to explore some other techniques such as the evolutionary PSD.

A National Institute of Standards and Technology (NIST) report, GCR-11-917-15, “Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analyses,” issued November 2011, similarly notes the frequency nonstationarity issue and makes the following statement:

> Anecdotally it seems that records of longer duration may converge more easily in RspMatch2005, and may also be modified less by the process. This makes some intuitive sense, as a longer record may have less correlation between the times at which peaks occur, and therefore, RspMatch2005 would alter different portions of the record for matching spectral ordinates at different periods. The longer duration records that pass through this screening may bias the demand for duration-sensitive structures.

For the second thought, the RS enveloping criteria cannot guarantee the correlation between the spectral frequency at which an oscillator reaches its maximum response and the major frequencies in the time history that contribute to the maximum response of the oscillator at this spectral frequency. This correlation is important for a time history to represent appropriately the DRS in seismic analysis because DRS are intended to represent the power distribution of the underlying ground motion using the maximum responses of oscillators. Otherwise, the results of the RSA method can be significantly different from those of the time history analysis method. The lack of such correlation would fail the role of the time history as a surrogate for the DRS. The previous example consisting of miniature time histories is another type of unacceptable representation of the DRS. The next example is to demonstrate the problem in which one or more frequency bands mask other frequencies in the RS enveloping process so that the resultant time history is deficient in power at those frequencies being masked.

The example of the sinusoidal ground motion at 0.6 Hz used in NUREG/CR-5347 indicated that an SSC at 2 Hz or above would behave pseudo-statically without amplification and that the response of the SSC would be underpredicted. However, this example does not meet the 90- to 130-percent DRS criterion in Option 1, Approach 2. The example below shows a case in which the time history meets the RS enveloping criteria, has usual appearance in time domain, and does not have the problem of frequency nonstationarity, but it is still not acceptable because of an obvious indication of power deficiencies.

In this example, 15 sinusoids were combined and then used as the seed record to generate a synthetic acceleration time history. These sinusoids were assumed to have random phases, and their frequencies were spaced linearly from 0.3 Hz to 24 Hz on the log scale. The amplitudes of these 15 sinusoids were initially selected so that a linear combination of their RS would fit best to the RG 1.60 horizontal DRS, as shown in Figure 2-3. Using the Option 1, Approach 2, RS enveloping criteria, some iterations and manipulations were performed on this seed to envelop the DRS. In this process, some low-amplitude components at other frequencies were inevitably introduced by baseline correction, application of intensity function, high pass filtering, and fractional folding. These procedures were necessary to remove residual velocity and displacement, introduce the rise and decay periods into the time history, remove very low frequency components, and chop acceleration peaks larger than zero-period acceleration (ZPA), respectively. The inclusion of these low-amplitude components was also necessary to meet the DRS enveloping criteria. Figure 2-4 shows that the RS of the resultant acceleration time history meets the Option 1, Approach 2, criteria from 0.1 Hz to 100 Hz. Figure 2-5 shows the acceleration, velocity, and displacement time histories. Although some effort to remove the very low frequencies from the time history can improve the overall appearance of the displacement time history, the acceleration time history and the velocity time history appear to be reasonable. Figure 2-6 and Figure 2-7 show the Fourier spectra with the frequency in linear scale and log scale, respectively. It is clear that the phase angles are uniformly distributed. Except for the first 2 major frequencies, Figure 2-7 clearly identifies the other 13 major frequencies, with their amplitudes significantly larger than the surrounding low-amplitude components.

Figure 2-8 shows a PSD check of this acceleration time history in which the strong motion duration was selected to be 10.6 seconds based on the Husid plot. The target PSD function is from SRP Section 3.7.1, Appendix A. The PSD check clearly shows that the raw PSD function is generally and significantly lower than the minimum target PSD function, indicating severe power deficiencies at many frequencies. The minimum target PSD function is 80 percent of the Appendix A target PSD function according to the guidance. However, quite surprisingly, the smooth PSD function using a ±20-percent frequency window does not represent the mean PSD curve in this particular case and could suggest that the power would be almost sufficient over the entire frequency range. In addition, the smooth PSD curve has peaks/values in the reverse direction as compared to the raw PSD curve because the ±20-percent frequency window can cover two spikes or only one spike depending on the location of the central frequency. In contrast, Figure 2-9 shows a PSD check with a ±10-percent frequency window for smoothing, which appears to produce a mean PSD curve that generally follows the raw PSD function. Even better, Figure 2-10 shows that a ±5-percent frequency window for smoothing produces a mean curve representing the trend of the raw PSD curve very well. In fact, the half-power window width for the amplification function of a 5-percent damped oscillator is 10 percent (i.e., ±5 percent). This observation suggests that PSD checks should probably also require an assessment of the raw PSD curve to see whether the ±20-percent frequency window is too large to produce a reasonable mean PSD curve.

This example clearly shows that the RS enveloping criteria alone, as currently given in Option 1, Approach 2, are not able to ensure power sufficiency and that this approach must be used in conjunction with a PSD check against the minimum target PSD function to determine whether the distribution of power is adequate over the frequency of interest.

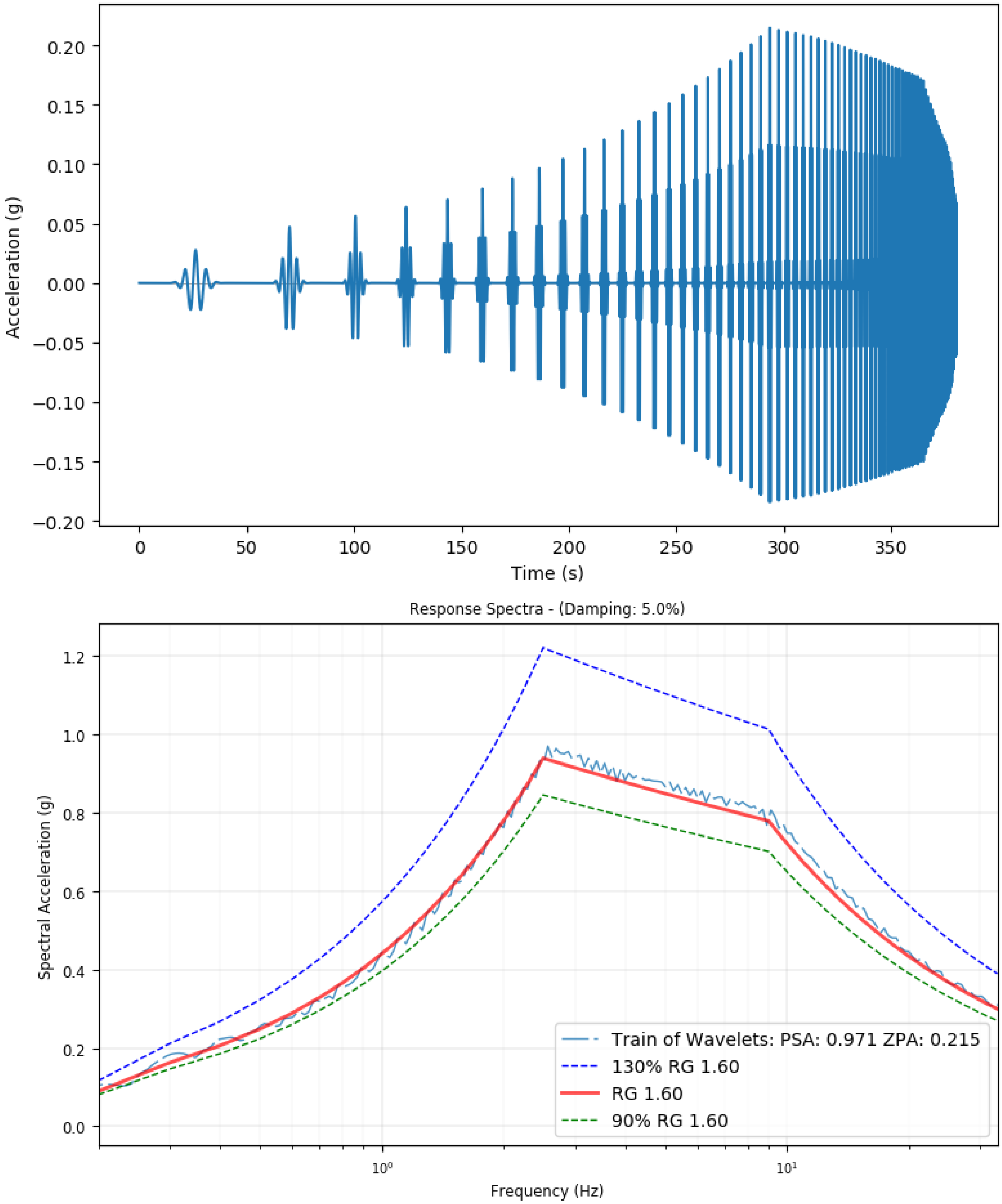


Figure 2-1 Illustration of a train of wavelets that matches well with the RG 1.60 DRS

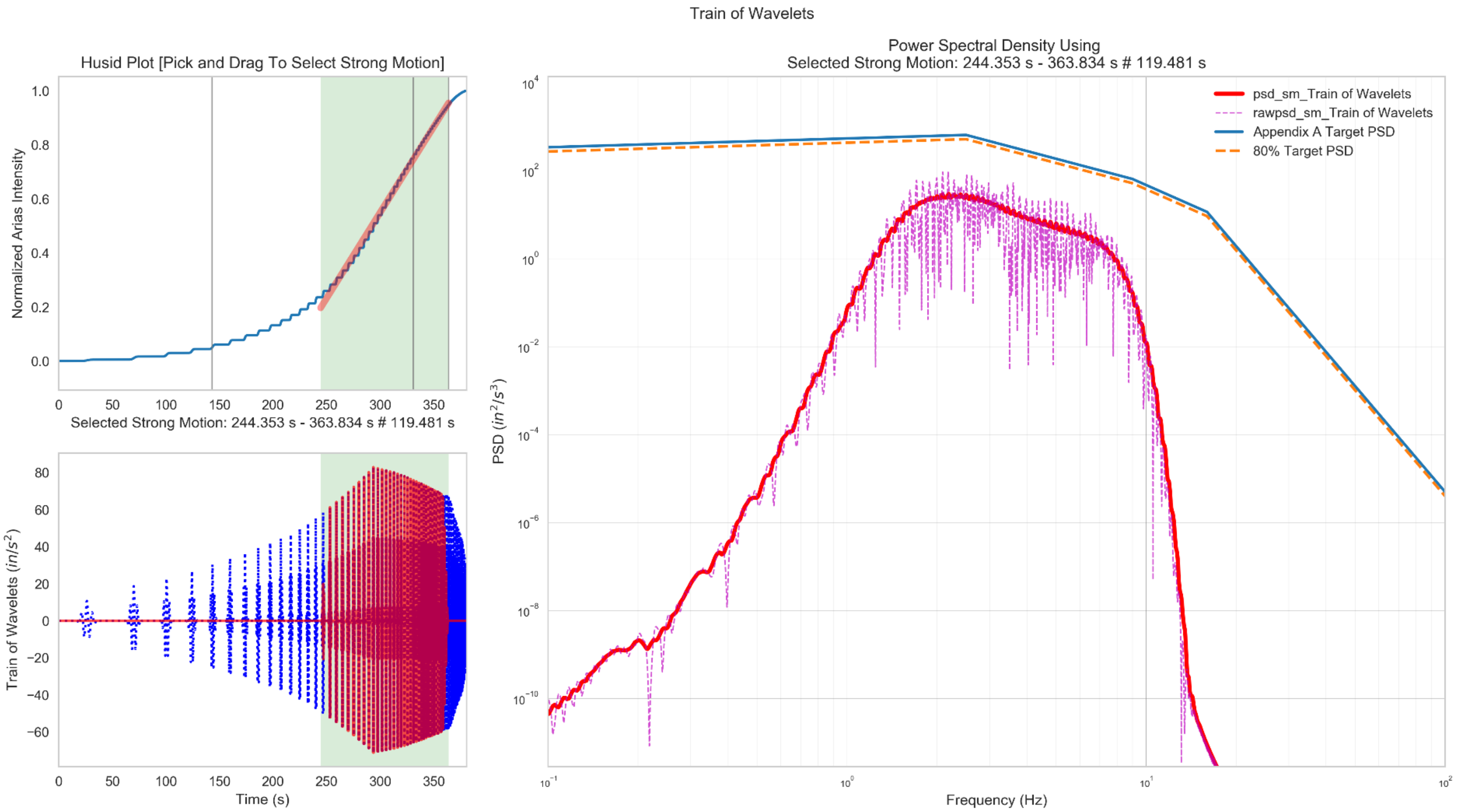


Figure 2-2 PSD check of the train of wavelets (±5 percent window)

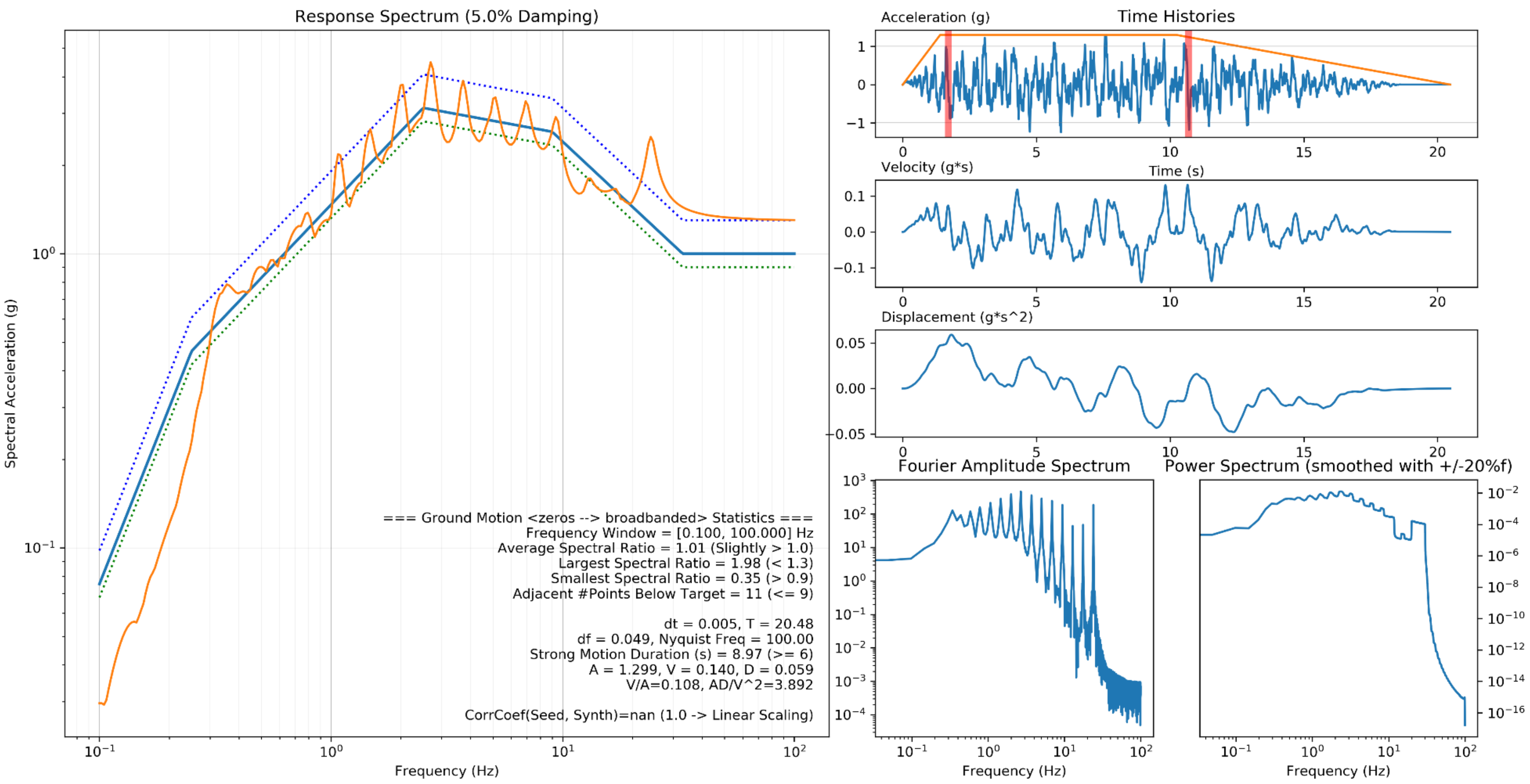


Figure 2-3 Seed with 15 frequencies

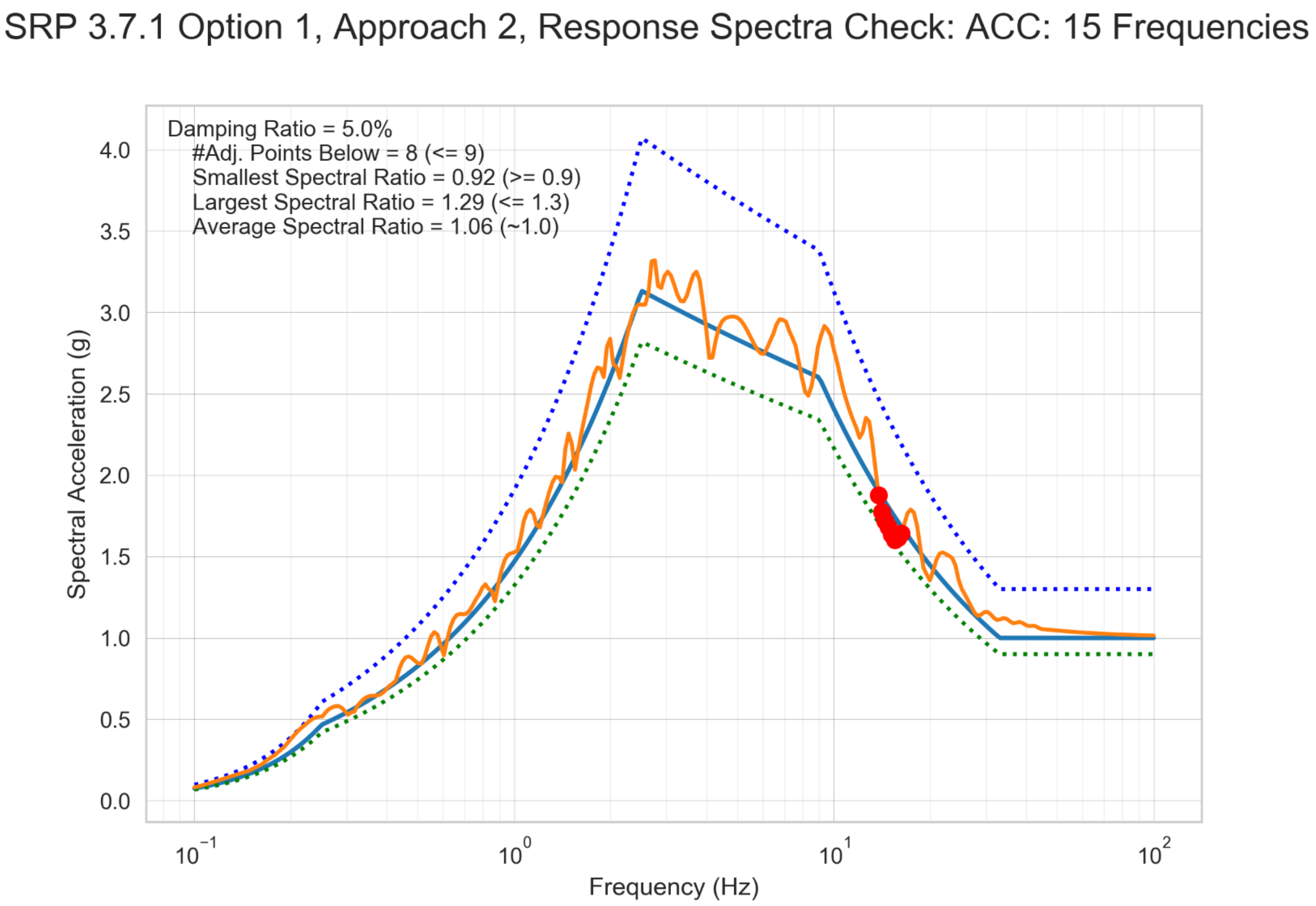


Figure 2-4 Accelerogram with 15 major frequencies that meet the Option 1, Approach 2, criteria (piecewise smooth curves showing the criteria)

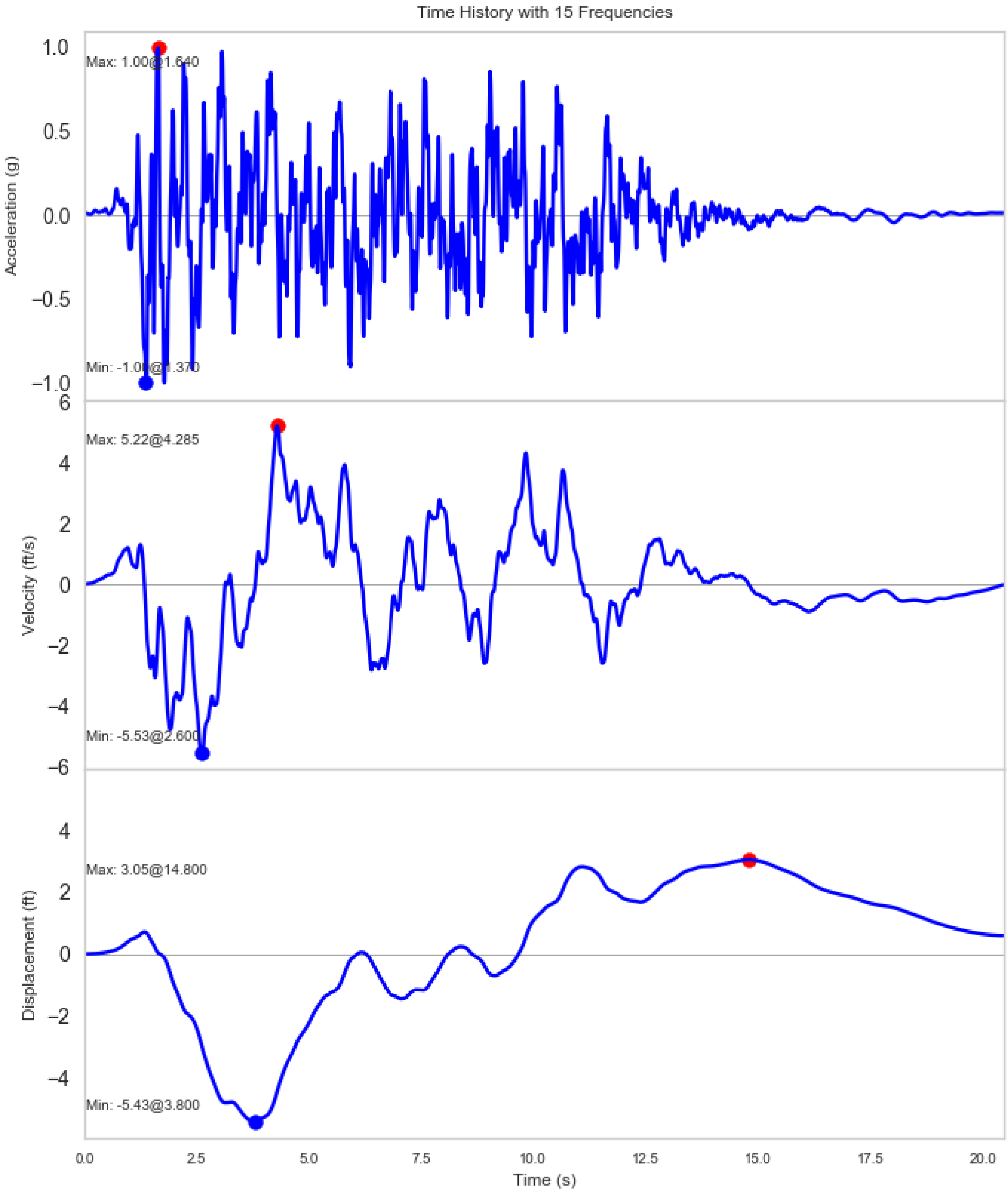


Figure 2-5 Acceleration, velocity, and displacement time histories with 15 major frequencies

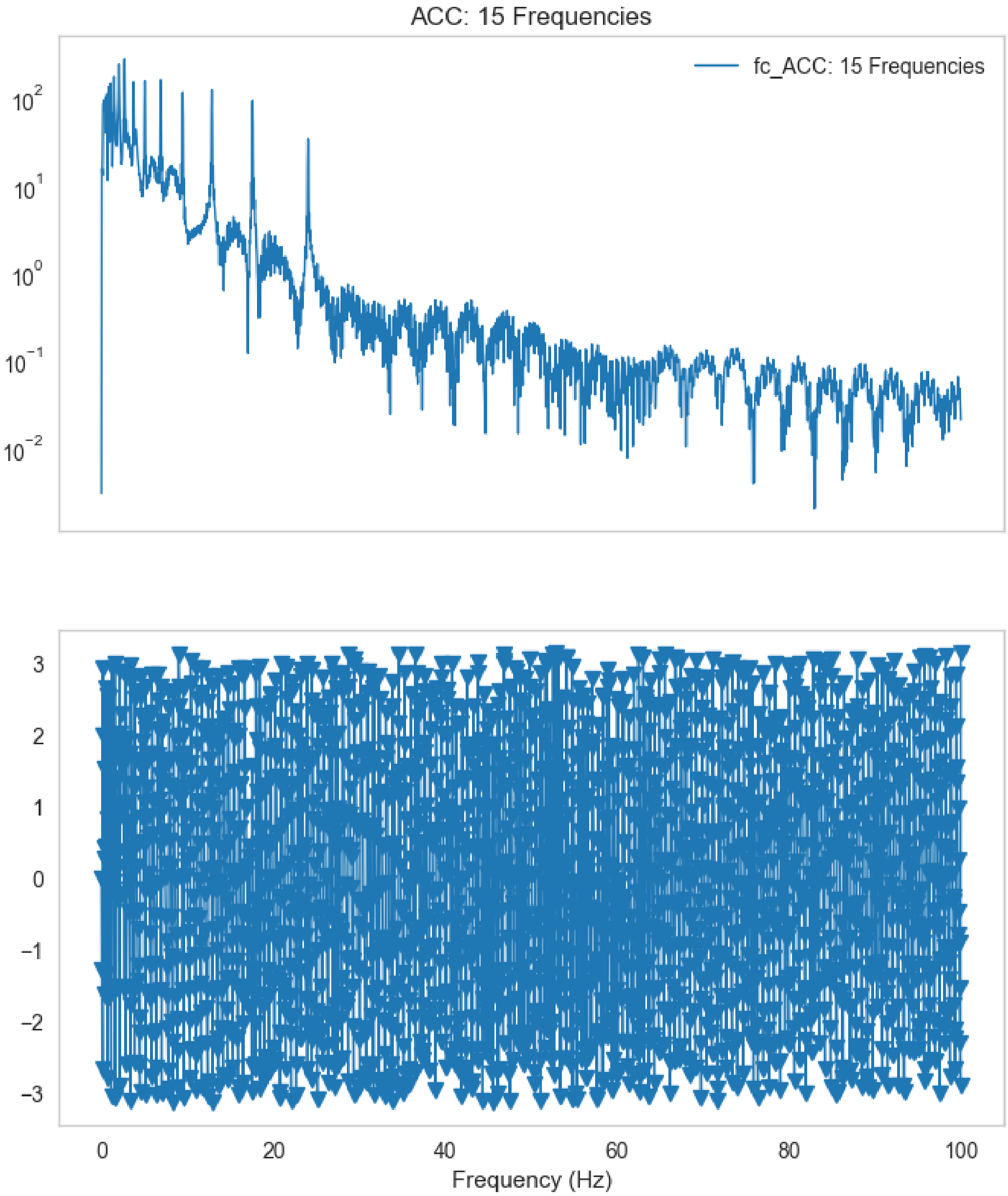


Figure 2-6 Fourier spectra with the frequency in linear scale

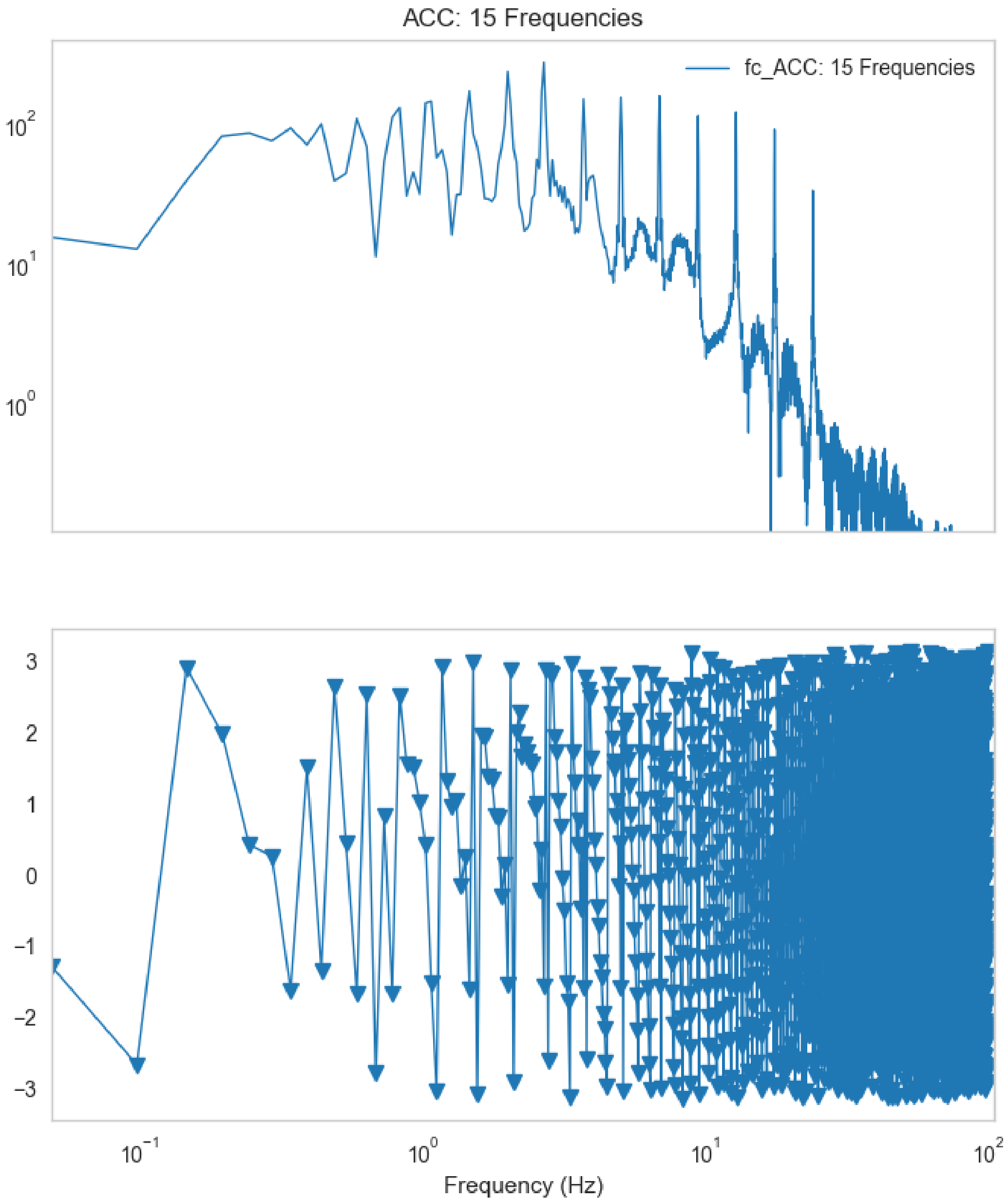


Figure 2-7 Fourier spectra with the frequency in log scale

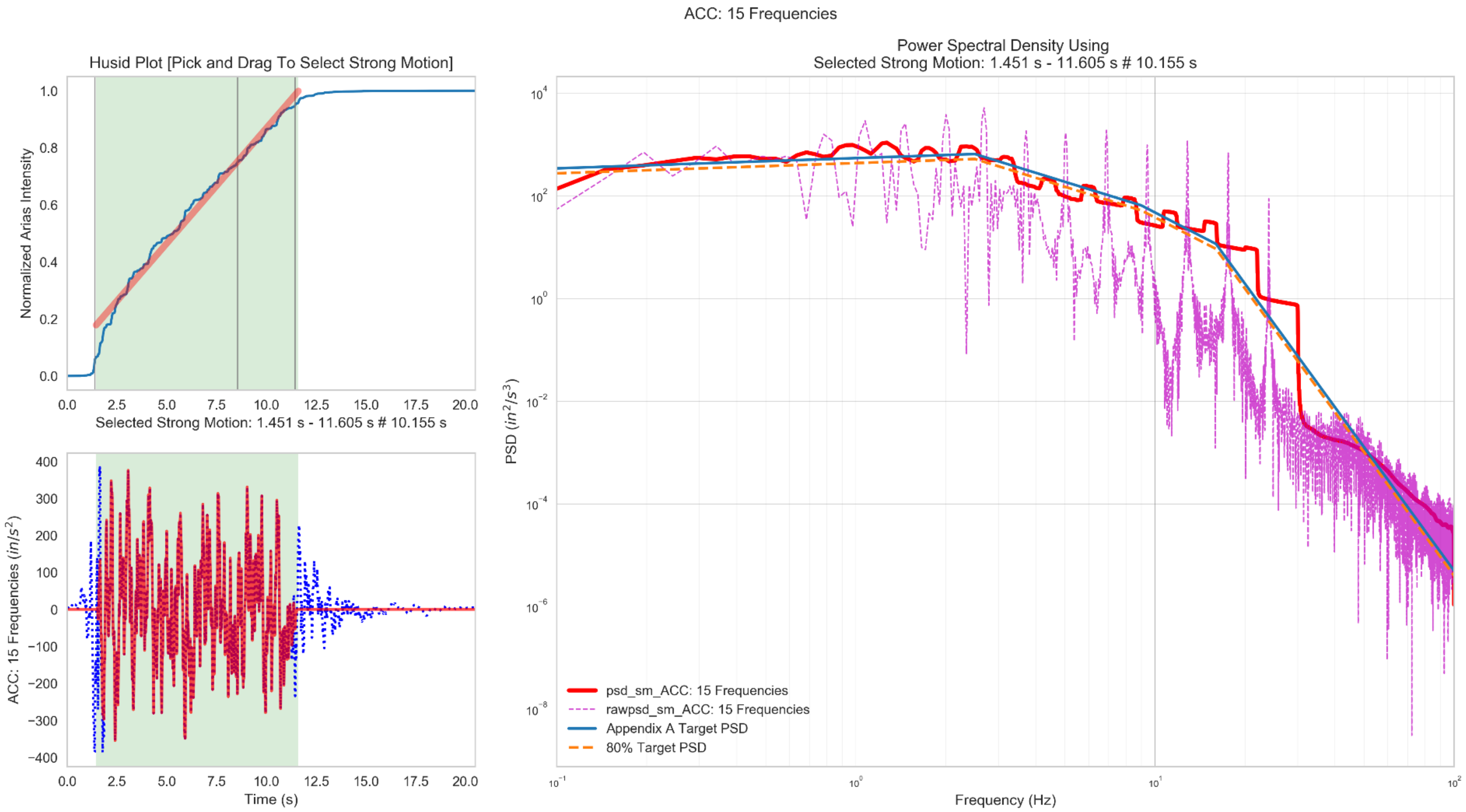


Figure 2-8 PSD check of the accelerogram with 15 major frequencies (±20-percent window)

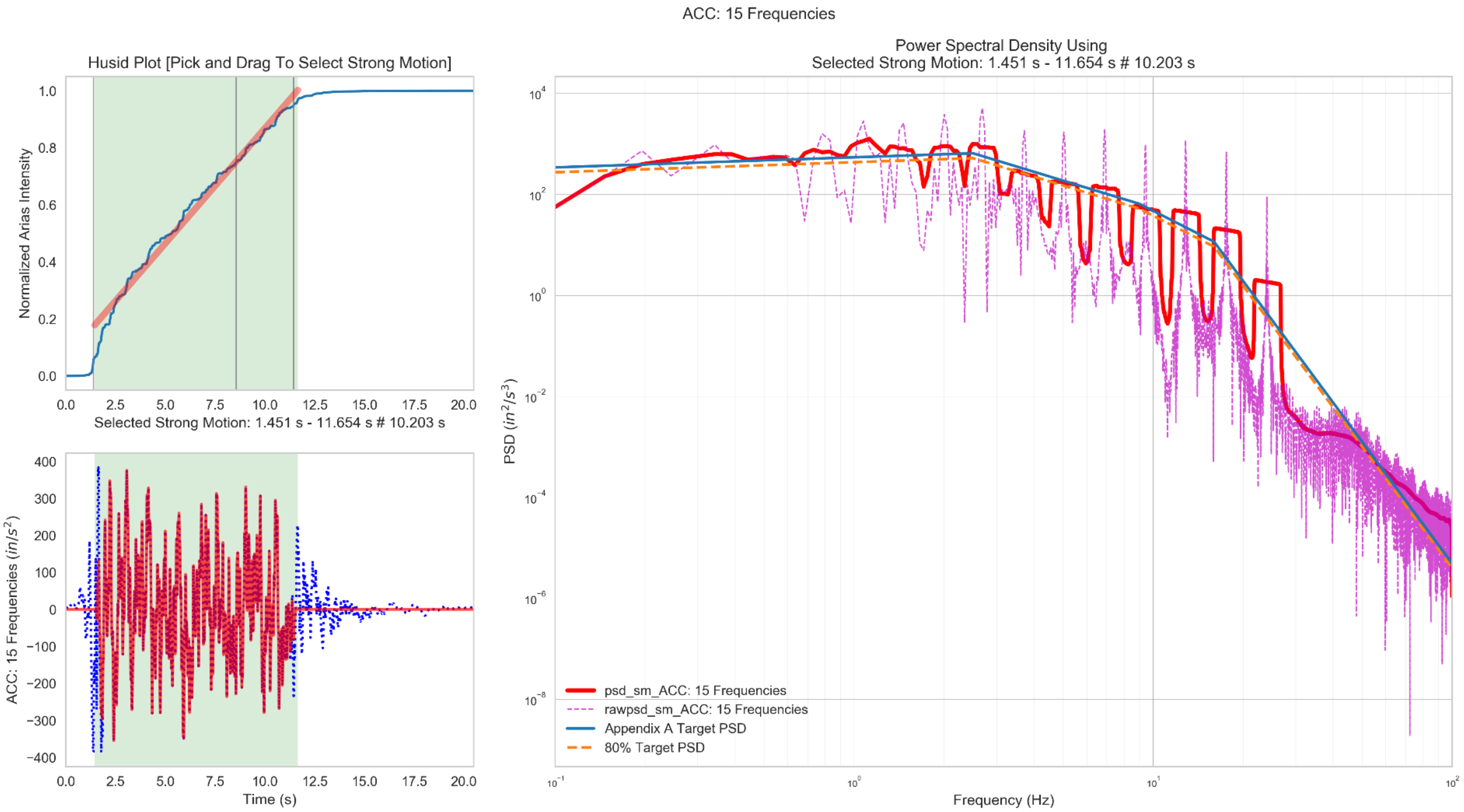


Figure 2-9 PSD check of the accelerogram with 15 major frequencies (±10-percent window)

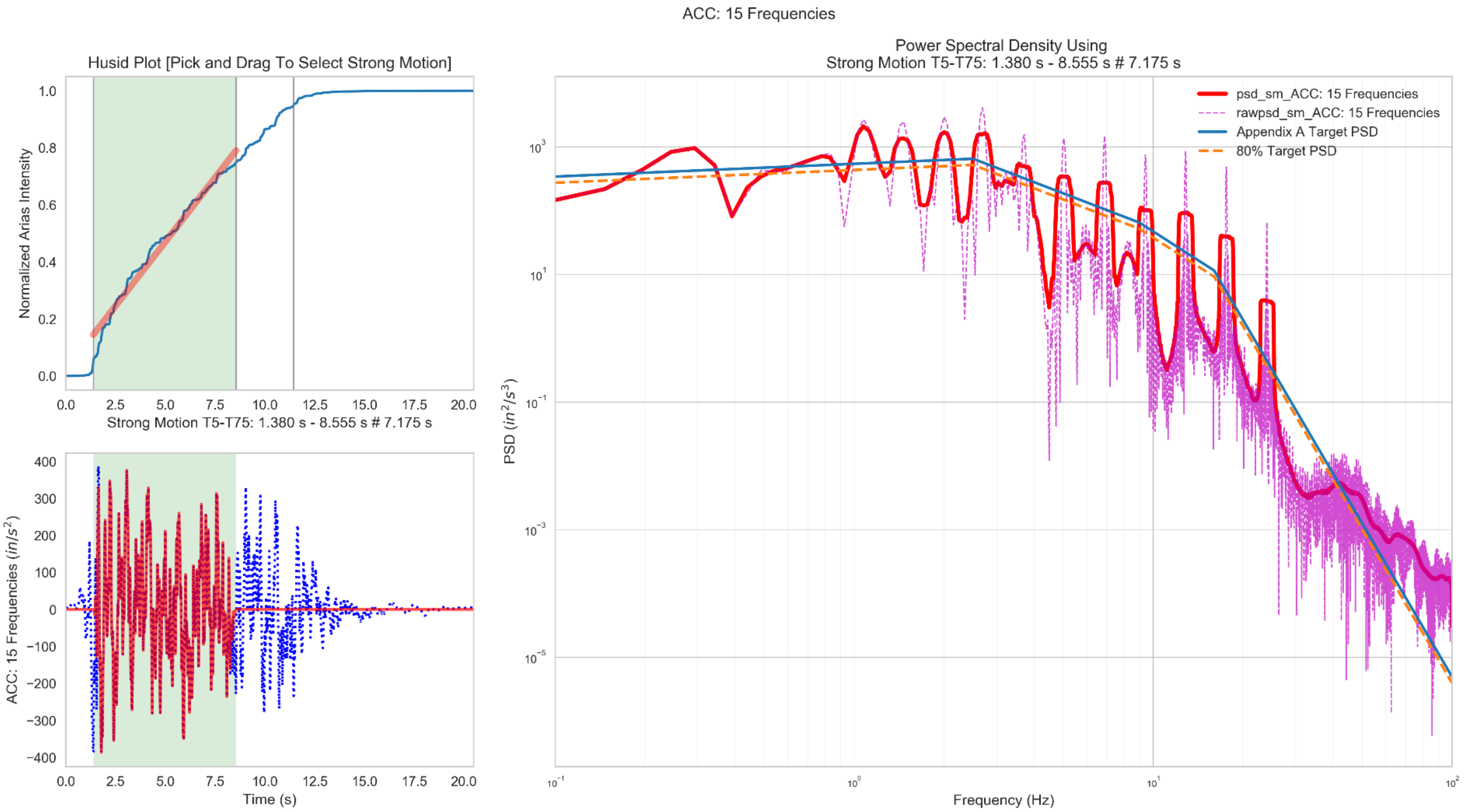


Figure 2-10 PSD check of the accelerogram with 15 major frequencies (±5-percent window)

2.1.2.3 Discussion of the Need for Target Power Spectral Density Functions

As discussed above, a PSD check is important to ensure power sufficiency in the frequency range of interest. However, it would be very difficult to make a definitive conclusion without comparing the estimated PSD function of a time history to a target PSD function. This section presents some conceptual examples to show the importance of target PSD functions in a PSD assessment.

As shown in the example in Figure 2-11, the estimated PSD function on the left side is smooth and resembles the shape of a typical PSD curve; therefore, it would naturally be considered to have no power deficiencies. In contrast, the PSD function shown on the right side includes an apparent dip in the midfrequency range; consequently, it would very likely be considered power deficient.

However, by overlaying the same estimated PSD functions with minimum target PSD functions that are assumed to be compatible with the DRS, as shown in Figure 2-12, the judgment of power sufficiency for these PSD functions would be completely different. The smooth curve without a dip could actually be power deficient, whereas the one with a dip could be power sufficient. The peaks beside the dip in the curve on the right side would simply indicate more power than necessary at those frequencies. Figure 2-13 shows another two possibilities for the smooth estimated PSD function to be power deficient at low frequencies or high frequencies, depending on the shape of the target PSD functions.

The power deficiencies demonstrated through these figures can happen in real situations, and the staff has encountered all three types of power deficiencies, at low, mid-, or high frequencies, in its review of licensing applications. Those affected time histories envelop the input RS based on the SRP Section 3.7.1, Approach 2, criteria. To evaluate the power distribution outside the strong motion portion of an acceleration time history, an evolutionary PSD function can be developed with a moving time window of 6 seconds wide and a moving step of 1 second. For a time history with power deficiencies in its strong motion duration, an evolutionary PSD function can be used to indicate whether (1) the time history has the same power deficiencies over the entire time history, or (2) it has sufficient power for some frequency bands but outside of the strong motion duration. For the second case, although there is sufficient power in the time history, the responses at those frequencies would not combine with those in the strong motion duration, and therefore, the overall structural responses might be underestimated. This case shows a typical problem of frequency nonstationarity; the time history has sufficient power at some frequencies, but those contents occur outside of the strong motion duration. Note that frequency nonstationarity is often observed in recorded ground motions. However, it is debatable whether these types of time histories are appropriate for the seismic design of SSCs because they do not necessarily represent all possible earthquake ground motions that the specific SSCs are expected to experience during their lifetime and because these time histories can potentially lead to lower structural responses.

Based on these examples, it can be concluded that, without a comparison to appropriately developed target PSD functions, power deficiencies may remain undetected in time histories that meet only the RS enveloping criteria. It should be noted that it is not difficult to develop a time history both to envelop DRS and, at the same time, to ensure its PSD function is higher than the minimum target PSD function. The staff has successfully developed such artificial acceleration time histories using the NRC in-house program P-CARES: Probabilistic Computer Analysis for Rapid Evaluation of Structures (NUREG/CR-6922, 2007). In summary, generating artificial acceleration time histories that envelop both the DRS and their compatible, minimum target PSD functions is feasible.

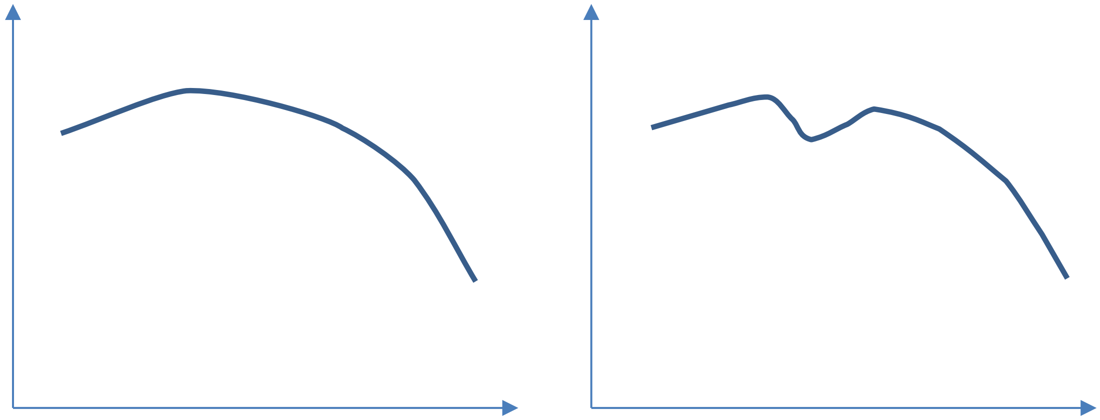


Figure 2-11 Illustrative estimated PSD functions with and without an apparent dip

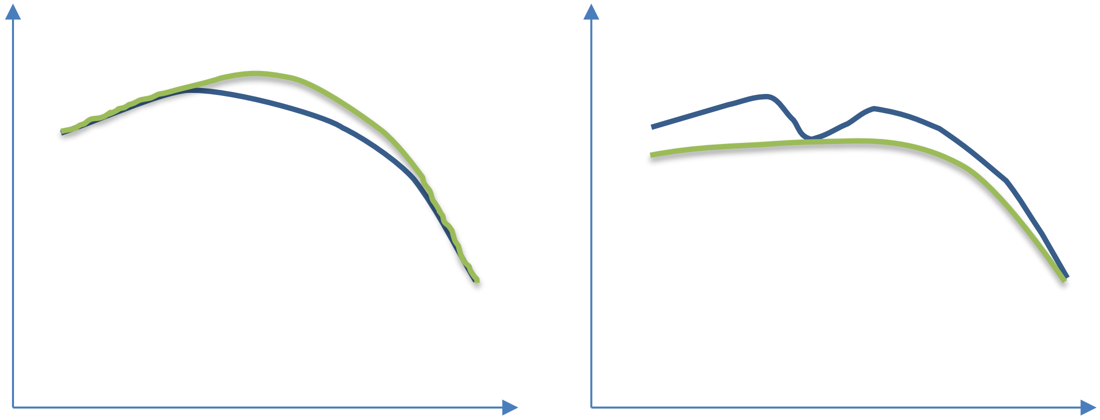


Figure 2-12 A comparison of illustrative estimated and target PSD functions

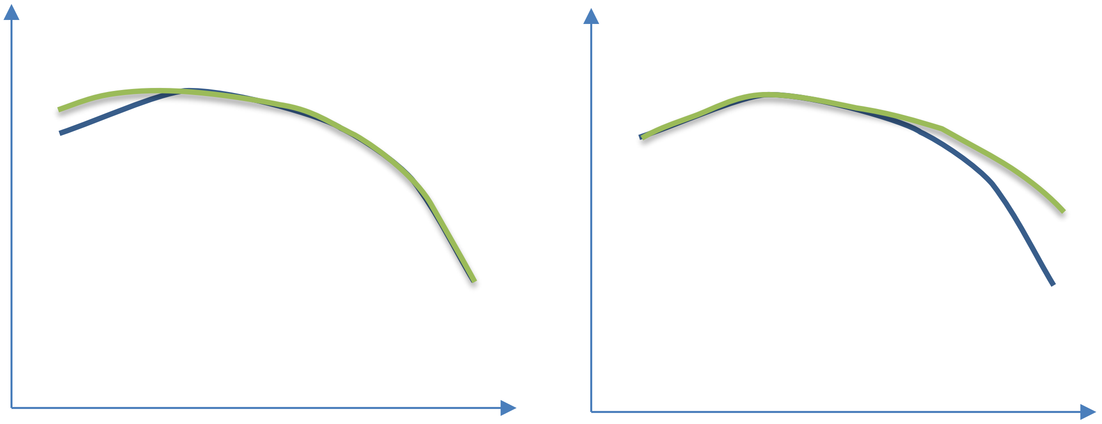


Figure 2-13 Illustrative estimated PSD functions deficient at low or high frequencies

2.1.2.4 Target Power Spectral Density Function Compatible with Design Response Spectra

As discussed and demonstrated above, target PSD functions are critical in determining whether artificial acceleration time histories have power deficiencies. The remaining question is whether a compatible target PSD function can be found for a given practical DRS. Many references in the literature involve the generation of a PSD function compatible with an RS (e.g., Davenport, 1964; Udwadia and Trifunac, 1974; Unruh and Kana, 1981; Igusa and Der Kiureghian, 1983; Park, 1995; Deng and Ostadan, 2008, 2012; Ghiocel and Grigoriu, 2013; Pozzi and Der Kiureghian, 2013; and Nie et al., 2015). The application of the random vibration theory (RVT) approach in SSI analysis, which has recently gained in popularity, relies on the relationship between the PSD functions and RS. Most common methods to convert a PSD function to an RS use the product of a peak factor and the standard deviation of the response of an oscillator to the PSD function. Many of these methods estimate the mean maximum response (i.e., the mean RS). Because different peak factors can lead to somewhat different estimates of the mean maximum responses (Ghiocel and Grigoriu, 2013), identifying one peak factor that is suitable for different RS shapes would be difficult.

In addition, Pozzi and Der Kiureghian (2013) found that not all RS shapes are admissible; for an RS to be admissible, it has to decay sufficiently fast at the tail (toward larger frequencies), but it cannot decay too fast at the same time. The same authors also noted that a given RS may not be admissible for some practical reasons. For example, some DRS were developed by fitting simple functions to the RS of recorded ground motions, and these functions, often piecewise linear functions, may not necessarily have an admissible shape at the tail.

To avoid selecting from the existing peak factors that can lead to somewhat different results, SRP Section 3.7.1, Revision 4, Appendix B, provides an iterative procedure that can generate target PSD functions for practical DRS. This procedure has been satisfactorily used to produce target PSD functions that are in good agreement with those developed using other methods (e.g., the method in SRP Section 3.7.1, Appendix A, and those methods submitted in licensing applications). Both staff experience and the submittals indicate that although some DRS may not be strictly admissible, target PSD functions can still be developed and considered compatible with the DRS in the sense of engineering, particularly because they are used for the purpose of the secondary PSD check.

Therefore, it can be concluded that, for practical purposes, a “unique” target PSD function exists for any given practical DRS and that methods exist for developing a good approximation of the target PSD function. This target PSD function is often described as being compatible with the DRS. To demonstrate the compatibility of the target PSD function and the DRS, an acceleration time history was generated using random phases from the target PSD function, as defined by the dotted line in Figure 2-14; the red line in Figure 2-15 illustrates the RS for that time history. The blue line in this figure is the DRS with which the target PSD function is compatible. Apparently, the RS of the time history fluctuates significantly and randomly around the DRS, consistent with the description in SRP Section 3.7.1, Option 1, Approach 1. Although the RS generally follows the DRS, the significant and random fluctuation does not correlate with a common expectation of compatibility. However, more time histories can be generated from the same target PSD function with different sets of phase angles, and the average of the RS of these time histories gets closer to the DRS as the number of time histories increases. Figure 2-16 shows the average RS of seven time histories, and Figure 2-17 shows the average RS of 500 time histories and demonstrates the convergence of the average RS to the DRS. Therefore, the compatibility of the target PSD function and the DRS can be established in terms of expectation (average).

The PSD check as a secondary check in Option 1, Approach 1, is accomplished by (1) the conservativeness in the RS enveloping process and (2) the use of minimum target PSD functions that are 0.8 or 0.7 of the target PSD functions, depending on whether Appendix A or Appendix B to SRP Section 3.7.1, Revision 4, is applied. The PSD function estimated from the time history should be smoothed using a ±20-percent frequency window before comparing it to the minimum target PSD function; consequently, small gaps should have already been smoothed out. Therefore, an indication of power deficiency by comparing the PSD function estimated from a time history to the minimum target PSD function represents some deficiency over a large frequency window.

As concluded earlier in this section, the adequacy of the ±20-percent frequency window to represent the mean PSD function needs to be assessed by evaluating the raw PSD function. A smaller frequency window should be considered if the ±20-percent frequency window cannot produce a mean PSD curve tracing the general trend of the raw PSD function.

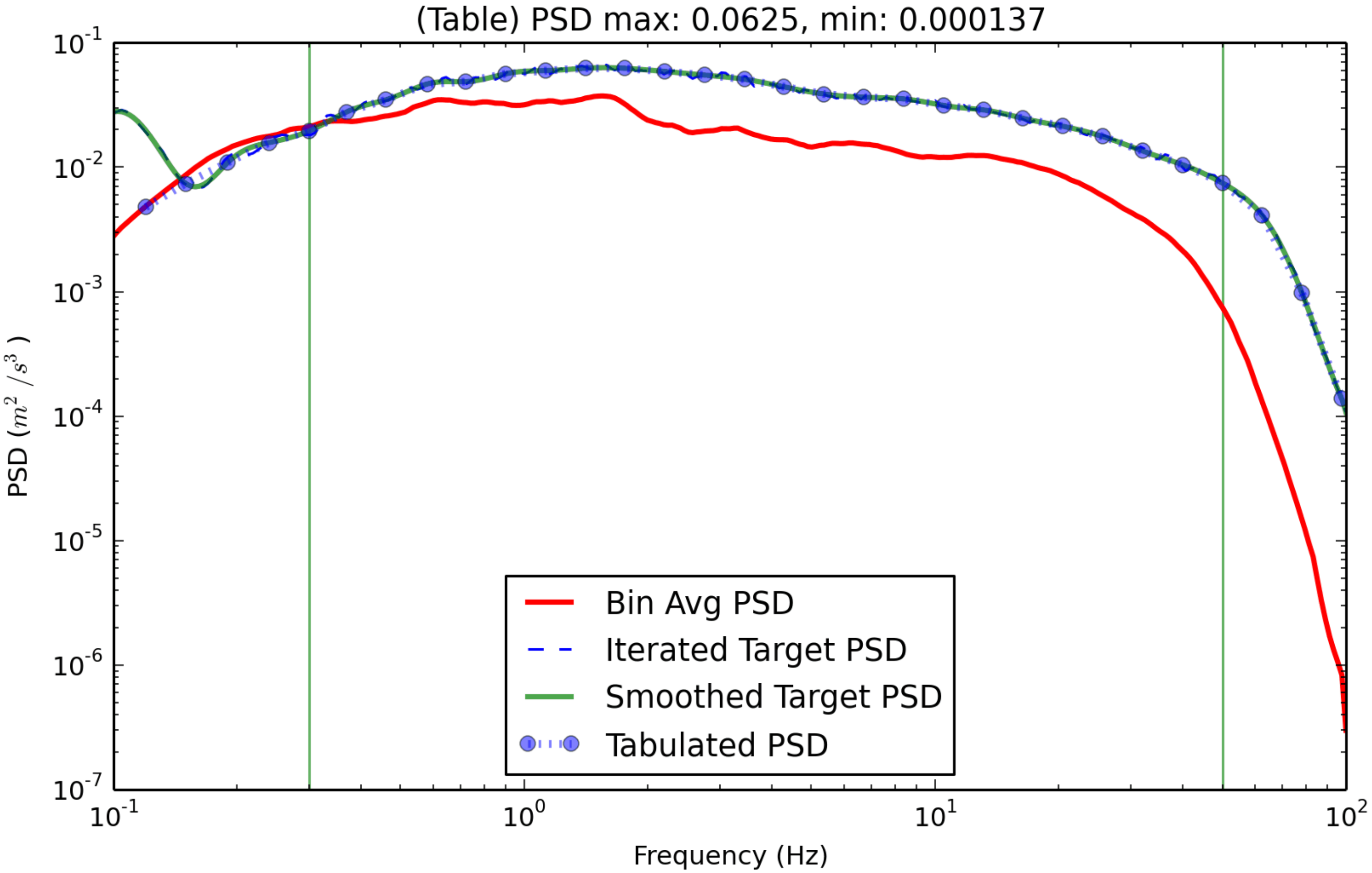


Figure 2-14 A target PSD function (dotted)

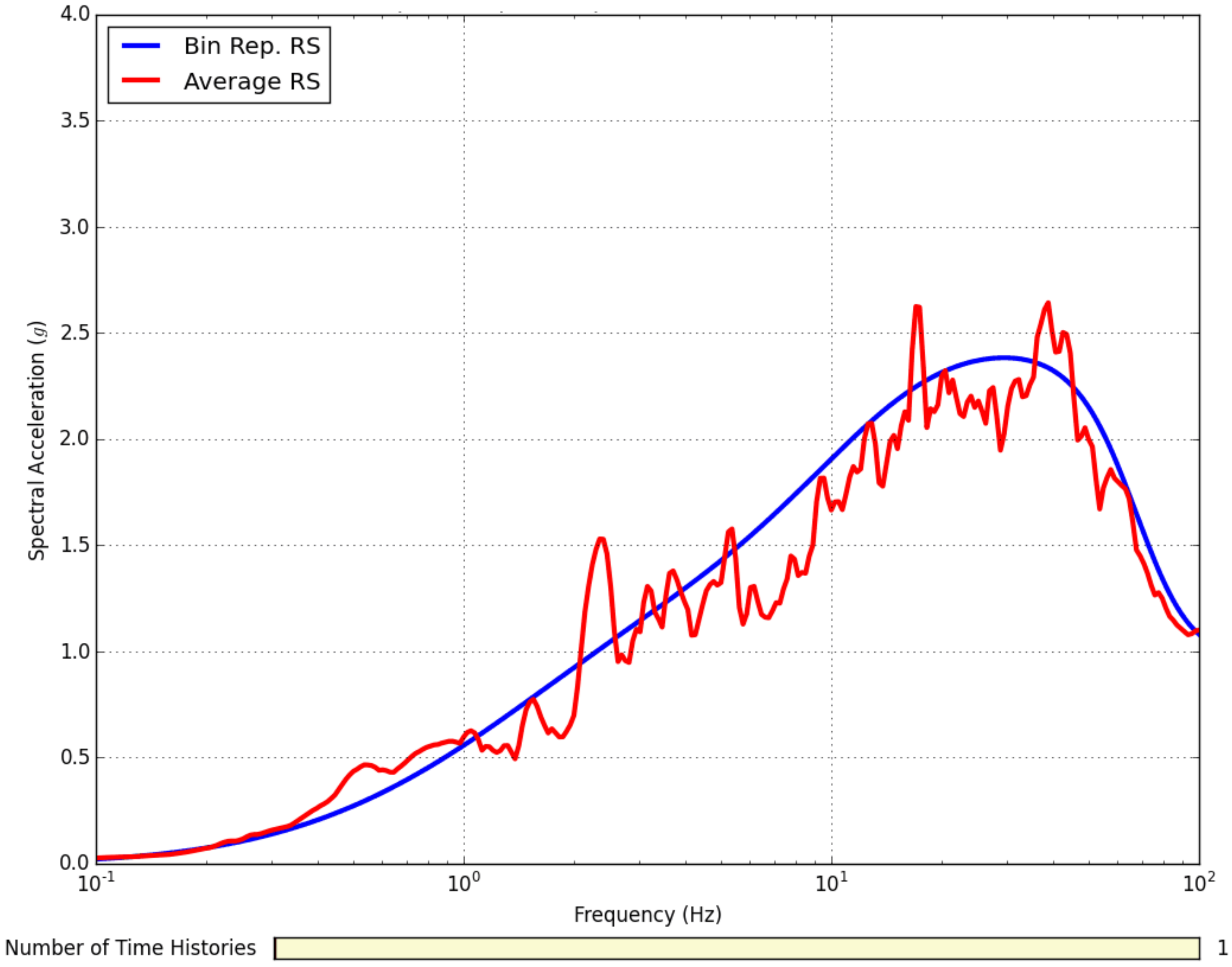


Figure 2-15 The RS of a time history generated from the target PSD function

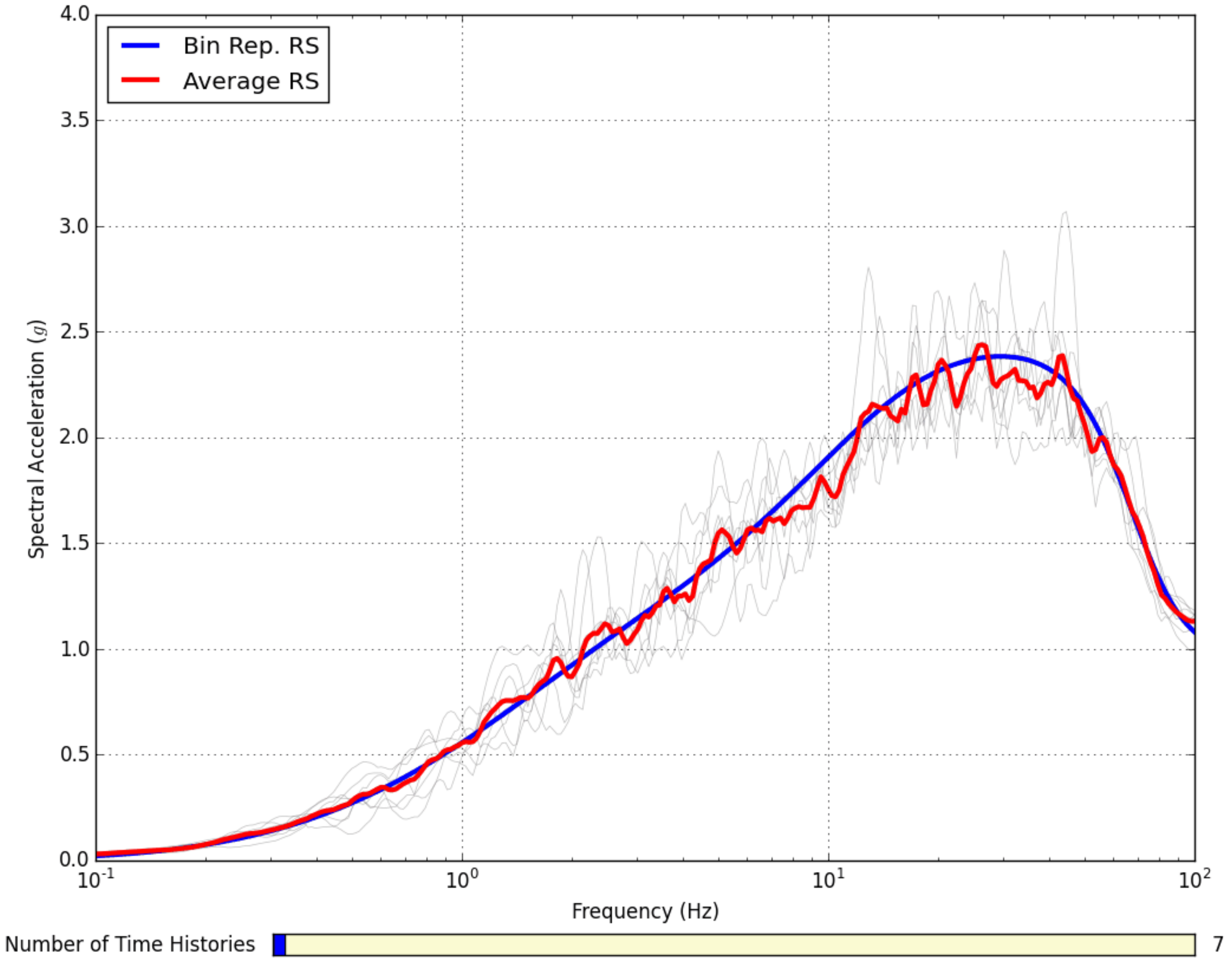


Figure 2-16 The average RS of seven time histories

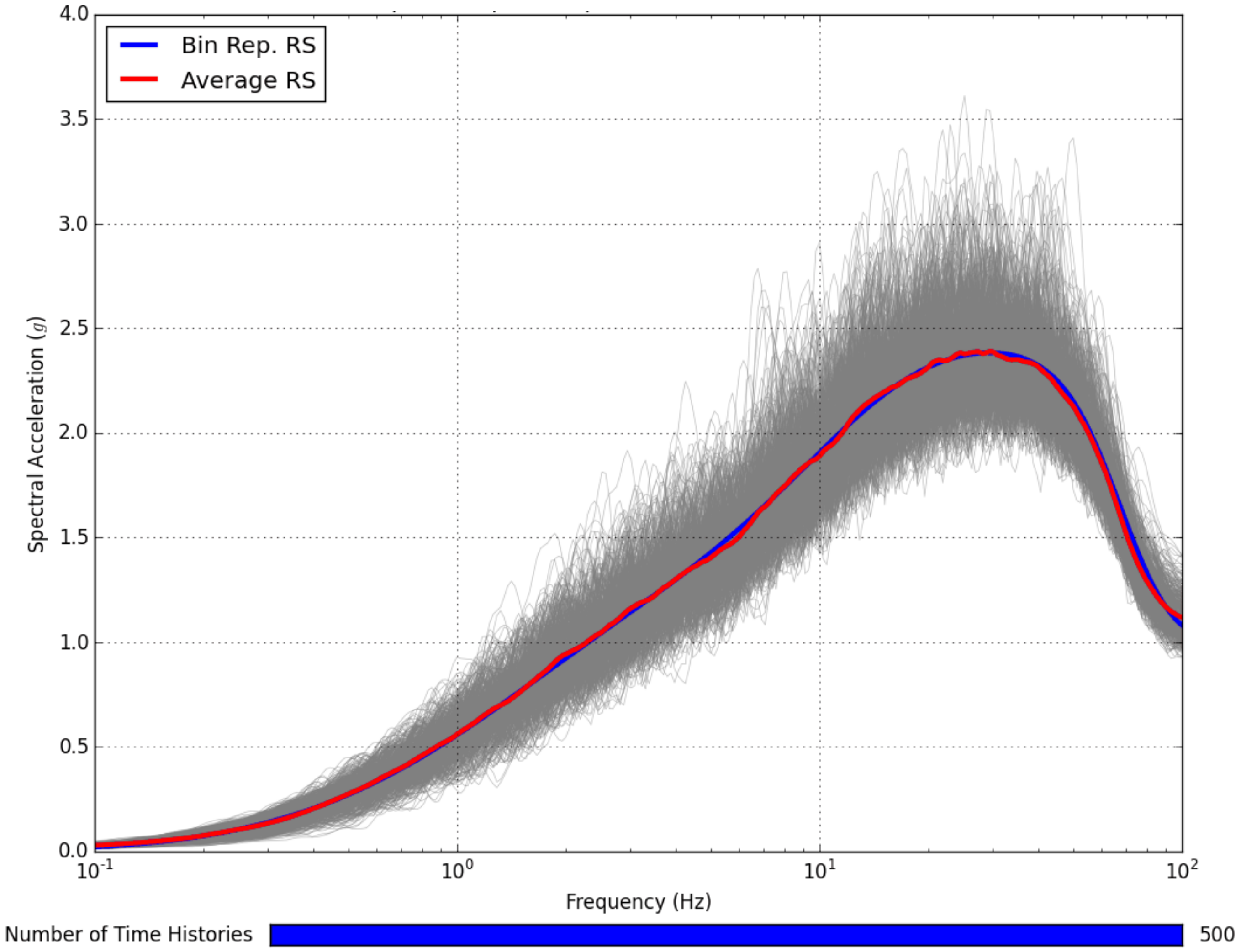


Figure 2-17 The average RS of 500 time histories

2.1.3 Conclusions, Clarification, and Recommendation

A review of the literature indicates that, when SRP Section 3.7.1, Revision 2, introduced the PSD check as a secondary yet necessary check, it was clear that a target PSD function is also necessary. SRP Section 3.7.1, Revision 3, first introduced Option 1, Approach 2, which was based on a recommendation in NUREG/CR-6728. However, NUREG/CR-6728 does not provide an explicit technical basis for why the 130-percent DRS can be used as a substitute for a PSD check. SRP Section 3.7.1, Revision 4, makes the PSD assessment in Option 1, Approach 2, unconditional on the result of RS enveloping but does not explicitly require a comparison to a target PSD function. The literature review, discussion, and examples provided in this section indicate the following:

- RS enveloping alone does not ensure power sufficiency.
- A PSD assessment without a comparison of the PSD function of the time history with a target PSD function is not conclusive. (For practical purposes, a “unique” target PSD function can be developed for a given DRS, and methods exist to develop such target PSD functions.)

Therefore, RES recommends that Option 1, Approach 2, be enhanced to require that the PSD function of the accelerogram should be computed and shown not to have significant gaps in power at any frequency over the frequency range, as described in Step (a) of Approach 2, by a comparison with the minimum target PSD function compatible with the DRS.

RES also recommends that the PSD check include a check of the raw PSD curve to determine whether the ±20-percent frequency window for smoothing adequately produces a mean PSD curve tracing the general trend of the raw PSD curve.

Alternatively, as discussed in other sections of this RIL, Approach 1 and Approach 2 may be combined to simplify the SRP criteria on the acceptance of acceleration time histories. The combined approach can take advantage of the existing approaches and avoid their disadvantages or defects.

2.2 Issue 3—Strong Motion Durations

2.2.1 The Issue and Affected SRP Text

The SRP has two definitions for strong motion duration: (1) the time for the cumulative Arias Intensity to rise from 5 percent to 75 percent ($T_{5\text{–}75}$) and (2) the duration of near maximum and nearly stationary power in the time history (T_D). Other definitions appear in the literature or in license applications. The strong motion duration in the SRP is mainly used to identify the most damaging portion of a time history and as a normalization factor in estimating the PSD function. The SRP guidance states that the strong motion portion of the time history, not the entire time history, should be used in the Fourier transform to estimate the PSD function of the time history. The issue concerns the guidance on which of these two definitions should be used in the review, and if the staff uses both definitions, it needs a basis for deciding which definition to use and when to use it.

The first definition appears in the following affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B:

> The strong motion duration is defined as the time required for the Arias Intensity to rise from 5 percent to 75 percent. The uniformity of the growth of this Arias Intensity should be reviewed. The minimum acceptable strong motion duration should be six seconds.

The second definition appears in the following affected text from SRP Section 3.7.1, Appendices A and B:

> The duration T_D represents the duration of near maximum and nearly stationary power of an acceleration time history record. Additional guidance on estimation of T_D for artificial time history or actual earthquake time history is provided in Appendix B of NUREG/CR-5347.

2.2.2 Technical Rationale and Basis

The literature and licensing applications have additional definitions of strong motion duration, including the time for cumulative Arias Intensity to rise from 5 percent to 95 percent ($T_{5–95}$) and the extended equivalent stationary duration (T_e) that some licensing applications have used. T_e is defined as $T_{5–75}/0.7$, which is used to estimate the PSD function in conjunction with the Fourier transform of the entire acceleration time history. When using $T_{5–95}$, Trifunac and Brady (1975) stated that “for definiteness, but quite arbitrarily, we delete the first 5% and the last 5% amplitudes of these integrals (Arias Intensity integrals of acceleration/velocity/displacement time histories) and defined the remaining 90% as the ‘significant’ or ‘strong-motion’ contribution.” Therefore, it seems that the use of $T_{5–75}$ or $T_{5–95}$ reflects a need for definiteness when dealing with many recorded ground motions in an automatic fashion.

$T_{5–75}$ or $T_{5–95}$ should be considered as simplified versions of T_D that are defined in SRP Section 3.7.1, Appendices A and B, as the duration of near maximum and nearly stationary power in the time history. This position is consistent with NUREG/CR-5347, Appendix A, which defines T_D as the time over which the power is near its maximum and states that, for most time histories, the results in NUREG/CR-3805, “Engineering Characterization of Ground Motion: Task II: Summary Report,” issued August 1986, recommend that the strong motion duration can be defined by $T_{5–75}$. In other words, NUREG/CR-5347 treats $T_{5–75}$ as a specialization of T_D for most time histories considered in NUREG/CR-3805. In addition, the guidance in SRP Section 3.7.1, Acceptance Criterion II.1.B, indicates that, to use $T_{5–75}$, a check is required on the uniformity of the growth of the cumulative Arias Intensity, which signifies the strong motion portion of the time history. Therefore, in cases where the check of uniformity fails, $T_{5–75}$ (or similarly $T_{5–95}$) may no longer be appropriate to represent the strong motion duration. In particular, a check of the uniformity of the growth of the cumulative Arias Intensity is often overlooked in practice. Even when it is checked, the determination of uniformity can be subjectively biased because the strong motion duration $T_{5–75}$ has already been calculated. From a procedural point of view, once the cumulative Arias Intensity is plotted to examine the uniformity of its growth, the strong motion duration can be easily identified from this plot based on the definition of T_D without even calculating $T_{5–75}$. Therefore, the use of $T_{5–75}$ or $T_{5–95}$ becomes unnecessary in the context of SRP guidance. Of course, these measures are valuable tools when many time histories need to be processed, rendering the above-mentioned manual check of uniformity infeasible.

As for the extended equivalent stationary duration T_e, because it is usually smaller than the total duration, the PSD estimate using T_e and the Fourier transform of the entire acceleration time history can overestimate the power for frequency components that have small amplitudes but cover a duration longer than T_e or even the entire duration. More importantly, the PSD function is a measure of energy per unit time, and the accuracy of its estimation is important in measuring how damaging the input motion is. Trifunac and Brady (1975) stated that "whether in a linear domain with viscous damping, or in the nonlinear range of responses, a particular structure can dissipate only a certain amount of vibrational energy per unit time." Therefore, by overestimating the power at certain frequencies, power defects in the time history may not be detected, and its use may lead to low structural responses that are used for the design of the structure.

Therefore, T_D appears to be most appropriate in estimating the PSD functions from the time histories because, unlike T_e, it ensures the consistency between the strong motion duration and the strong motion portion used in the Fourier transform and because unlike $T_{5\text{–}75}$ and $T_{5\text{–}95}$, the procedure to determine T_D intrinsically ensures the uniformity of the growth of the Arias Intensity. The use of the strong motion portion of an acceleration time history in PSD estimation is important because that portion represents the most damaging portion where the peak structural responses are usually expected to occur.

The determination of the strong motion duration T_D relies on the Husid plot, which shows the cumulative Arias Intensity of the acceleration time history. This process usually involves manually and subjectively picking the strong motion from the time history. Although the selection of T_D usually does not affect PSD functions significantly, to facilitate a robust and convenient definition of the strong motion duration, it is helpful to develop a method to automatically identify the strong motion and its duration. For example, a function similar to a log-sigmoid can be used to fit the cumulative Arias Intensity. The fitted log-sigmoid can then be used to determine definitively the strong motion and its duration. This approach can ensure consistency between different analysts. Such a method can be very helpful to avoid the use of the arbitrary $T_{5\text{–}75}$ or $T_{5\text{–}95}$ in situations where batch processing of many recorded motions is necessary.

2.2.3 Clarification and Recommendation

2.2.3.1 Near-Term Recommendations

The strong motion duration T_D as defined in SRP Section 3.7.1, Appendices A and B, is recommended for use throughout the SRP guidance. In particular, the use of $T_{5\text{–}75}$ in the current SRP Section 3.7.1, Acceptance Criterion II.1.B, requires a check of the uniformity of the growth of the cumulative Arias Intensity, which is often overlooked in practice. Even when it is checked, the determination of uniformity can be subjectively biased. In addition, when T_D is chosen based on the uniformity of the growth of the cumulative Arias Intensity, there would be no need to compute $T_{5\text{–}75}$.

2.2.3.2 Long-Term Recommendations

The cumulative Arias Intensity curve usually shows a shape similar to a log-sigmoid function. Therefore, a log-sigmoid function or other similar functions can be used to determine a best fit to the cumulative Arias Intensity curve, and the parameters of the fitted curve can then be used to calculate the strong motion duration, as defined by the duration of near maximum and nearly stationary power in the time history. The relationship between T_D and the parameters of the fitted curve needs to be determined based on the analysis of many real and synthesized acceleration time histories.

2.3 Issue 5, Part A—Frequency Range and Damping Consideration for a Power Spectral Density Check

2.3.1 The Issue and Affected SRP Text

The SRP provides different guidance for DRS enveloping and the secondary PSD check, including the number of frequencies for RS calculation, specified damping ratios, and the frequency range for PSD check. This issue includes the following three specific aspects of the SRP guidance:

(1) Option 1, Approach 1, uses fewer frequency points than does Approach 2 in RS calculation and comparison.

(2) Option 1, Approach 1, uses more damping ratios than does Approach 2 in RS enveloping.

(3) For the PSD check, SRP Section 3.7.1, Appendix A, requires a frequency range of 0.3 Hz to 24 Hz, whereas Appendix B requires a frequency range of 0.3 Hz to an unspecified upper bound frequency to be consistent with the RS shape.

Of these three items, Item 3 is related to PSD functions and is included in this section. Although Item 2 is related more to the RS enveloping criteria, it also requires some evaluation of how to develop a target PSD function when multiple RS at different damping ratios are specified. Therefore, this section addresses Items 2 and 3 of Issue 5 (Part A), and Section 5 of this RIL addresses Items 1 and 2 of Issue 5 (Part B). The issue concerns the need for these differences and requests a basis if such differences will remain in the guidance.

For Item 2, the following excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B.i, Option 1, Approach 1:

> The spectrum from the design ground motion time history should envelop the free-field design response spectra for all damping values used in the seismic response analysis.

The following excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B.i, Option 1, Approach 2:

> …(c) The computed 5 percent damped response spectrum of the acceleration time history should not fall more than 10 percent below the target response spectrum at any one frequency. To prevent response spectra in large frequency windows from falling below the target response spectrum, the response spectra within a frequency window of no larger than ±10% centered on the frequency should be allowed to fall below the target response spectrum.
>
> …(d) The computed 5 percent damped response spectrum of the acceleration time history should not exceed the target response spectrum at any frequency by more than 30 percent (a factor of 1.3) in the frequency range of interest.

For Item 3, the following excerpt is the affected text from SRP Section 3.7.1, Appendix A:

> The power above 24 Hz for the target PSD is so low as to be inconsequential so that checks above 24 Hz are unnecessary; however, note that the response spectrum calculations are performed beyond 24 Hz as governed by RG 1.60 definitions. Similarly, power below 0.3 Hz has no influence on stiff nuclear plant facilities, so that checks below 0.3 Hz are unnecessary.

The following excerpt is the affected text from SRP Section 3.7.1, Appendix B:

> In general, power below 0.3 Hz has no influence on stiff nuclear plant structures, so that checks below 0.3 Hz are unnecessary. The upper bound frequency (cutoff frequency) should be consistent with the design response spectrum.

2.3.2 Technical Rationale and Basis

2.3.2.1 Option 1, Approach 1, Uses More Damping Ratios Than Does Approach 2 in Response Spectra Enveloping

To summarize, a study in the Technical Rationale for Enhancements to Seismic and Structural Review Guidance (Xu et al., 2014), shows that the use of 5-percent damped RS is sufficient in the development of target PSD functions as long as the RS at all damping ratios are consistent with each other. RS are considered to be consistent when they can be generated from the same set of time histories. However, many practical DRS prescribed at different damping ratios, such as the RG 1.60 DRS, are not strictly consistent. The process to derive these DRS (e.g., linearization and utilization of the same anchor frequencies) can disturb the consistency between the DRS that are intrinsically related through structural dynamics. When DRS at different damping ratios are specified for a design, the level of consistency between the DRS needs to be assessed to determine whether the 5-percent damped RS alone can be used in the development of target PSD functions. Otherwise, target PSD functions can be developed for all DRS individually, and the envelope of these target PSD functions can be used as the target PSD function for the DRS.

To support the conclusions in the above summary, the following discussion is adopted from the Technical Rationale for Enhancements to Seismic and Structural Review Guidance (Xu et al., 2014), in a section entitled “Development of Target PSD for Multiple Consistent Response Spectra.”

The guidelines and procedures described in SRP Section 3.7.1, Appendix B, are consistent with the approach described in NUREG/CR-5347, which was also used to develop the target PSD function for the RG 1.60 RS in SRP Section 3.7.1, Appendix A. The target PSD functions presented in Tables 1 and 2 of SRP Section 3.7.1, Revision 4, Appendix B, were developed for the bin representative design acceleration RS in NUREG/CR-6728, which are defined for a 5-percent damping ratio only. On the other hand, the target PSD function for SRP Section 3.7.1, Appendix A, was developed based on the 2-percent damped pseudo-relative velocity RS. The development of target PSD functions following the SRP Section 3.7.1, Appendix B, procedure should not be sensitive to the selection of a particular damping value because the calculation of the PSD function is independent of damping, as confirmed by the study described below.

To demonstrate that the tabulated target PSD values in SRP Section 3.7.1, Appendix B, are not sensitive to damping ratios, two representative bins from the NUREG/CR-6728 database, central and eastern United States (CEUS)_ROCK_M75D000.010 and western United States (WUS)_ROCK_M75D000.010, were selected to represent the CEUS rock sites and WUS rock sites, respectively. These two bins are those with the highest earthquake magnitude and shortest fault distance in the NUREG/CR-6728 database. For each of these two bins, the following steps were performed to demonstrate the insensitivity of the target PSD function to the damping values associated with the RS:

(1) Use the target PSD function of SRP Section 3.7.1, Appendix B, to generate 1,000 synthetic acceleration time histories, which should be sufficient to produce smooth average RS.

(2) Compute the RS for these synthetic acceleration time histories at 2-percent and 10-percent damping values, and obtain the average RS for the respective damping values.

(3) Use cubic splines to obtain the smoothed average RS.

(4) Apply the procedure in SRP Section 3.7.1, Appendix B, to generate two target PSD functions from the 2-percent and 10-percent damped, smoothed average RS.

(5) Compare these two target PSD functions to the tabulated target PSD function that was computed from the 5-percent damped bin representative DRS in NUREG/CR-6728.

The top plots in Figure 2-18 through Figure 2-21 show the smoothed RS for 2-, 5-, and 10-percent damping ratios. The use of 1,000 synthetic acceleration time histories produced sufficiently smooth average RS as expected, and the cubic spline smoothing further removed the minor irregularity from these spectral curves. These average RS were generated based on the tabulated target PSD functions; they generally have the same shapes, but they are not as smooth as the design spectra prescribed by the NUREG/CR-6728 formula because the tabulated target PSD functions are represented at only a few dozen of frequency points. Nevertheless, the minor deviation in RS shapes from the formula does not affect the investigation of whether the development of the target PSD function is sensitive to the damping ratio associated with the RS because the smoothed average RS are compatible with the same tabulated target PSD functions.

Figure 2-18 and Figure 2-19 compare the target PSD functions computed based on the RS with 2- and 10-percent damping ratios to the tabulated target PSD functions in SRP Section 3.7.1, Appendix B. These target PSD functions were calculated with 30 iterations by assuming an initial PSD value at a constant 0.001 g·g·s (gravity × gravity × second, equal to 0.096 square meters per cubic second (m^2/s^3)) for all frequencies. More than the 10 iterations recommended in SRP Section 3.7.1, Appendix B, were needed because the initial PSD function was assumed to be constant for all frequencies. Figure 2-18 and Figure 2-19 show that the target PSD functions closely agree. This exercise also confirms that a proper choice of an initial PSD function can accelerate the convergence process, as indicated in SRP Section 3.7.1, Appendix B.

In particular, the tabulated target PSD function is a good choice of an initial PSD function for this sensitivity study because the PSD calculation does not involve damping and the PSD function should be the same regardless of what damping value is used for RS. Figure 2-20 and

Figure 2-21 show excellent agreement in the target PSD functions that were generated using the tabulated target PSD functions as the initial PSD functions.

In conclusion, the development of a target PSD function is not sensitive to the damping ratio associated with the RS. The minor difference between the target PSD functions that were developed based on differently damped RS does not represent a practical problem in using the target PSD function because it is used as a secondary check.

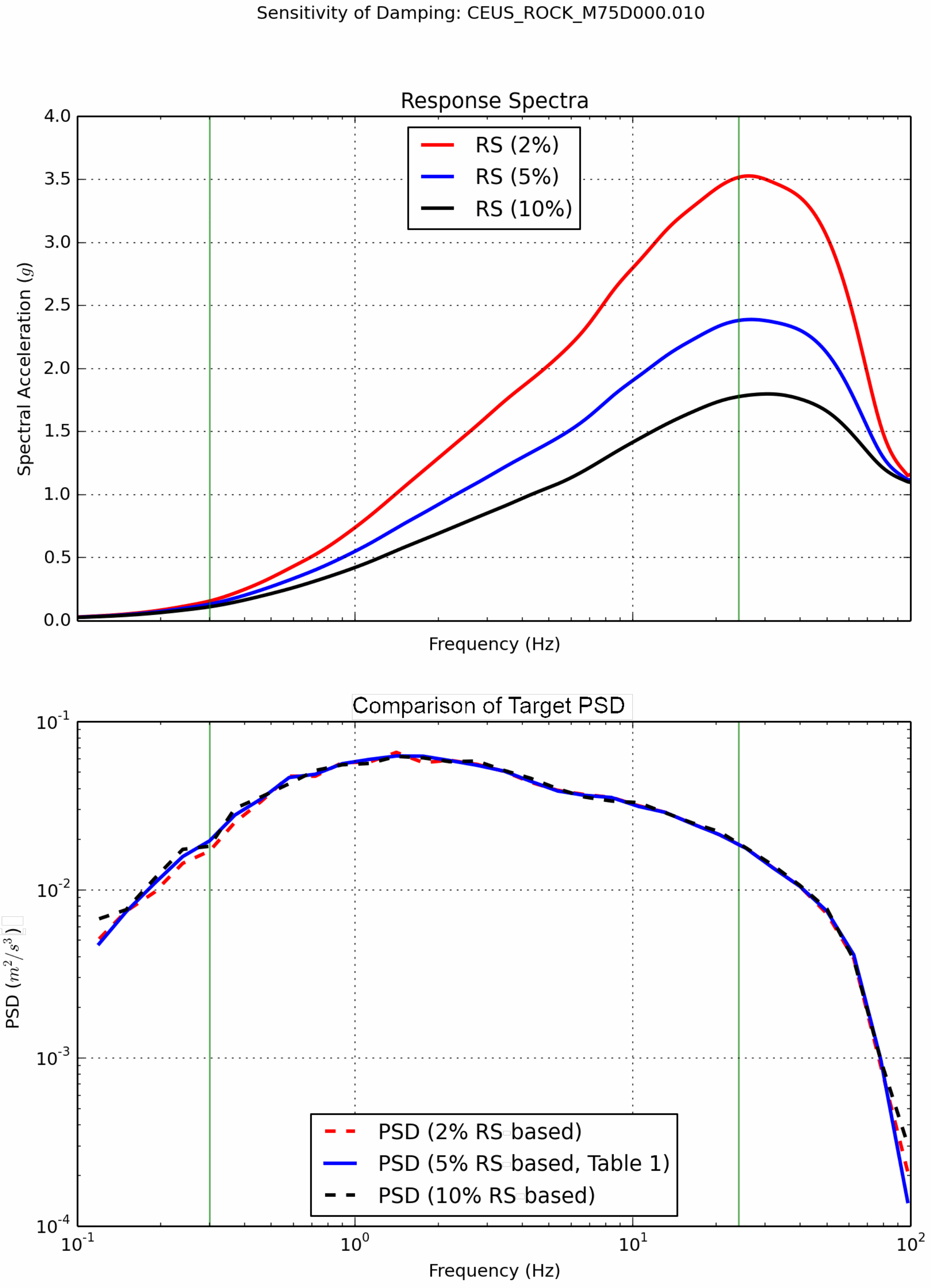


Figure 2-18 A comparison of PSD functions generated from differently damped RS, 30 iterations (CEUS_ROCK_M75D000.010)

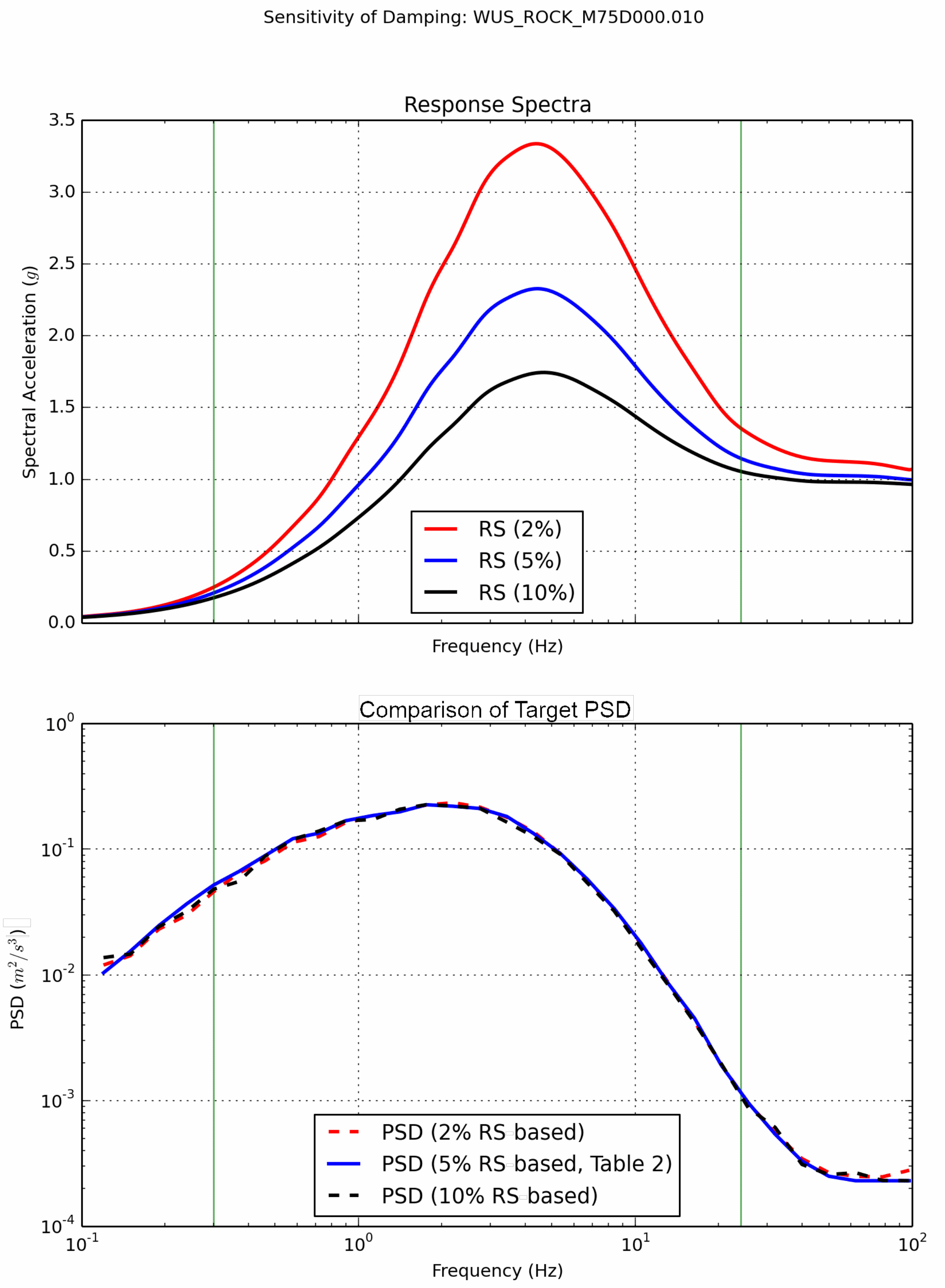


Figure 2-19 A comparison of PSD functions generated from differently damped RS, 30 iterations (WUS_ROCK_M75D000.010)

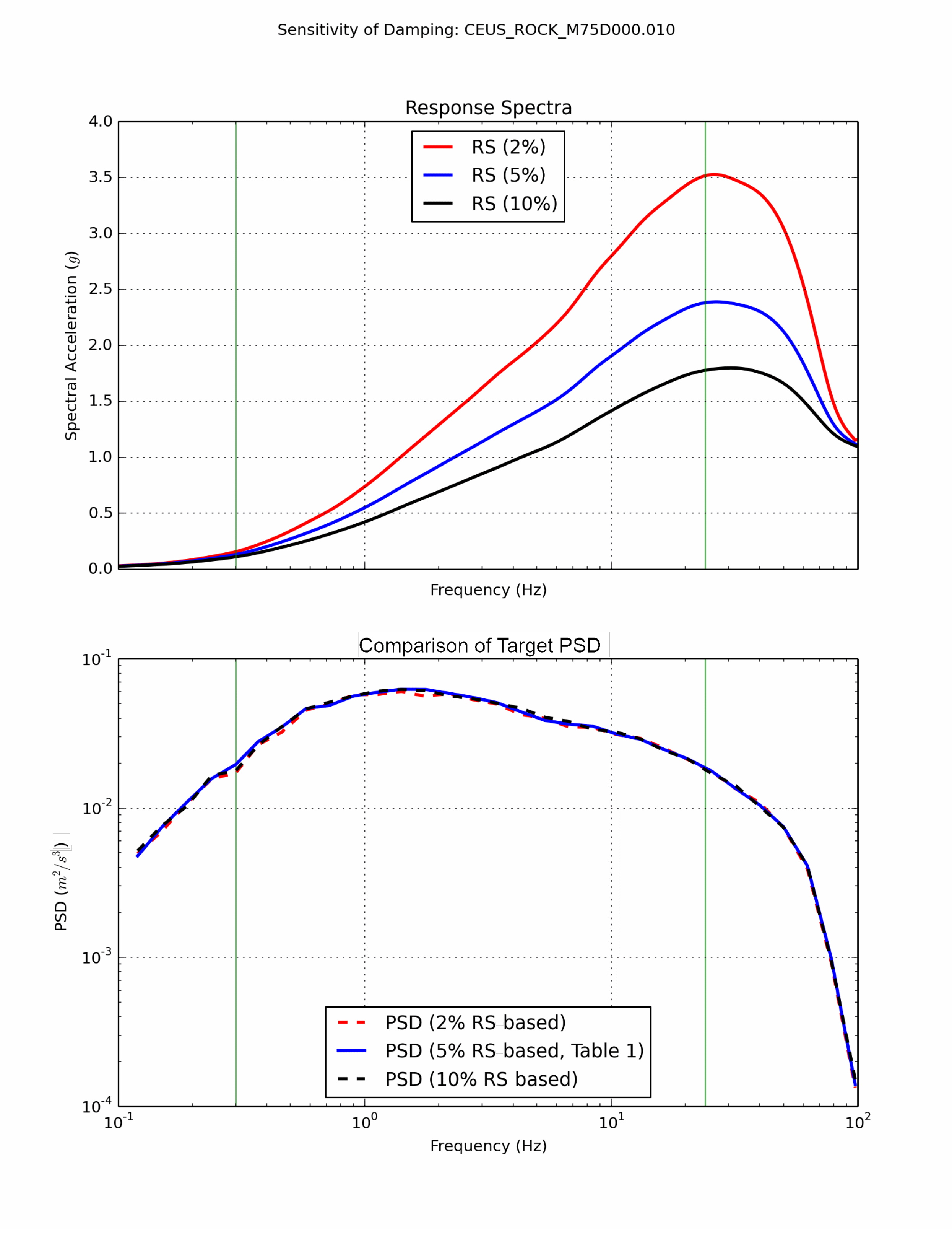


Figure 2-20 A comparison of PSD functions generated from differently damped RS, initialized with tabulated target PSDs (CEUS_ROCK_M75D000.010)

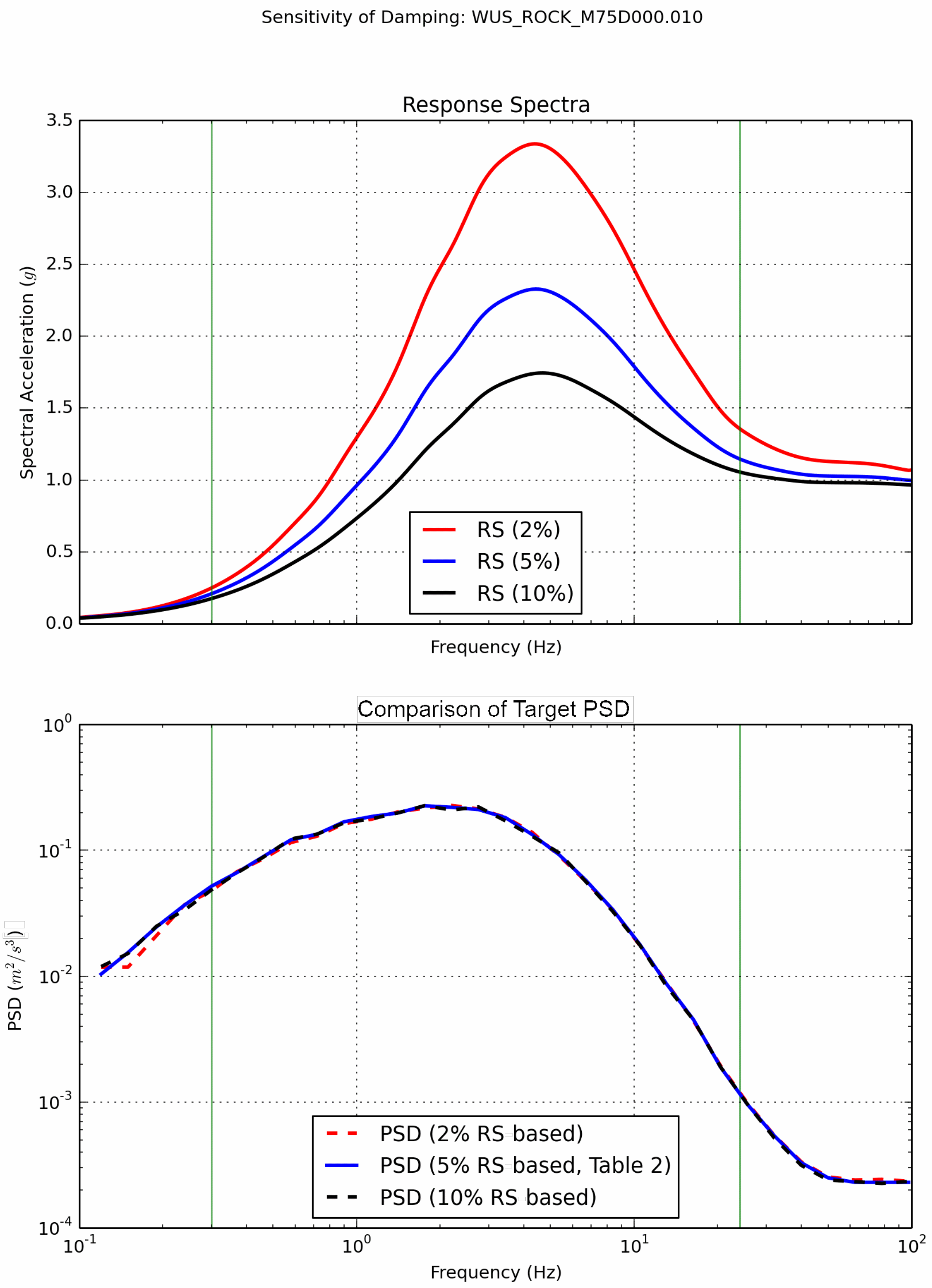
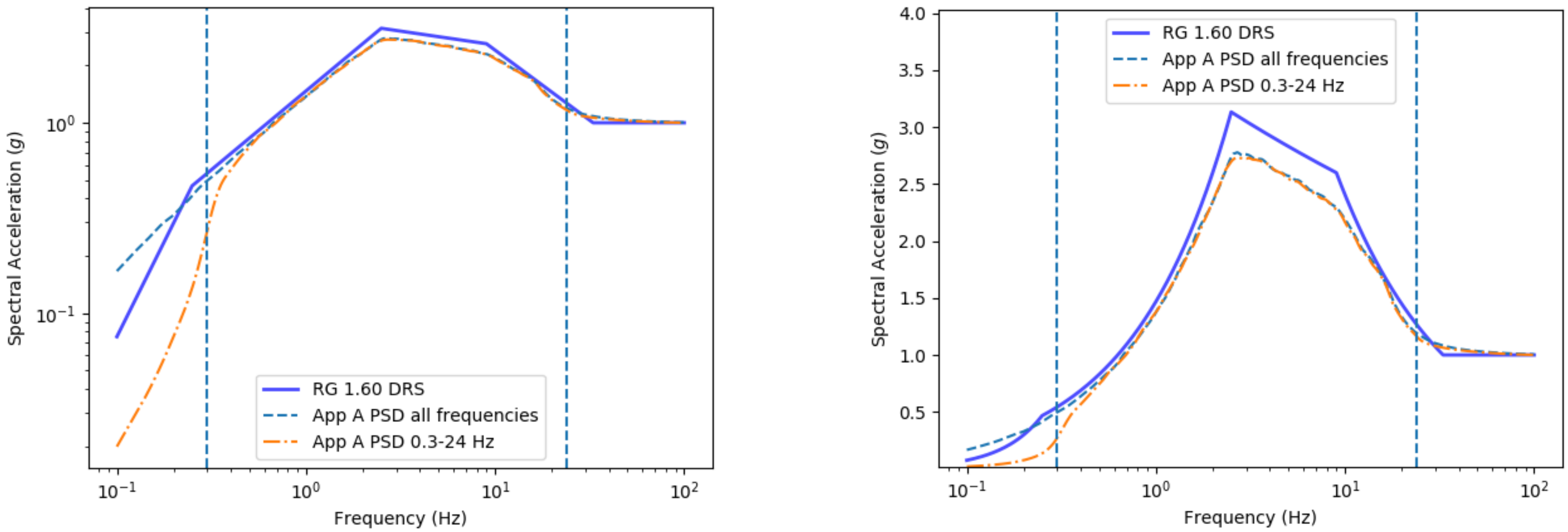


Figure 2-21 A comparison of PSD functions generated from differently damped RS, initialized with tabulated target PSDs (WUS_ROCK_M75D000.010)

2.3.2.2 Frequency Range for a Power Spectral Density Check

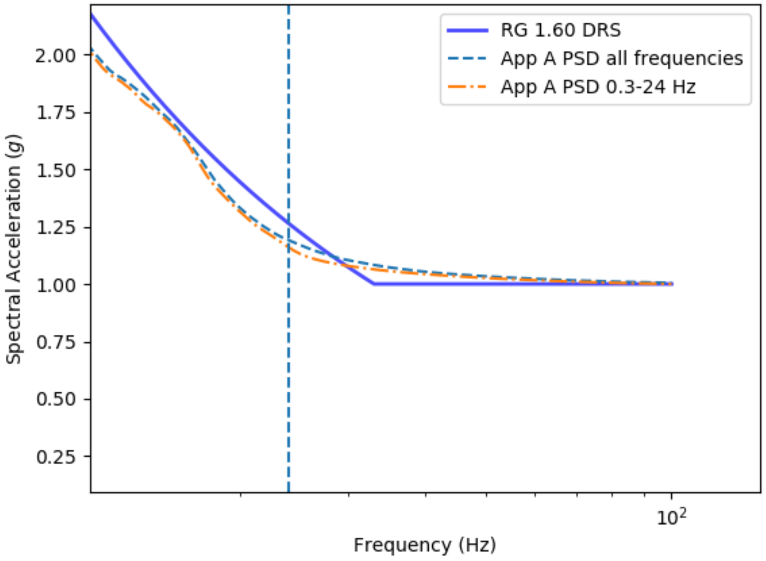
Since Revision 2, SRP Section 3.7.1, Appendix A, has required that the PSD check be performed for a frequency range of 0.3 Hz to 24 Hz. As stated in Appendix A, the power above 24 Hz for the target PSD is so low that checks above 24 Hz are unnecessary because it is inconsequential. Similarly, power below 0.3 Hz has no influence on stiff nuclear plant facilities; therefore, checks below 0.3 Hz are unnecessary. These criteria are based on recommendations in NUREG/CR-5347, which does not offer an additional explanation beyond the subjective recommendations above. Note that, as presented in NUREG/CR-5347, an earlier draft of SRP Section 3.7.1, Revision 2, recommended checking power sufficiency over a frequency range of 0.2 Hz to 34 Hz, which is generally consistent with the RG 1.60 DRS that has a ZPA frequency of 33 Hz. The RS enveloping criteria based on SRP Section 3.7.1, Table 3.7.1-1, starts at 0.2 Hz. In addition, note that, although 24 Hz was recommended as the upper bound frequency for a PSD check, Equation (10) of NUREG/CR-5347 indicates that the time history actually had frequency content up to 159 Hz. NUREG/CR-5347 does not explicitly demonstrate the effect of the power above 24 Hz or below 0.3 Hz on RS enveloping.

To assess this effect, the expected (average) RS associated with the target PSD function in SRP Section 3.7.1, Appendix A, and that associated with the same target PSD function, but with the power below 0.3 Hz and above 24 Hz removed, are compared in Figure 2-22 with the RG 1.60 DRS. Overall, the expected RS are generally lower than the DRS, consistent with the intent of the target PSD function as described in NUREG/CR-5347. Removing the power below 0.3 Hz significantly reduces the expected RS below and around 0.3 Hz, whereas removing the power above 24 Hz appears to have a very minor effect. Nonetheless, removal of power in these two frequency ranges does not noticeably affect the expected RS from 0.6 Hz to 24 Hz. From this assessment, it appears that a PSD check should be performed for frequencies below 0.3 Hz if the time histories are used for SSCs that have very low fundamental frequencies (such as large tanks and deep soil sites). For frequencies higher than 24 Hz, this assessment confirms the position in SRP Section 3.7.1, Appendix A, that a PSD check is not necessary because the very low power above 24 Hz does not significantly reduce the expected RS.



(a) Log-Log Scale

(b) Log-Linear Scale



(c) Zoom in at 24 Hz

Figure 2-22 SRP Section 3.7.1, Appendix A, PSD functions and RG 1.60 DRS

NUREG/CR-3509 recommends that an acceptable artificial acceleration time history should envelop the DRS and envelop a prescribed percentage of the target PSD function "everywhere in the frequency range considered."

NUREG/CR-6728 states the following about the frequency range for a PSD check:

> The frequency range specified, from 0.3 Hz to 24 Hz, is based on two relatively subjective considerations. First, the power in actual ground motion recordings above 24 Hz was considered negligible so that there is no need to consider spectral content above this value. Secondly, the check below 0.3 Hz was considered unnecessary since most nuclear facilities are relatively stiff and have response frequencies well above this lower bound cutoff. However, since those recommendations were promulgated, several issues have arisen which make these limits potentially problematic. First, at some deep soil sites, it was noted that site response fundamental frequencies extend to values well below 1 Hz. The details of the ground motion at these low frequencies could become important in evaluating site response, requiring more consideration of the frequency content at these lower frequencies of interest. Secondly, at some CEUS rock sites, rock outcrop motions may have significant energy at frequencies as high as 50 Hz. Thus, even though these motions may not have a significant percentage of their total power at these high frequencies, the Fourier amplitudes of the high frequency components of the motion could become important when these rock outcrop motions are used as input to convolution calculations to determine surface motions at low frequency soil sites.

As for the lower bound frequency of 0.3 Hz, tanks built in the NPP buildings or installed on the ground surface have shown sloshing mode frequencies lower than 0.2 Hz in some licensing applications. Structures and components seismically isolated can also be very sensitive to low-frequency ground motions. Because the low frequencies close to 0.3 Hz can be important to SSI at some deep soil sites, liquid storage tanks, and seismically isolated structures, the lower bound frequency (cutoff frequency) for a PSD check should be consistent with the DRS. This proposed criterion does not impose extra computational effort because the target PSD functions once developed cover the same frequency range as the DRS.

A calculation in the Technical Rationale for Enhancements to Seismic and Structural Review Guidance (Xu et al., 2014), indicates that an upper bound frequency cannot be predetermined because it severely depends on the shape of the DRS. In addition, performing a PSD check up to the ZPA frequency, or even higher when the DRS do not exhibit a ZPA frequency, does not appear to be a practical burden following the current SRP Section 3.7.1, Appendix B, guidance. The required calculation of a target PSD function can be completed in minutes using a regular desktop computer. However, a frequent argument is that high-frequency components in the ground motion may not have a significant impact on structural responses, as stated similarly in the current SRP Section 3.7.1, Appendix A, and would be inconsequential because the power is so low for RG 1.60 RS. Nevertheless, supporting this argument for not performing a PSD check at high frequencies is difficult. The review practice has included a check on whether all flexible walls and floors are adequately modeled up to 50 Hz. More important, if the high-frequency power is not significant, the DRS could have had their ZPA frequency reduced to the same upper bound frequency as that used for the PSD check in the argument. Even more important, structural deamplification at higher frequencies means only that the input power at those higher frequencies is reduced but does not normally mean the input power is reduced to a trivial level.

Without an actual evaluation with sufficient input power at those high frequencies, the seismic demand on the equipment installed in the structures, reduced because of structural deamplification, would be lower than the actual demand that the input DRS represents. In particular, if the power-deficient time histories are used in SSI analysis to generate the RS at the basemat for subsequent structural analysis, the estimated structural responses may be underpredicted and the design of SSCs may be unconservative. This argument is especially true for the CEUS region where very high input power at the higher frequencies is considered.

Therefore, RES recommends that the PSD check be performed in the frequency range consistent with the DRS. To further support this position, the following discussion is adopted from the Technical Rationale for Enhancements to Seismic and Structural Review Guidance (Xu et al., 2014), in a section entitled "Effect of High-Frequency Power on PSD-RS Compatibility." The RES staff performed some new calculations for this RIL to incorporate a new interpolation scheme. For SRP Section 3.7.1, Appendix B, Revision 4, the upper frequency limit for the PSD check cannot be explicitly set to a fixed frequency because it applies to the bin representative RS in NUREG/CR-6728 and other DRS, and the guidance in SRP Section 3.7.1, Appendix B, states that it should be consistent with the DRS. To develop the technical basis for this SRP provision, Section 2.3.2.2.1 of this RIL investigates whether upper frequency limits can be determined by using a power level equal to what the 24-Hz frequency limit implies in SRP Section 3.7.1, Appendix A. Section 2.3.2.2.2 describes a study showing the effect of the higher frequency PSD values on the compatibility between the target PSD function and the corresponding bin representative RS in NUREG/CR-6728.

2.3.2.2.1 Approaches Based on the Cumulative Power Spectral Density Function or Cumulative Square Root of the Power Spectral Density Function

A plateau in the cumulative power with respect to frequency could indicate that the power beyond a certain frequency (e.g., 24 Hz in SRP Section 3.7.1, Appendix A) is very low and that frequency along with other considerations, such as the ZPA frequency of the DRS and the dynamic characteristics of the soil-structure equipment system, could potentially be used to develop an upper frequency limit for the PSD check. This section presents the results of an attempt to determine upper frequency limits using the cumulative PSD function or cumulative square root of the PSD function (effectively equivalent to cumulative Fourier amplitude spectra) as a measure to signify negligible power.

Using the target PSD function in SRP Section 3.7.1, Appendix A, the level of cumulative target PSD function that corresponds to the upper bound frequency 24 Hz was determined in the Technical Rationale Document to be 0.9955 of the maximum cumulative target PSD function. Based on a different interpolation scheme, this study found a new limit of 0.999973. Similarly, the level of cumulative square root of target PSD function at 24 Hz was calculated to be 0.97 (and a new limit of 0.998298 in this study). These levels are considered very close in practice; however, they can lead to a large difference in the determined frequencies. Two other levels, 0.90 and 0.95, were also used to estimate the cutoff frequencies for all 20 bins associated with Tables 1 and 2 in SRP Section 3.7.1, Appendix B, Revision 4.

Table 2-1 shows that, even though both the level of 0.9955 for the cumulative PSD and the level of 0.97 for the cumulative square root of the PSD function correspond to the same cutoff frequency of 24 Hz in SRP Section 3.7.1, Appendix A, these levels do not lead to the same or close cutoff frequencies for the PSD functions in Tables 1 and 2 in SRP Section 3.7.1, Appendix B. A similar observation can be reached for the new cutoff levels of 0.999973 and 0.998298. A small difference in these cumulative measures (e.g., 0.9955 versus 0.999973) can lead to significantly large differences in cutoff frequency estimates because the cumulative curves are very flat at higher frequencies. For the target PSD functions associated with WUS spectral shapes, the levels of 0.9955 for the cumulative PSD and 0.97 for the cumulative square root of the PSD led to generally small upper limit frequencies (smaller than 33 Hz). As extreme cases, both approaches led to cutoff frequencies of less than 10 Hz for WUS M75D100-200, which are considered too low. Most importantly, many of these estimated cutoff frequencies can lead to significant incompatibility between the truncated PSD and the RS, which can be seen by comparing these cutoff frequencies to the figures presented in Section 2.3.2.2.2. The upper limit frequencies based on 0.999973 (PSD) and 0.998298 (Fourier spectra) do not significantly affect the PSD-RS compatibility; however, they are so close to the highest frequency of the DRS that the benefit of using them in PSD checks would be minimal.

2.3.2.2.2 Assessment of Compatibility of the Truncated Target Power Spectral Density Functions and Response Spectra

For each bin shown in Tables 1 and 2 in SRP Section 3.7.1, Appendix B, Revision 4, the RES staff performed a sensitivity study by progressively removing the PSD value at the highest frequency from the target PSD function and generating the corresponding RS by averaging the RS of 100 time histories generated from the truncated target PSD curve. Figure 2-23 and Figure 2-24 show two representative comparisons of the resultant RS (dashed lines) and the bin representative DRS in NUREG/CR-6728 (solid blue lines). The vertical lines in these figures indicate the frequencies at which the PSD curves were truncated from higher frequencies. Similar figures can be used for the determination of upper bound (cutoff) frequencies for a PSD check along with other considerations such as the ZPA frequency of the DRS and the dynamic characteristics of the soil-structure equipment system. The criterion is that removing all tabulated PSD values above the cutoff frequencies does not significantly affect the compatibility between the PSD and RS.

Table 2-1 Cutoff frequencies calculated based on cumulative measures

Level	M[*] 5–6		M[*] 6–7				M[*] 7+			
	0–50 km	50–100 km	0–10 km	10–50 km	50–100 km	100–200 km	0–10 Km	10–50 km	50–100 km	100–200 km
Calculated Cutoff Frequency Based on Cumulative CEUS PSD										
0.90	27.89	26.29	20.68	19.16	17.81	16.41	13.92	12.25	11.09	9.99
0.95	37.75	36.51	30.61	28.71	26.96	25.57	22.52	20.30	18.85	17.01
0.9955	*63.89*	*62.37*	*59.38*	*57.92*	*57.31*	*55.47*	*52.82*	*50.67*	*49.36*	*47.59*
0.999973	*96.84*	*96.86*	*96.16*	*92.50*	*94.82*	*94.32*	*93.80*	*90.66*	*90.06*	*82.10*
Calculated Cutoff Frequency Based on the Cumulative Square Root of CEUS PSD										
0.90	34.60	33.67	28.25	26.61	25.55	24.66	22.18	20.61	19.61	18.19
0.95	47.73	46.97	41.74	39.82	39.13	38.01	35.48	33.88	32.62	30.92
0.97	*56.57*	*55.86*	*50.61*	*48.61*	*48.37*	*47.08*	*44.87*	*43.23*	*42.16*	*40.01*
0.998298	*91.29*	*91.36*	*88.61*	*81.34*	*85.33*	*84.39*	*83.25*	*78.60*	*78.07*	*76.13*
Calculated Cutoff Frequency Based on Cumulative WUS PSD										
0.90	7.28	6.87	5.52	5.09	4.77	4.35	4.22	3.82	3.41	3.08
0.95	9.59	9.12	7.30	6.66	6.34	5.86	5.64	5.09	4.64	4.11
0.9955	*25.89*	*24.09*	*17.43*	*15.69*	*14.43*	*13.00*	*12.73*	*11.33*	*9.98*	*9.02*
0.999973	*96.55*	*96.36*	*94.96*	*94.19*	*92.98*	*91.08*	*91.97*	*87.77*	*79.09*	*69.31*
Calculated Cutoff Frequency Based on the Cumulative Square Root of WUS PSD										
0.90	11.99	11.32	8.72	7.99	7.41	6.7	6.59	5.87	5.22	4.67
0.95	20.41	19.19	14.38	12.95	11.87	10.69	10.49	9.25	8.04	7.23
0.97	*31.29*	*29.26*	*21.05*	*19.04*	*16.95*	*15.15*	*15.07*	*12.78*	*10.80*	*9.72*
0.998298	*91.02*	*90.41*	*87.08*	*85.74*	*83.76*	*81.24*	*82.47*	*77.89*	*71.10*	*65.22*

[*] *M—the moment magnitude of the earthquake.*

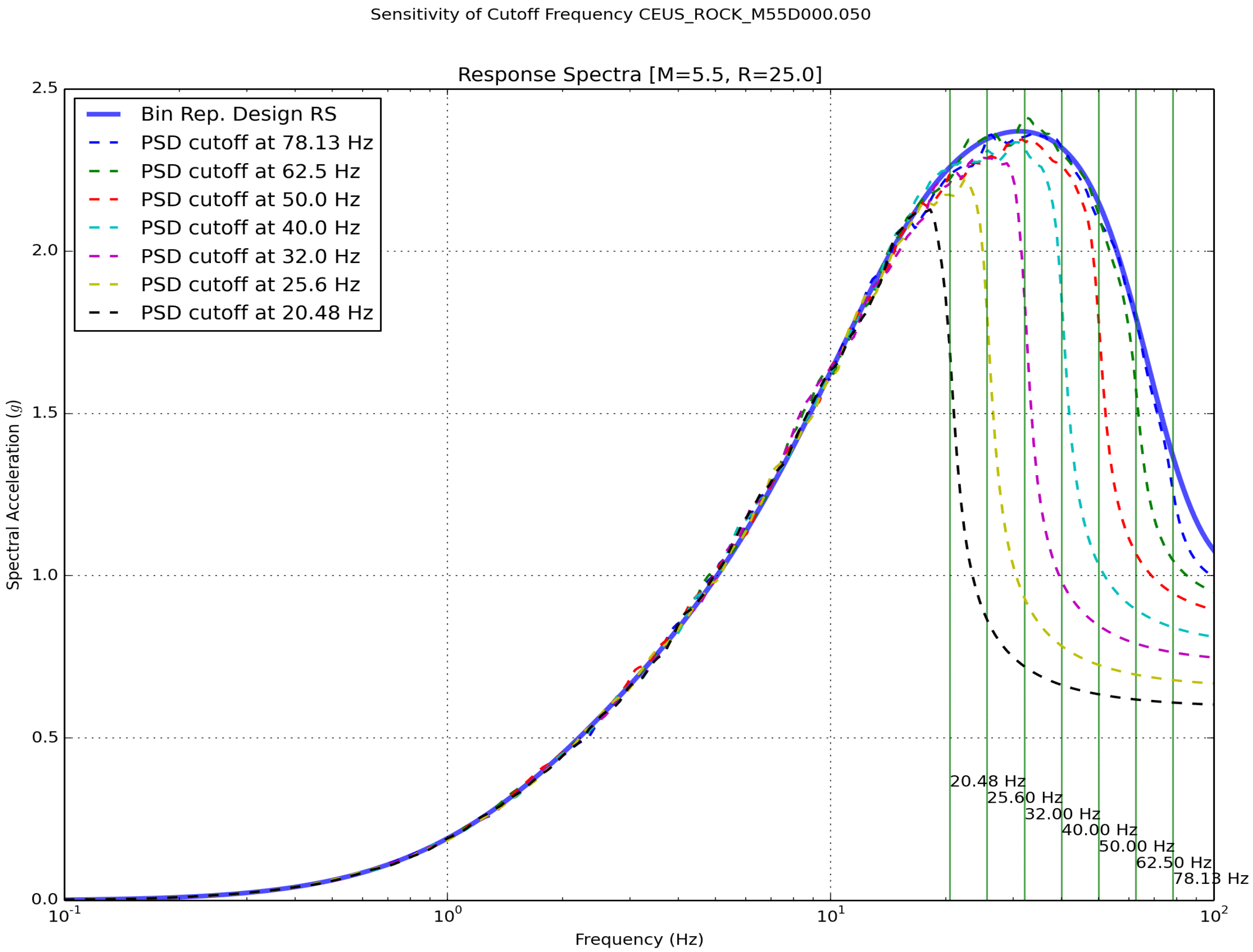


Figure 2-23 Sensitivity of the target PSD cutoff frequency for CEUS_ROCK_M55D000.050

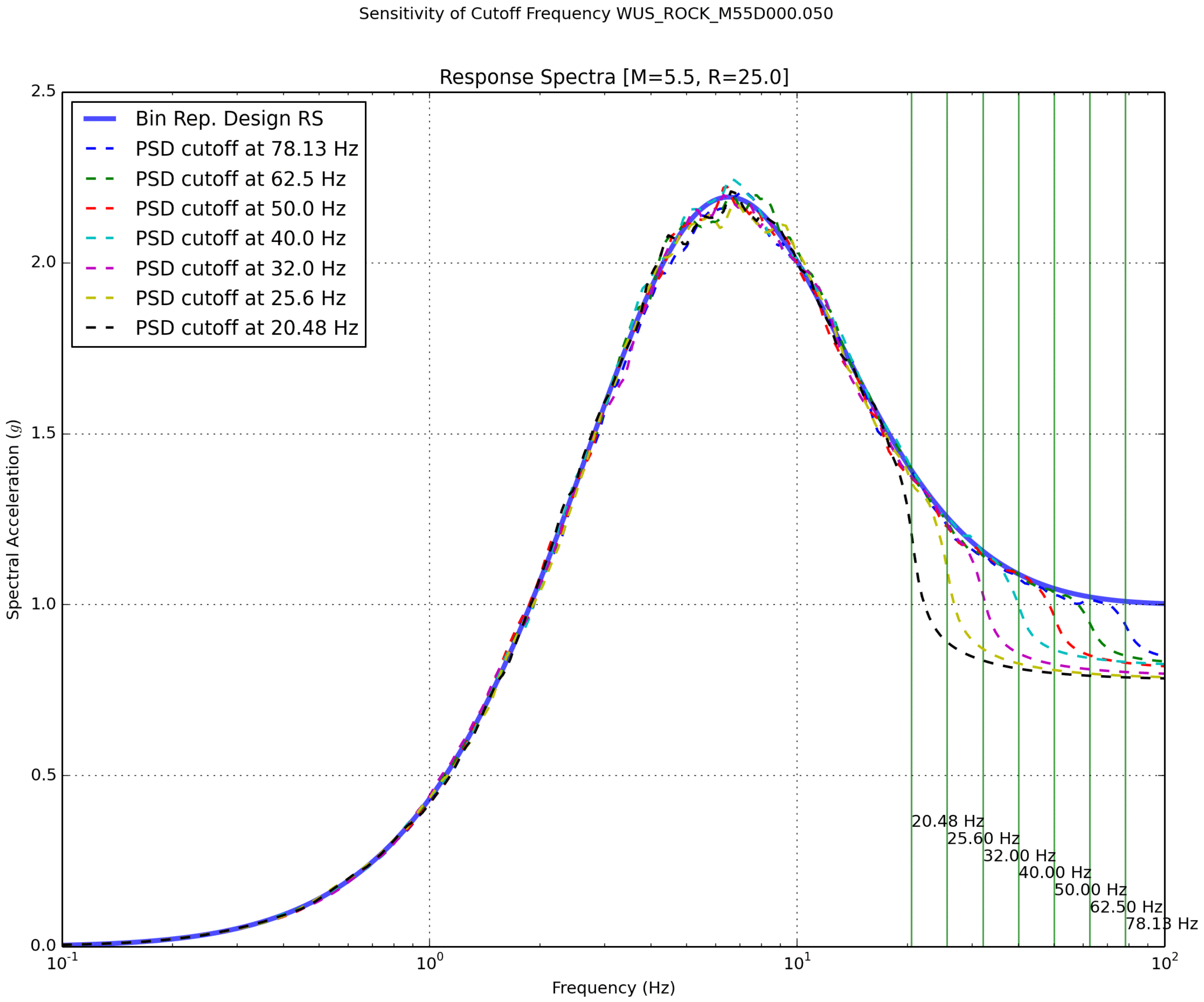


Figure 2-24 Sensitivity of the target PSD cutoff frequency for WUS_ROCK_M55D000.050

2.3.3 Clarification and Recommendation

For the upper bound frequency used in a PSD check, the current guidance in Appendix B to SRP Section 3.7.1 is recommended to remain because the upper bound frequency for the PSD check depends on the shape of the DRS. The upper bound frequency of 24 Hz may remain in SRP Section 3.7.1, Appendix A, or be revised to follow the same guidance as in Appendix B. The practical impact of such revision is minimal.

The lower bound frequency for the PSD check, which is currently set at 0.3 Hz, may be removed from the guidance because low frequencies close to this frequency can be important for the SSI phenomenon at some deep soil sites and for large tanks. As a replacement, the lower bound frequency (cutoff frequency) for the PSD check should be consistent with the DRS. It should be emphasized that the same single set of time histories is often used in different analyses such as the SSI analysis of major buildings or storage tanks installed on the ground surface.

If the consistency between the DRS at different damping ratios can be demonstrated, the use of the 5-percent damped DRS is appropriate in developing the target PSD function. Otherwise, the target PSD function should take the envelope of the target PSD functions developed for the DRS at all damping ratios.

2.4 Issue 8—Effect of Power Deficiency in Very Low or High Frequencies

2.4.1 The Issue and Affected SRP Text

Staff experience has shown that in some cases, the acceleration time histories developed following the current Option 1, Approach 2, can still have power deficiencies in some frequency ranges, including low or high frequencies. This issue focuses on the effects of power deficiency in time histories on structural responses at very low frequencies or high frequencies.

RES recognizes the use of two general methods to address the effect of power sufficiency:

(1) Ensure that the power is sufficient over the entire frequency range of interest during the development of input time histories.

(2) Assess the effect of power deficiencies on the structural responses.

This issue concerns the second method and indicates a need for an assessment of the significance of a power deficiency at very low frequencies or high frequencies in the structural response to make a reasonable assurance of safety determination. The question on the effect of power deficiency in very low or high frequencies reflects the common impression that most vibrational energy occurs in midfrequencies where velocity response dominates the RS, whereas vibrational energy would be lower in low frequencies where displacement response dominates and in high frequencies where acceleration response dominates.

There is no affected text in the SRP associated with this issue.

2.4.2 Technical Rationale and Basis

2.4.2.1 Literature Review

As discussed in NUREG/CR-5347, Appendix A, and in NUREG/CP-0054 and as described in Section 2.1 of this RIL, a time history that envelops the DRS but that has power deficiencies can underpredict the structural responses. NUREG/CR-5347 provided an example of a sinusoidal ground motion to demonstrate that issue; however, this ground motion was not considered realistic because it has only one frequency at 0.6 Hz, which is much lower than the dominant structural frequencies at 2 Hz and higher.

NUREG/CR-6728 evaluated the effect of the gaps in the PSD function or Fourier spectra on the RS of several time histories. It concluded that the level of reduction in the RS was similar to that in the PSD at frequencies between 1 Hz and 10 Hz and decreased as the frequency moved away from this frequency range. In other words, this study showed that a good RS match at low or high frequencies could conceal the large power deficiencies in these frequency ranges. Indeed, the introduction in Section 5 of NUREG/CR-6728 similarly recognized that a DRS could be enveloped by the computed free-field RS across a given frequency range, even though the PSD (or equivalently, the Fourier amplitude spectrum) of the input ground motion could have low levels (gaps) within the same frequency range. This is consistent with the guidance in SRP Section 3.7.1, Revision 2 (and subsequent versions), Option 1, Approach 1, which states that enveloping the DRS alone is not sufficient to ensure there is no power deficiency in the time history. More importantly, NUREG/CR-6728 continues to indicate that, in the case of power deficiency, although RS enveloping criteria have been met, the computed system response may be underpredicted if, for example, the SSI frequencies fall within those gaps. However, NUREG/CR-6728 does not provide a reference or a calculation to support this indication. Also, because the gaps implemented in the PSD functions also introduced gaps in their RS at the same time, the cases in NUREG/CR-6728 do not demonstrate how a time history that envelops the DRS but is deficient in its PSD function affects the structural responses.

Of critical importance in this regard is the more recent study by Houston et al. (2010), which showed that the ASCE/SEI 43-05 RS enveloping criteria can sometimes lead to an underprediction of ISRS by as much as 70 percent at some frequencies. The goal of this study was to evaluate the effect of seed selection on structural response, and its results indicated some limitations in the ASCE/SEI 43-05 RS enveloping criteria, which were initially proposed in NUREG/CR-6728 and were also adopted as Option 1, Approach 2, in SRP Section 3.7.1, Revision 3. This study analyzed a soil-structure system using hundreds of artificial time histories, each of which was obtained by modifying a seed to envelop the DRS following the ASCE/SEI 43-05 criteria. The soil-structure system consisted of a structural model from the System for Analysis of Soil-Structure Interaction (SASSI) 2000 user's manual (Lysmer et al., 1999) and three soil profiles. Site-specific DRS for these soil profiles were developed as the mean surface RS using one-dimensional equivalent linear soil convolutions of the rock outcrop uniform hazard response spectra (UHRS). The RS shape from NUREG/CR-0098, "Development of Criteria for Seismic Review of Selected Nuclear Power Plants," issued May 1978, was used as another DRS. The study used the mean and standard deviation of the ISRS generated from all the time histories to show the variability in the structural response. The authors selected the seed records from the Next Generation Attenuation of Ground Motion Database and from the NUREG/CR-6728 empirical database.

This study found that, for some cases, the level of variability of the ISRS was reasonably consistent with general expectations; however, for other cases, the study found that large variations in computed peak SSI response were associated with seed selection. The maximum coefficient of variation in 5-percent damped ISRS was as much as 70 percent, indicating a high probability of significantly underpredicted structural response at some frequencies. These high variabilities in ISRS occur at frequencies where the transfer functions have narrow-banded large amplifications. The study also compared the PSD functions of three input motions that generate a low ISRS, a median ISRS, and a high ISRS, respectively, and considered the bandwidth of the transfer functions of an SDOF oscillator at 2-, 5-, and 15-percent damping ratios. This comparison clearly showed that the input motion with a dip in its PSD function was the cause of the underpredicted ISRS. Because the RS enveloping procedure is the same for all time histories, the study concluded that the selection of seed records had a significant effect on the computed structural response for low damped systems. In other words, the ASCE/SEI 43-05 RS enveloping criteria were not capable of preventing such cases, without running hundreds of SSI analyses with different input time histories.

The study further investigated the correlation between the variation of the ISRS and the magnitude and fault distance for the seeds but did not find statistically significant effects of these parameters. The study also proposed a method to develop DRS at 2- and 20-percent damping ratios based on 5-percent damped DRS; these two DRS can be used in addition to the 5-percent damped DRS to improve the input motion, effectively making the RS enveloping approach use multiple DRS. The three DRS in the proposed method are not fully consistent because they are not generated from the same set of time histories. The inconsistency between the DRS partially contributed to the fact that all three DRS can be controlling but at different frequencies. The study did not examine in detail the effect of the adjustment on ISRS.

The above literature review leads to the conclusion that a time history that is deficient in power at some frequencies at important structural modes can greatly underpredict structural responses, even though its RS envelops the DRS properly. This conclusion is consistent with the findings in Section 2.1 of this RIL.

2.4.2.2 Discussion

In the case of an input motion shown to have a power deficiency in some frequency band, the next step of the review would be to ask the applicant to either regenerate the time histories or justify that the identified power deficiency has no significant effect on the structural response. For the staff to review the applicant’s justification, the important factor in deciding whether a power deficiency at any frequency is significant to structural responses is to check whether there are important modes in the deficient frequency ranges. The same holds true for power deficiencies at the very low frequencies and high frequencies specifically covered in this issue. If there are such modes, for a definitive conclusion on whether, and how much, the power deficiency affects the structural response, one can perform an analysis using other methods (e.g., RSA or RVT methods) or using time histories that are shown to have no power deficiency. The justification needs to cover the entire system, including soil columns, structural systems, and the equipment.

For very low frequencies, as discussed in Section 2.3 of this RIL, modal frequencies can be very low in a number of instances. Examples include (1) soil-structure systems at some deep soil sites that often have site response fundamental frequencies well below 1 Hz, (2) water tank sloshing modes (e.g., even lower than 0.2 Hz in some licensing applications), (3) seismically isolated structures and components, and (4) cases involving the sliding and uplifting of foundations.

High frequencies are important for some CEUS rock sites at which rock outcrop motions may have significant power at frequencies as high as 50 Hz. Although it is widely recognized that these high-frequency motions may not contribute significantly to structure response, they are important to equipment and components that are vulnerable to high-frequency motions. In fact, the staff emphasizes in its review that all flexible walls and floors should be adequately modeled up to 50 Hz. Structural deamplification at higher frequencies means only that the input power at those higher frequencies is reduced; however, without an actual evaluation, such deamplification does not necessarily mean that a very high input power at the higher frequencies would be reduced to a level insignificant to equipment installed in the structures.

Narrow transfer functions, modes with very low damping (e.g., water sloshing mode), and an insufficient combination of modal response when input time histories are frequency nonstationary can help transmit the potentially adverse effects of power deficiencies in time histories to the structures and equipment; therefore, these effects can be dependent on structure and response. ISRS are particularly sensitive to the frequency components in the input motion around the modal frequency of the supporting structure. For an oscillator at rest subjected to an input motion with proper ramping, the oscillator responds only in the frequencies of the input motion, and its modal frequency determines only how the input motion is amplified. In other words, if an input motion lacks certain frequencies, the response of the oscillator would also lack the same frequencies. To illustrate this point, a broadband acceleration time history was developed. Figure 2-25 through Figure 2-27 show its RS meeting the Option 1, Approach 2, criteria; the acceleration, velocity, and displacement time histories; and PSD function exceeding the minimum target PSD function, respectively. The minor dips in the PSD function below the minimum target PSD function are not considered significant, and these dips are not in the range of frequencies around 10 Hz that will be used below in this example. In practice, these dips can be removed by slightly increasing the Fourier amplitudes at those affected frequencies.

This example uses the broadband acceleration time history and the time history with mainly 15 frequencies (as shown in Figure 2-5) to drive three SDOF structures (oscillators), with modal frequencies at 9.4 Hz, 12.8 Hz, and 11.0 Hz, respectively. These frequencies are chosen approximately at the two spikes close to 11 Hz and the midfrequency between these spikes as shown in Figure 2-8. These SDOF structures are assumed to have a damping ratio of 5 percent, the same as that used in meeting the Option 1, Approach 2, criteria. Therefore, these oscillators are essentially three of those used to generate the RS (9.5 Hz, 11.2 Hz, and 12.9 Hz). Figure 2-28 compares the relative responses of the 11.0-Hz oscillator subjected to the two input motions. Although the RS of the two input motions are very close at 11.0 Hz, the peak spectral acceleration (PSA) of the oscillator for the power-deficient input motion (PSA_{15}) is about half of that for the broadband input motion ($PSA_{broadband}$). In addition, the shape of the RS and the PSA frequency are somewhat different. Figure 2-29 shows the relative responses of the 9.4-Hz oscillator, and Figure 2-30 shows those of the 12.8-Hz oscillator. For the 9.4-Hz oscillator, $PSA_{broadband}$ is 60 percent more than the PSA_{15}. This result is consistent with the PSD functions; the broadband input motion has high power in a range of frequencies around 9.4 Hz, at a level close to the only spike of the power-deficient input motion around this frequency. For the 12.8-Hz oscillator, the PSA for the broadband input motion is lower than that for the power-deficient time history as expected because the broadband time history has much lower power than the spike of the power-deficient time history around 12.8 Hz. Despite the large differences in PSA and the RS shapes, the ZPAs of these three SDOF structures are the same as the spectral accelerations at the corresponding frequencies in the input motions, which confirms the only assurance that an RS can provide (i.e., the maximum response of the oscillators). Except for ZPA, ISRS reflects the power distribution of the input motion around the structural modal frequencies rather than the RS of the input motion.

Figure 2-31 through Figure 2-39 show the absolute responses of SDOF structures with the same frequencies as above. In addition to the 5-percent damping ratio, the 2- and 10-percent damping ratios were also considered. Table 2-2 lists the PSA ratios for various combinations of the oscillator frequency, oscillator damping ratio, damping ratio for RS computation, and relative versus absolute responses and compares the differences in responses between the broadband input motion and the input motion with only 15 major frequencies. As shown in these figures and Table 2-2 and as expected, the lower the damping ratios, the higher variation the PSA shows among the SDOF structures. When the damping ratio is 10 percent, the difference in $PSA_{broadband}$ and PSA_{15} becomes small, and the RS shapes become similar. The reasons are twofold: (1) the three SDOF structures at a 10-percent damping ratio cover a wider frequency window of the input motions to generate the responses, and (2) the 10-percent damping ratio used in ISRS computation allows the coverage of a larger frequency window of the responses. To show the effect of the second reason, Figure 2-40 through Figure 2-45 show the 2- and 5-percent damped RS of the responses of the SDOF structures with 10-percent damping ratio. Table 2-2 also lists the PSA ratios from these figures. These PSA ratios at lower damping ratios in the computed RS show more of a significant difference in response than those using the 10-percent damping ratio, but the difference is not as significant as that from SDOF structures of a 2- or 5-percent damping ratio.

To assess the effect of the damping ratio on frequency coverage, it is helpful to know that the relative half-power window width is approximately proportional to the damping ratio of the oscillator. For example, as shown in Figure 2-46, the relative half-power window size for the amplification function of a 10-percent damped oscillator is 20 percent (i.e., ±10 percent) as compared to the 36-percent difference between the 15 major frequencies. At the bounding frequencies for the half-power window, the amplification value is still high at 70.7 percent of the peak amplification. When considering the significant amplification value to be one-third of the peak amplification, the frequency window is about 183 percent larger than the half-power window (i.e., for a damping ratio of 10 percent, the window size would be 56.6 percent, which is larger than the 36-percent difference between the 15 major frequencies).

Houston et al. (2010) concluded that the high variabilities in ISRS occur at frequencies where the transfer functions of the SSI systems have narrow-banded large amplifications. For the above example, because the RS enveloping was performed based on 5-percent damped RS, an SSC with smaller damping ratios (e.g., 0.5 percent or 2 percent) would possibly represent a narrow-banded transfer function relative to the 5-percent damped oscillators used to generate the RS. However, the example in this RIL shows that, even for an SSC with the same damping ratio as that used in the RS enveloping process, the variation of ISRS resulting from different input time histories can still be significantly large. This can even occur at frequencies where the input motions envelop the DRS with similar conservativeness (i.e., the RS of the two input motions in the above example are very close at 11.0 Hz). Therefore, this example reinforces the conclusion of Houston et al. (2010) and clearly demonstrates that RS enveloping criteria alone cannot ensure that the generated acceleration time history is adequate. On the other hand, a PSD check by a comparison with a target PSD function can clearly identify power deficiencies.

Table 2-2 Differences in the responses of the SDOF structures

Oscillator Damping Ratios (Damping Ratios to Calc. RS)	**Ratio of Absolute PSA (Broadband/15 Frequencies)**		
	9.4 Hz	11.0 Hz	12.8 Hz
2% (2%RS)	1.21	3.60	0.44
5% (5%RS)	1.52	1.85	0.77
10% (10%RS)	1.06	1.07	0.93
10% (2%RS)	1.58	1.70	0.76
10% (5%RS)	1.25	1.37	0.89
	Ratio of Relative PSA		
5% (5%RS)	1.63	1.90	0.74

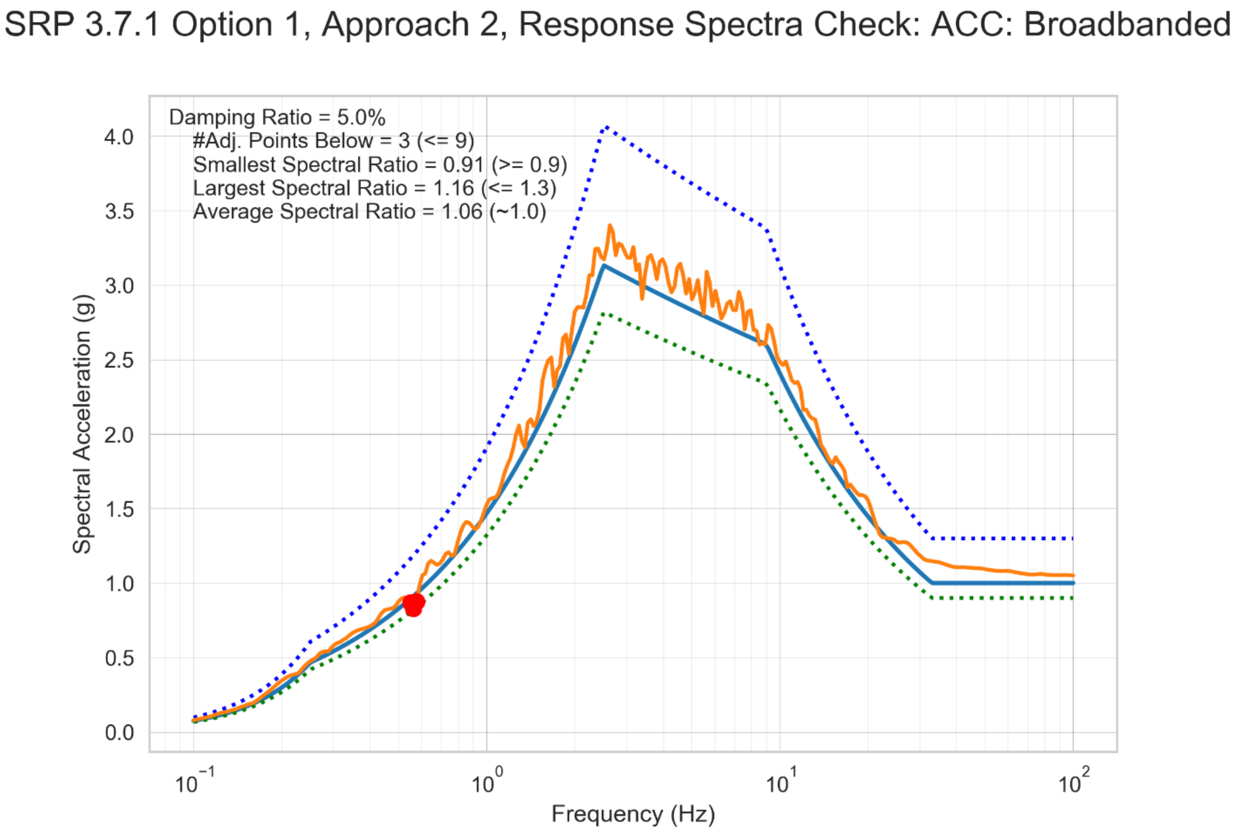


Figure 2-25 A broadband accelerogram enveloping DRS (piecewise smooth curves showing the criteria)

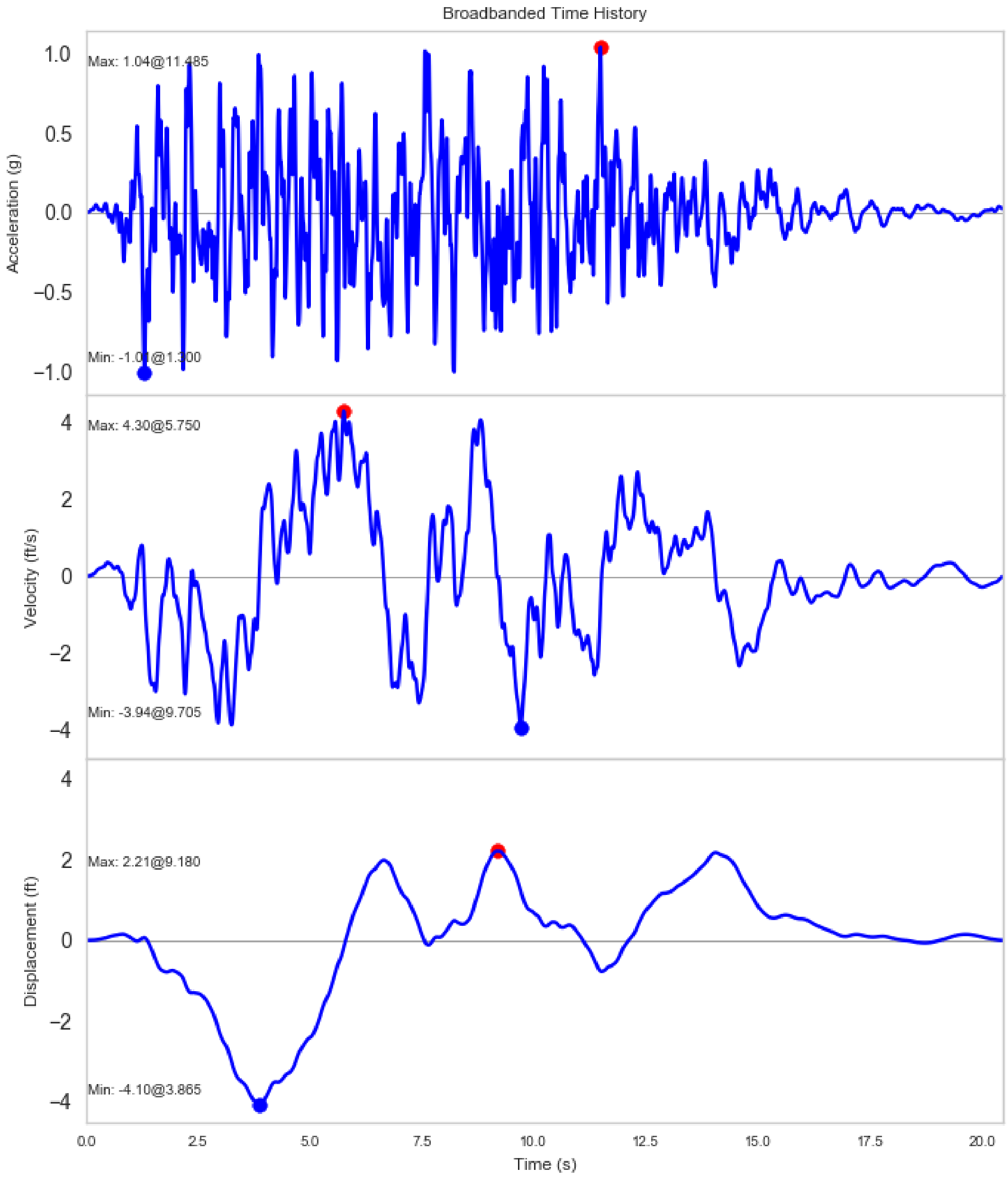


Figure 2-26 The acceleration, velocity, and displacement of the broadband accelerogram

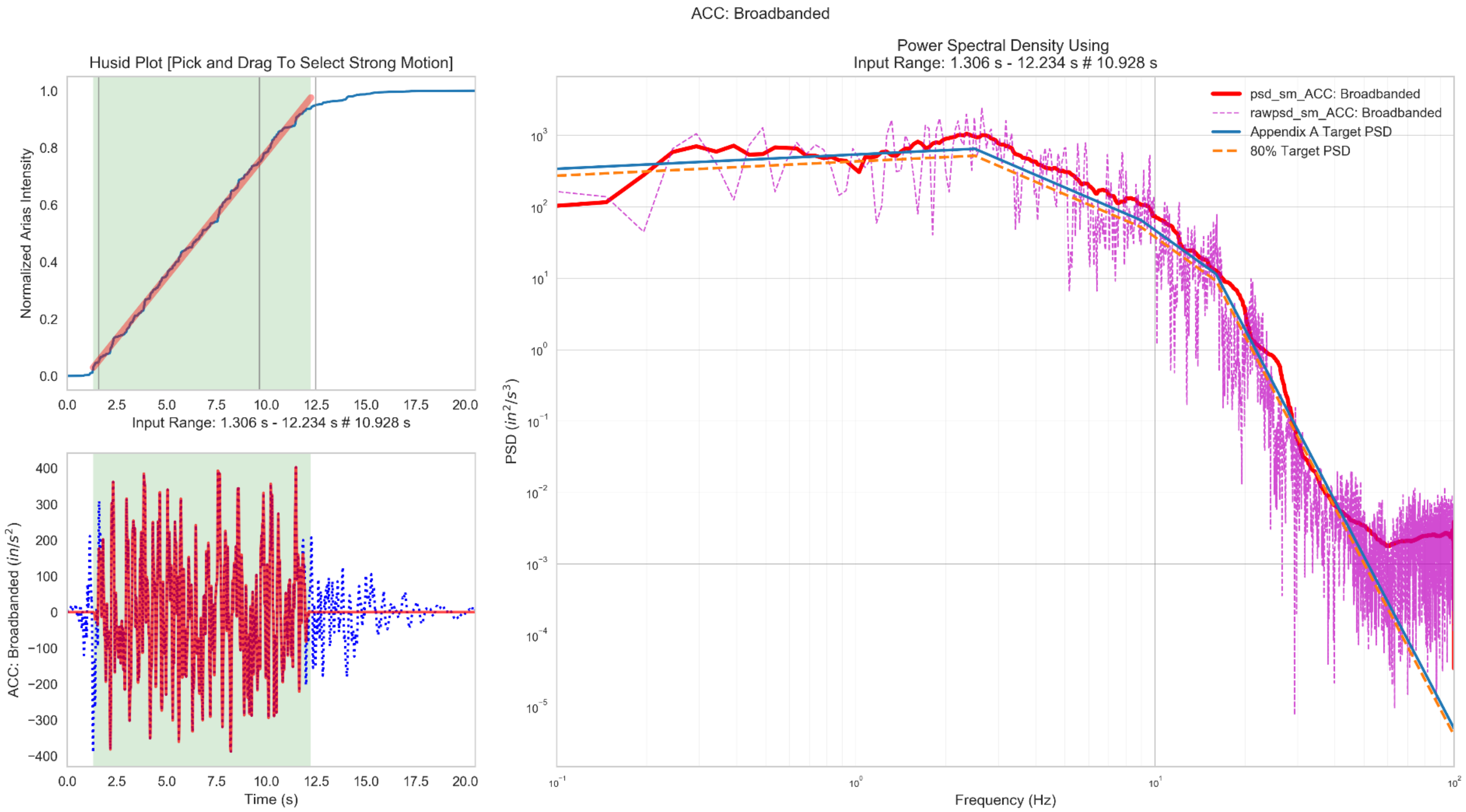


Figure 2-27 A PSD check of the broadband accelerogram

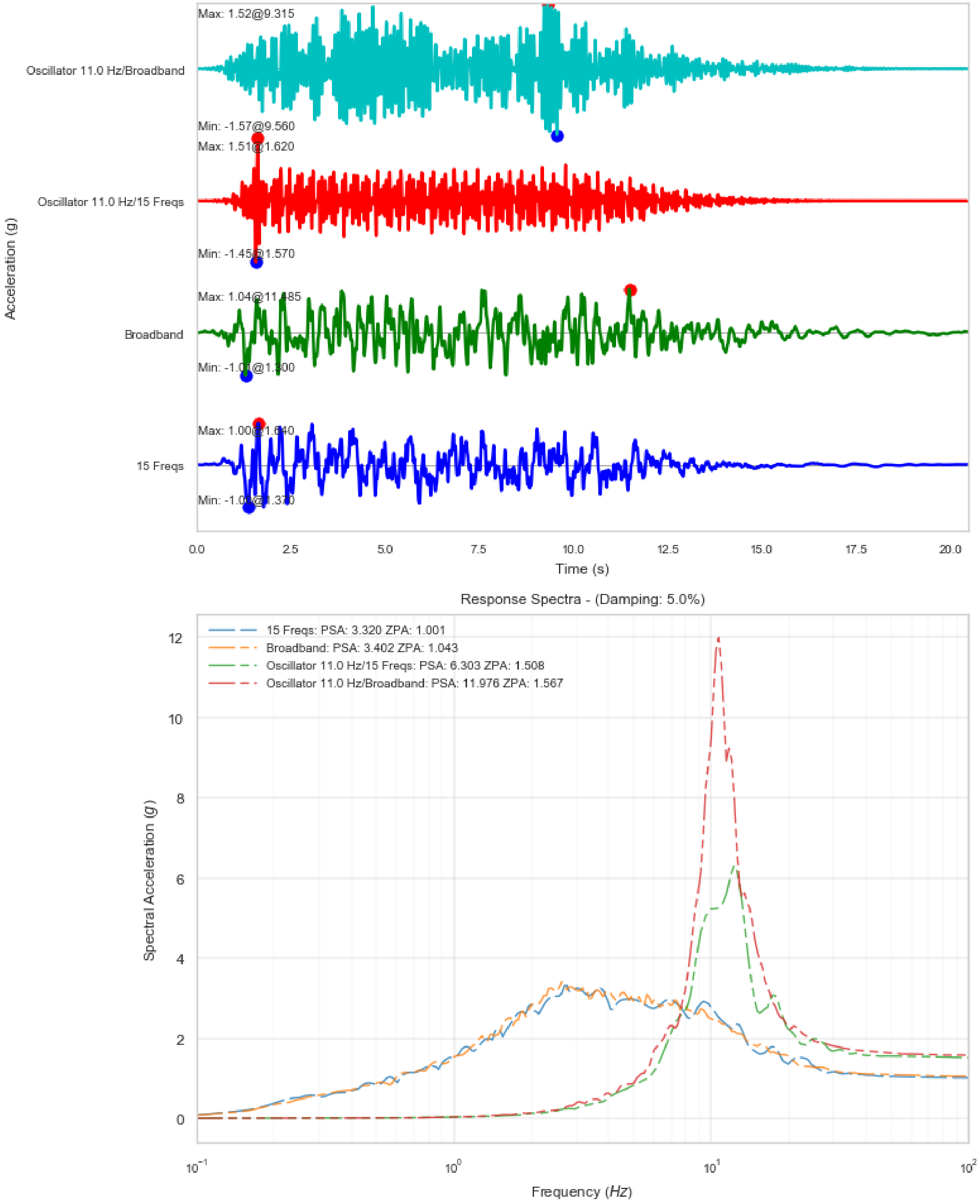


Figure 2-28 Relative responses of the 11.0-Hz SDOF structure

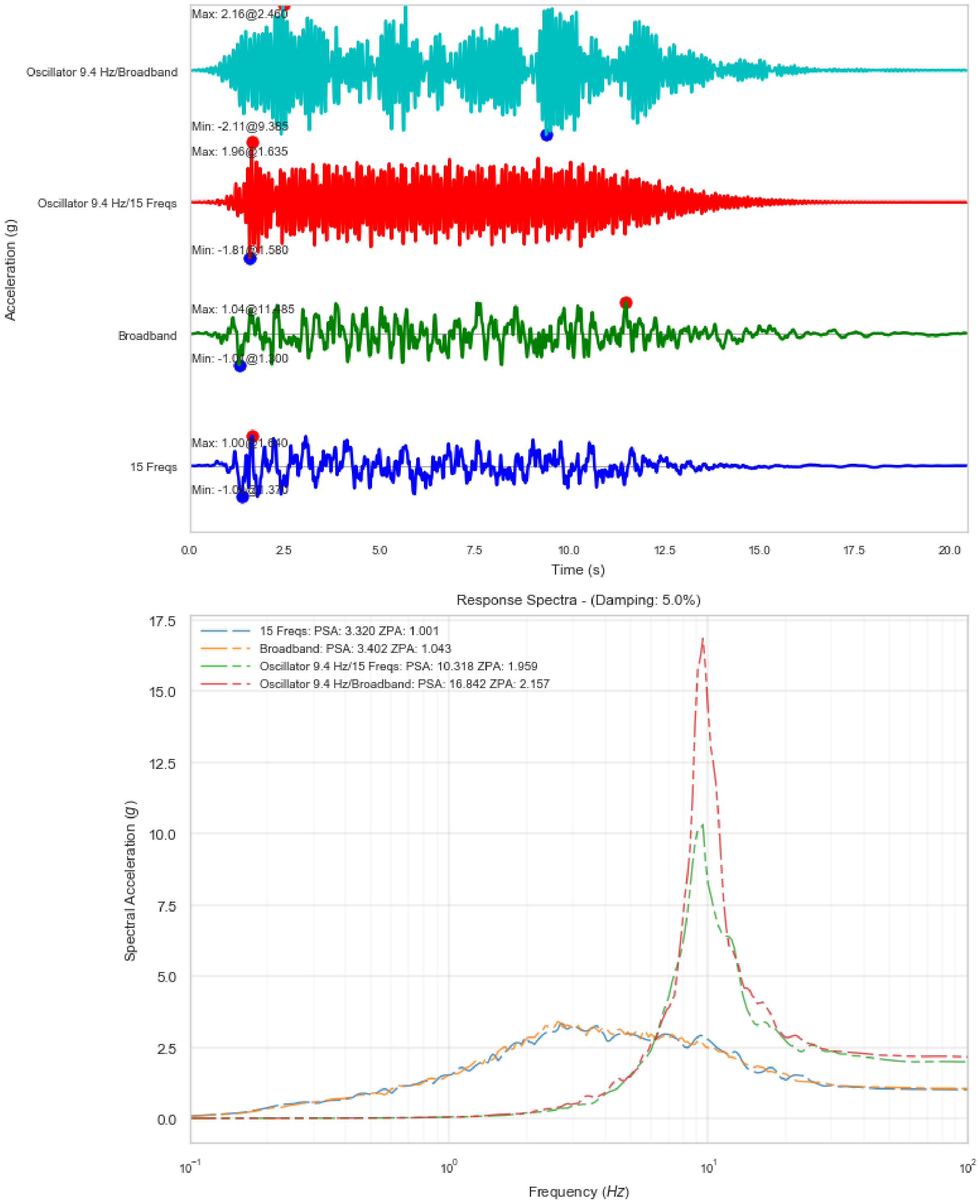


Figure 2-29 Relative responses of the 9.4-Hz SDOF structure

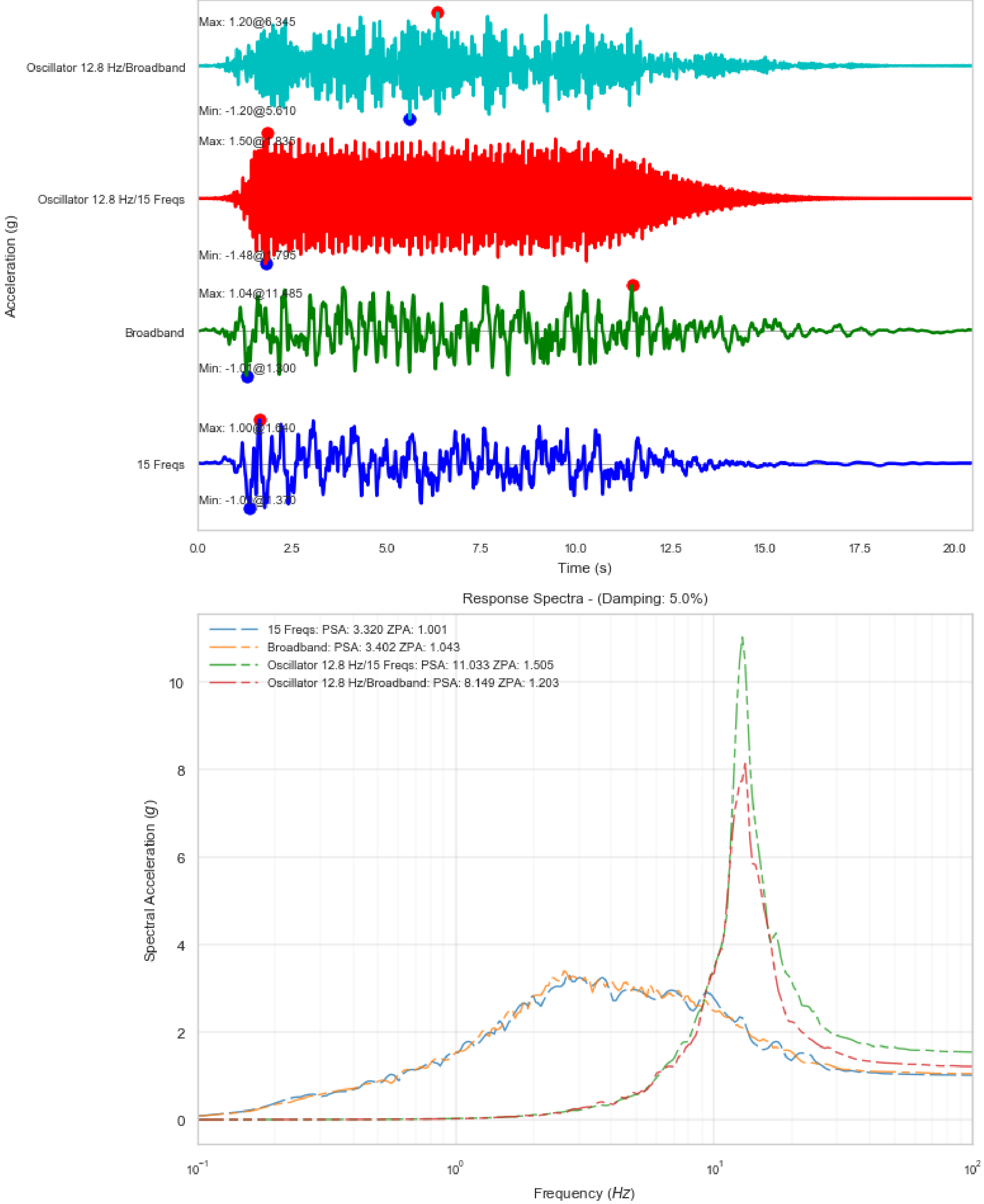


Figure 2-30 Relative responses of the 12.8-Hz SDOF structure

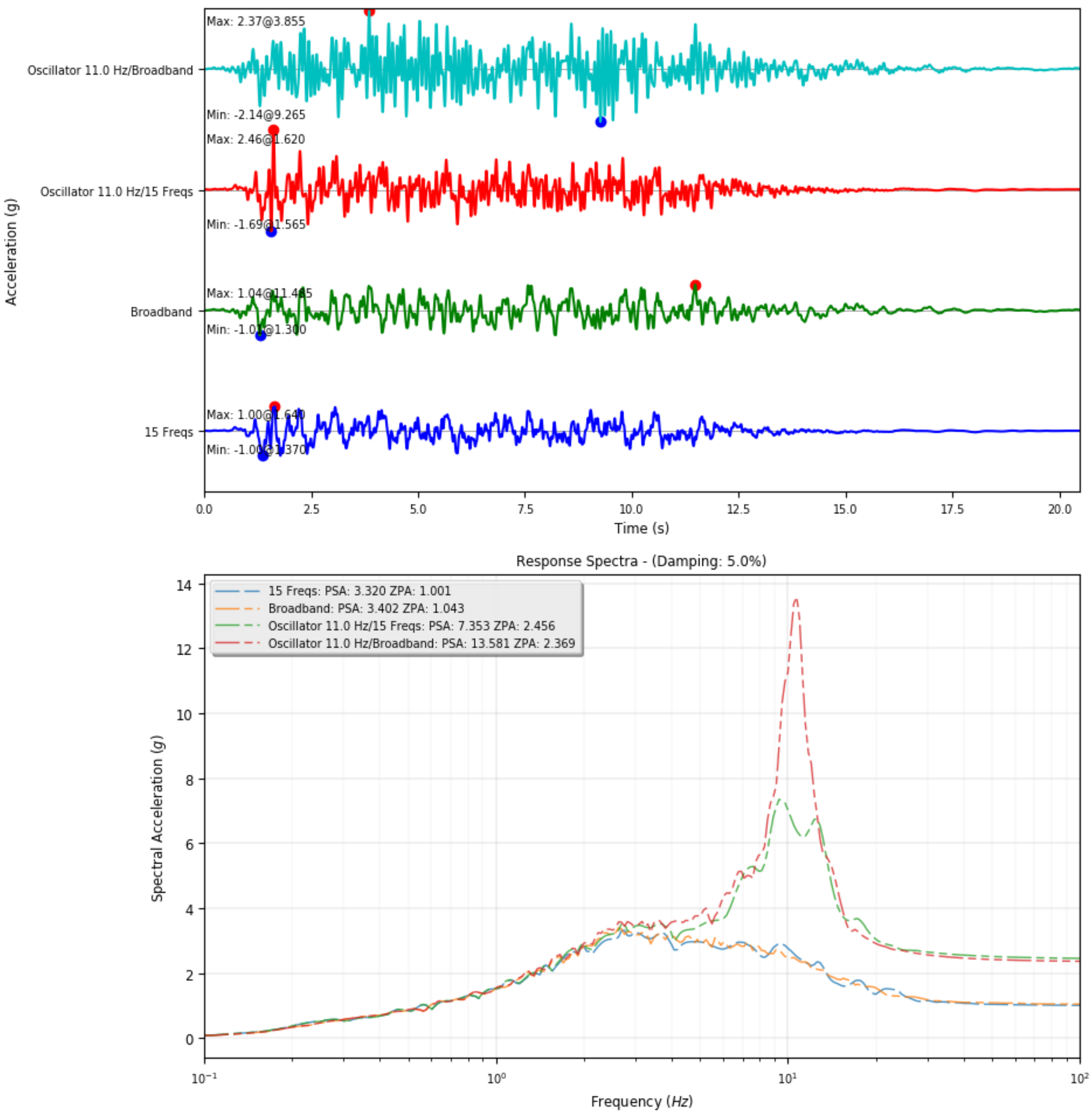


Figure 2-31 Absolute responses of the 11.0-Hz SDOF structure with a 5-percent damping ratio

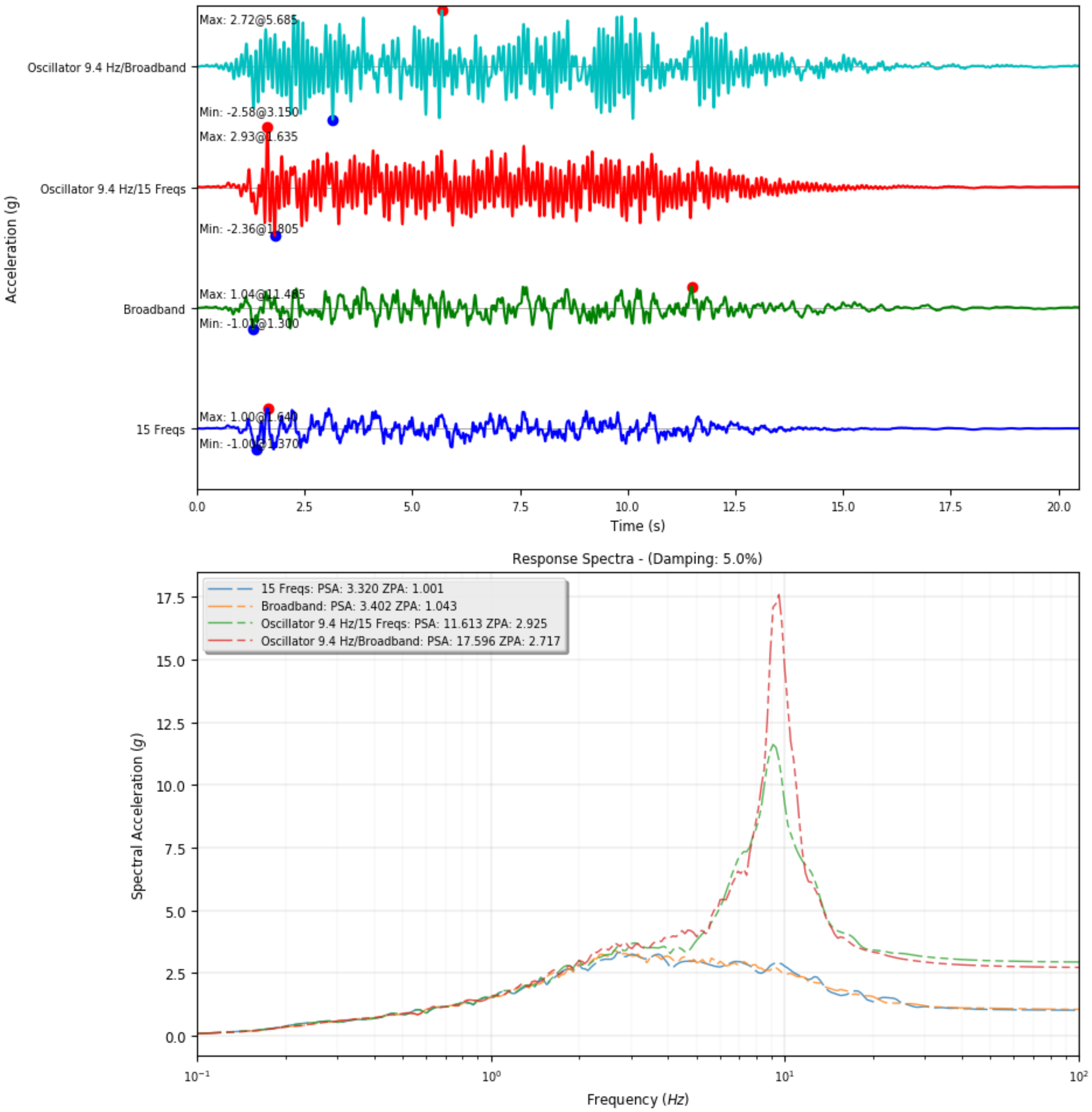


Figure 2-32 Absolute responses of the 9.4-Hz SDOF structure with a 5-percent damping ratio

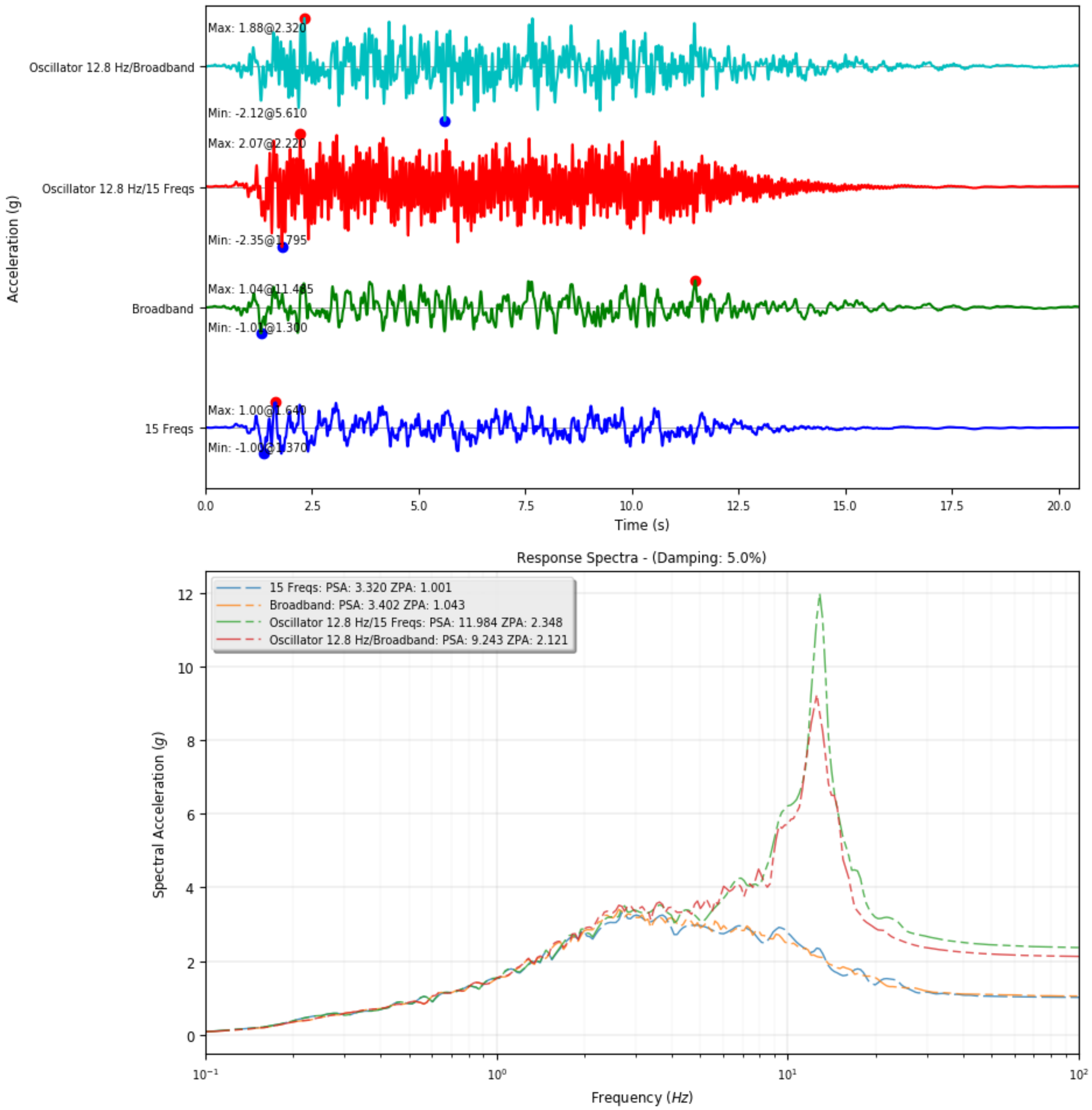


Figure 2-33 Absolute responses of the 12.8-Hz SDOF structure with a 5-percent damping ratio

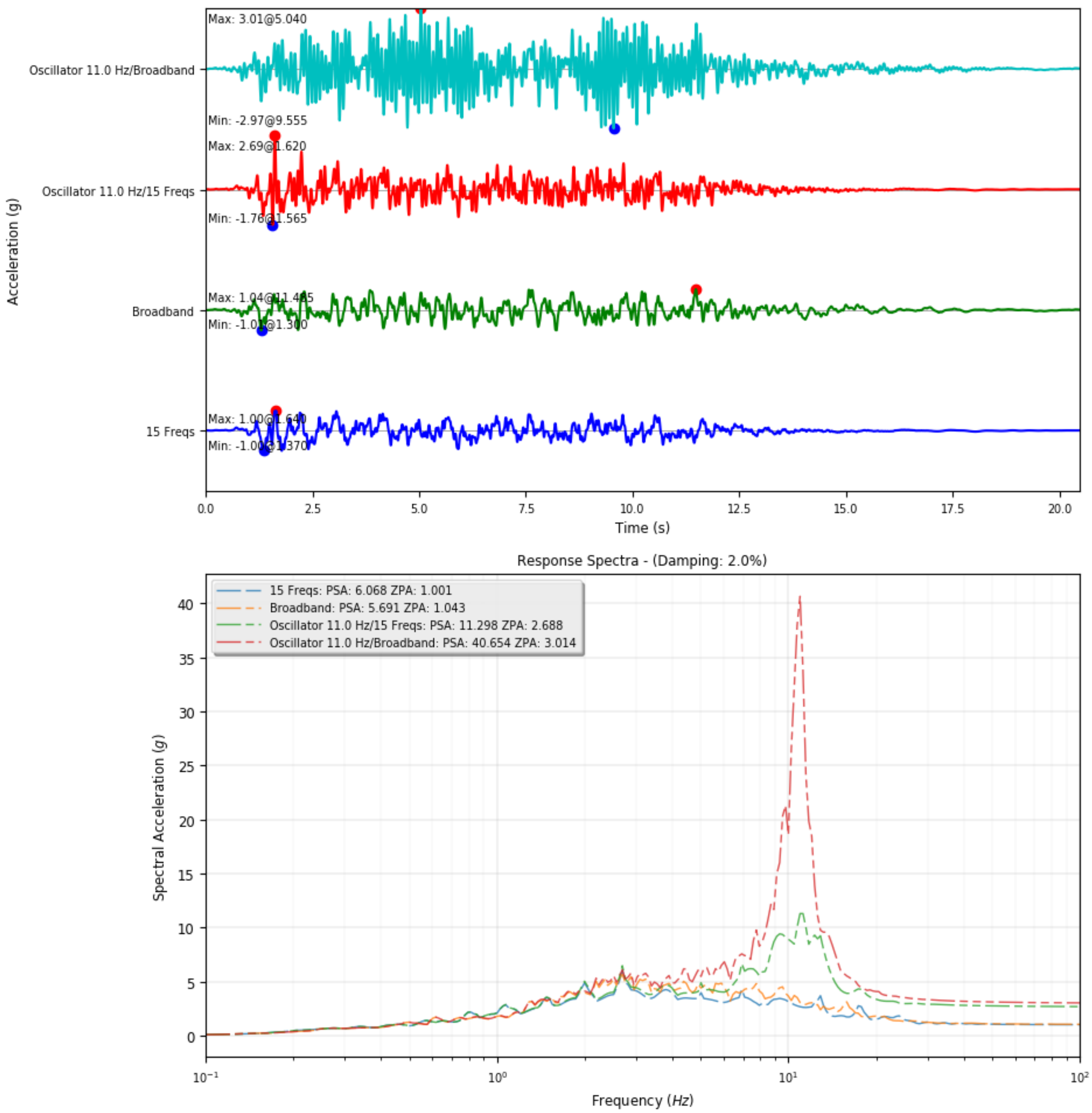


Figure 2-34 Absolute responses of the 11.0-Hz SDOF structure with a 2-percent damping ratio

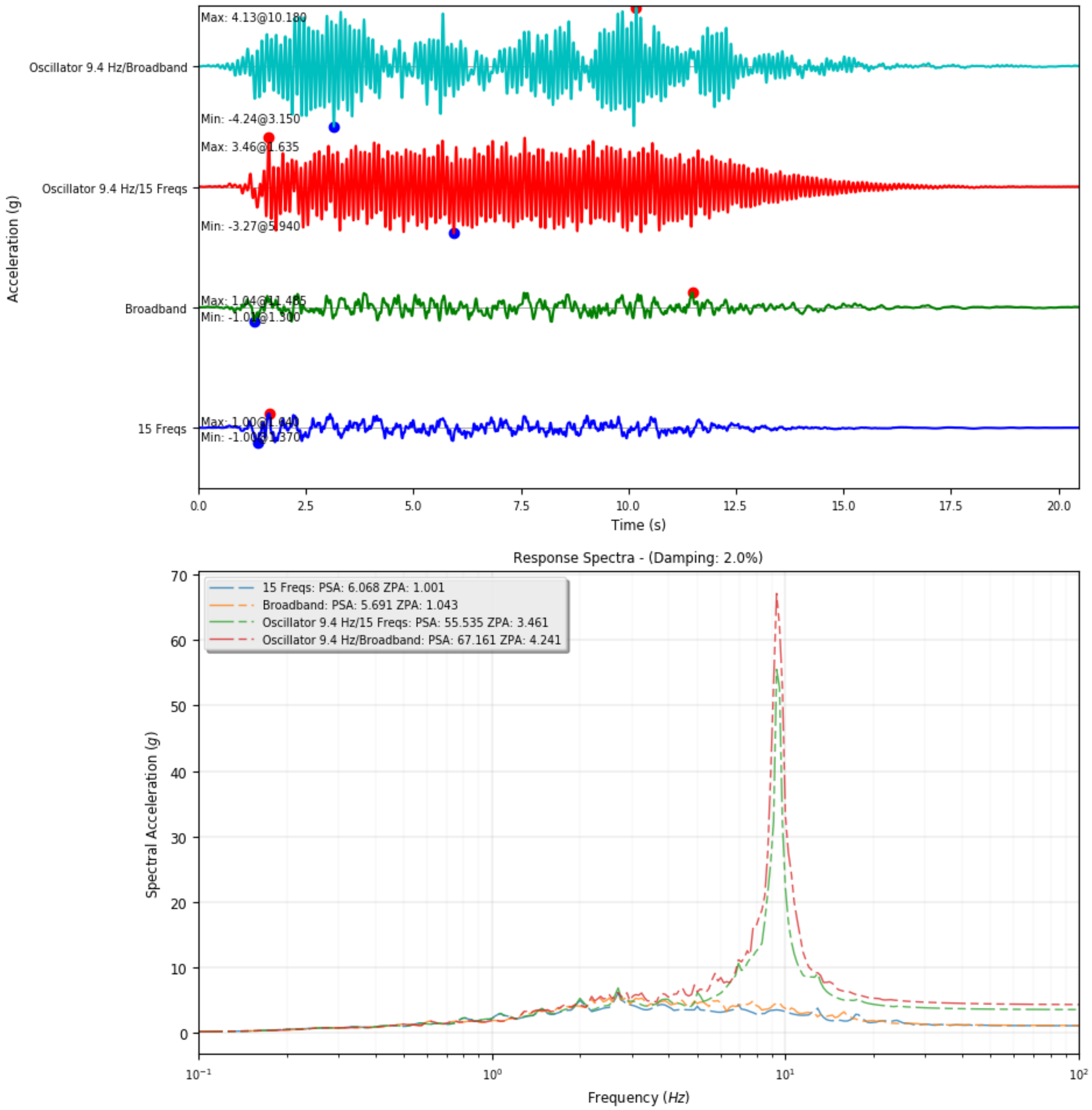


Figure 2-35 Absolute responses of the 9.4-Hz SDOF structure with a 2-percent damping ratio

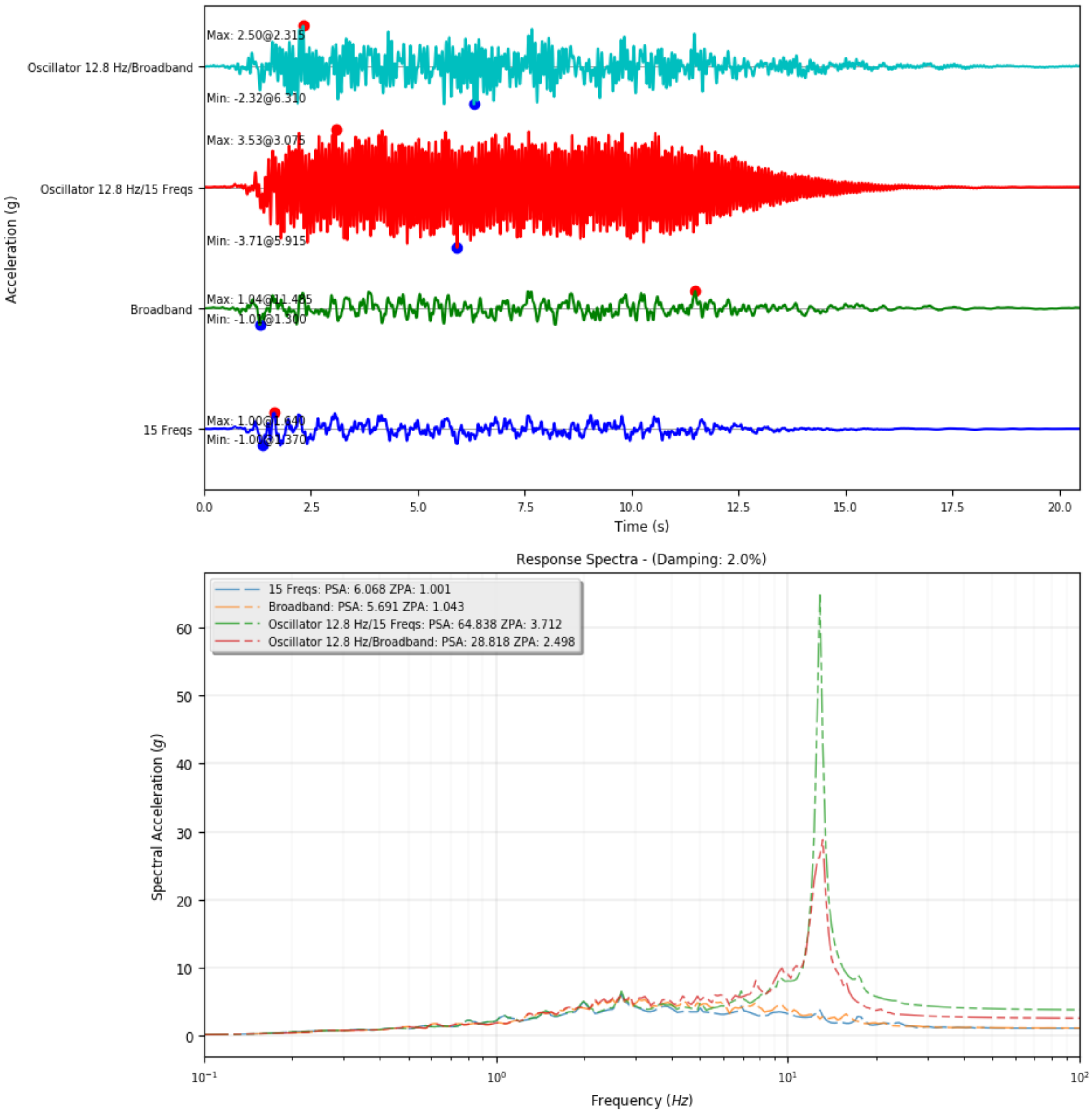


Figure 2-36 Absolute responses of the 12.8-Hz SDOF structure with a 2-percent damping ratio

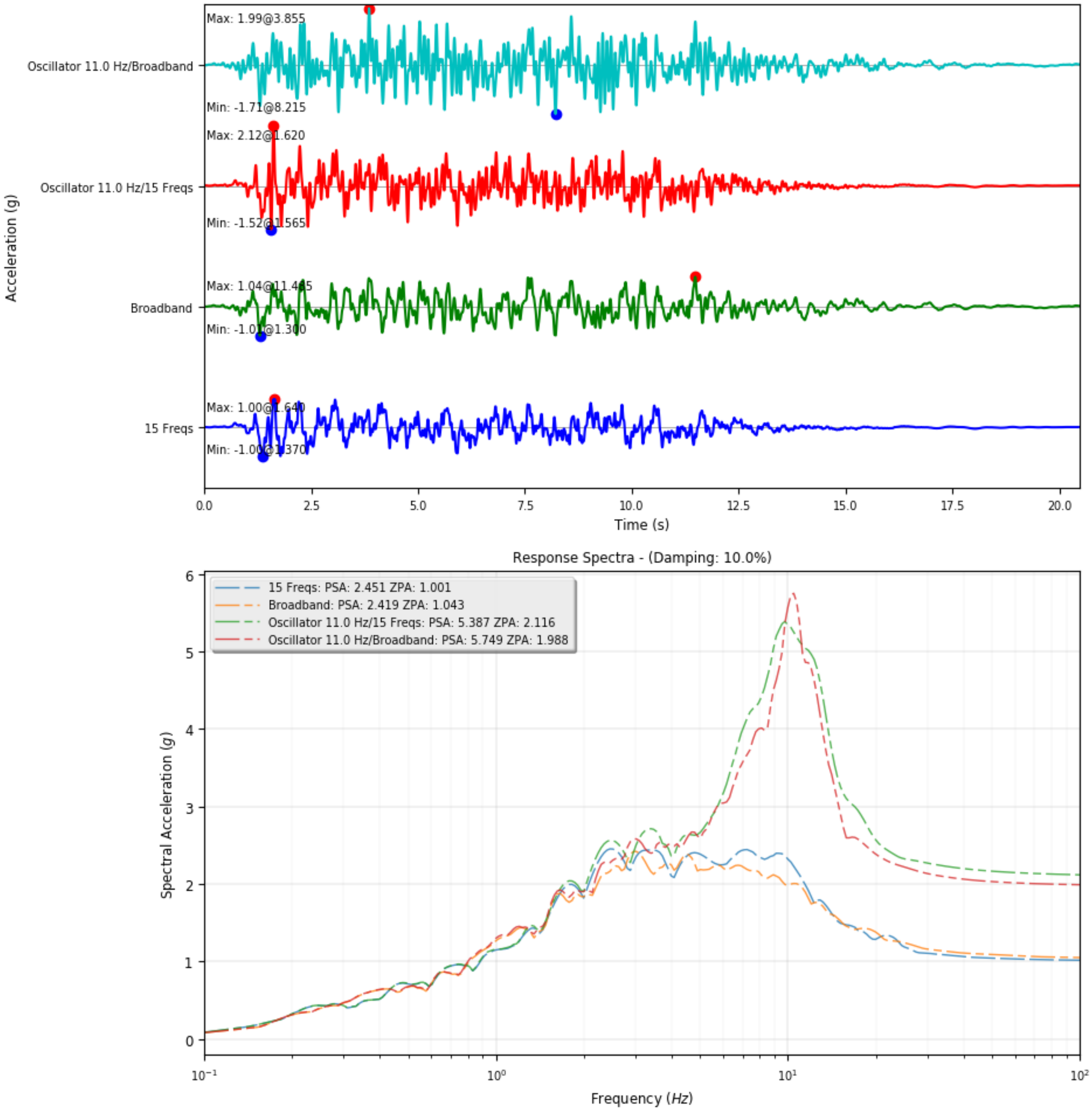


Figure 2-37 Absolute responses of the 11.0-Hz SDOF structure with a 10-percent damping ratio

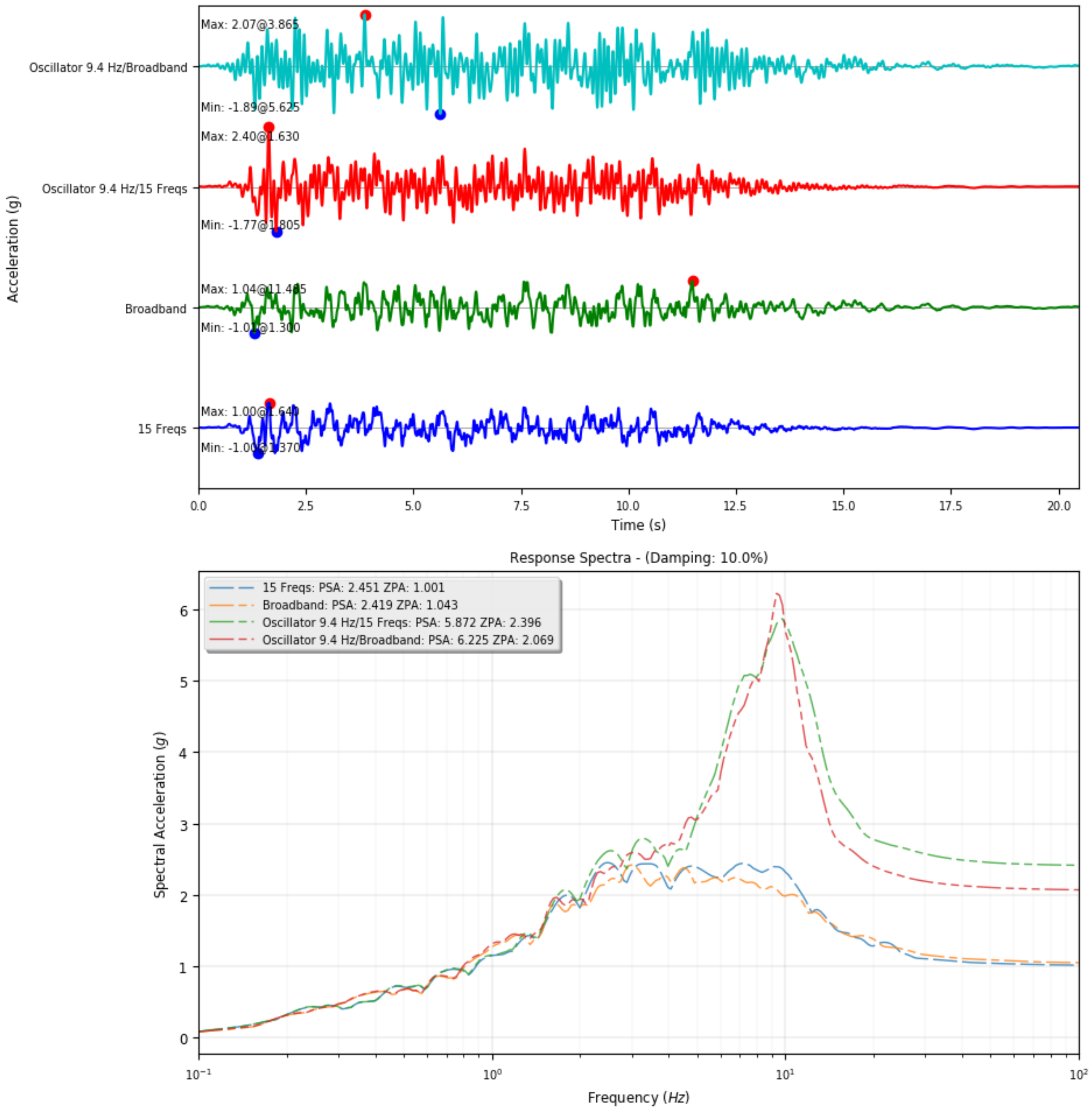


Figure 2-38 Absolute responses of the 9.4-Hz SDOF structure with a 10-percent damping ratio

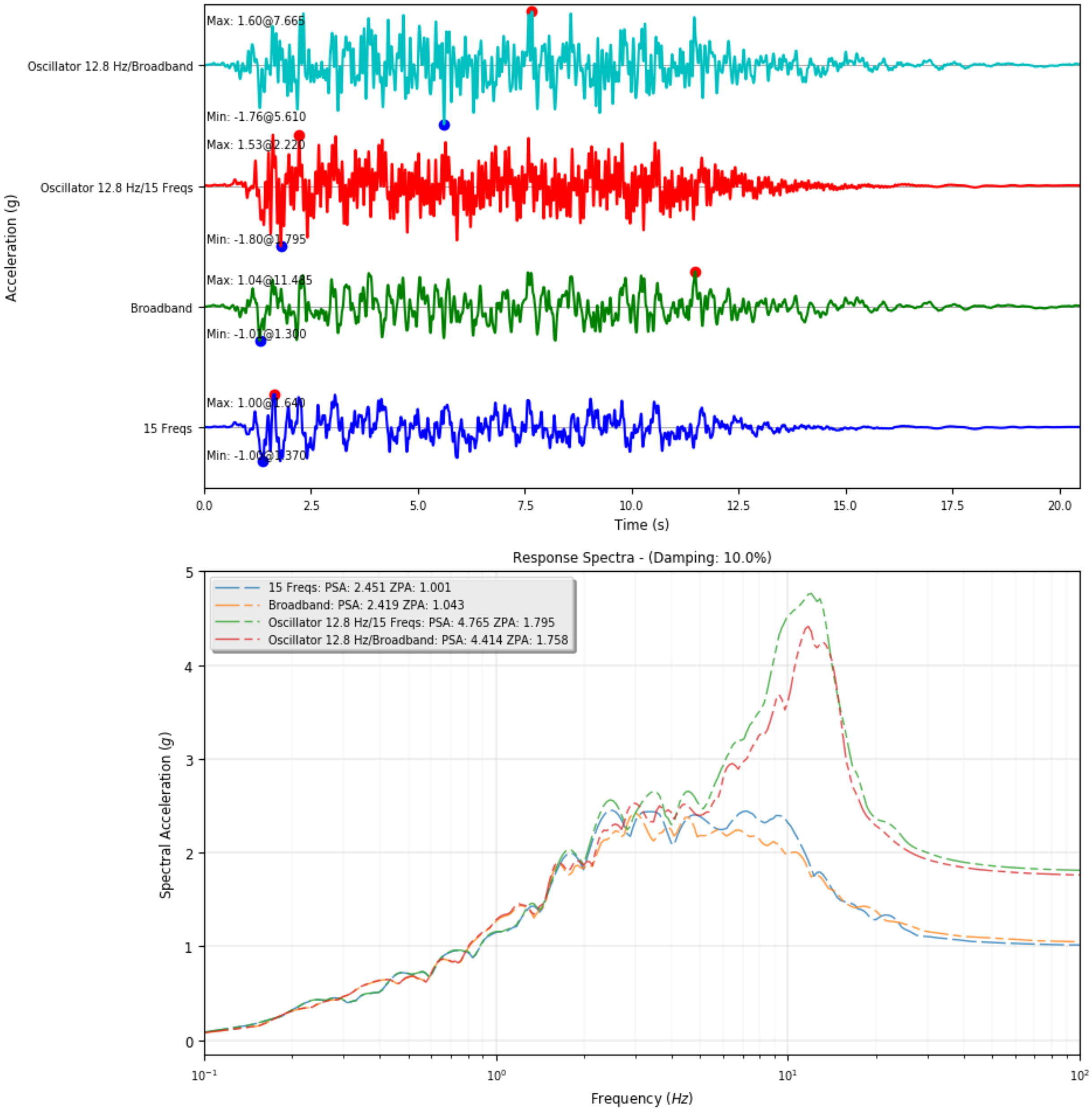


Figure 2-39 Absolute responses of the 12.8-Hz SDOF structure with a 10-percent damping ratio

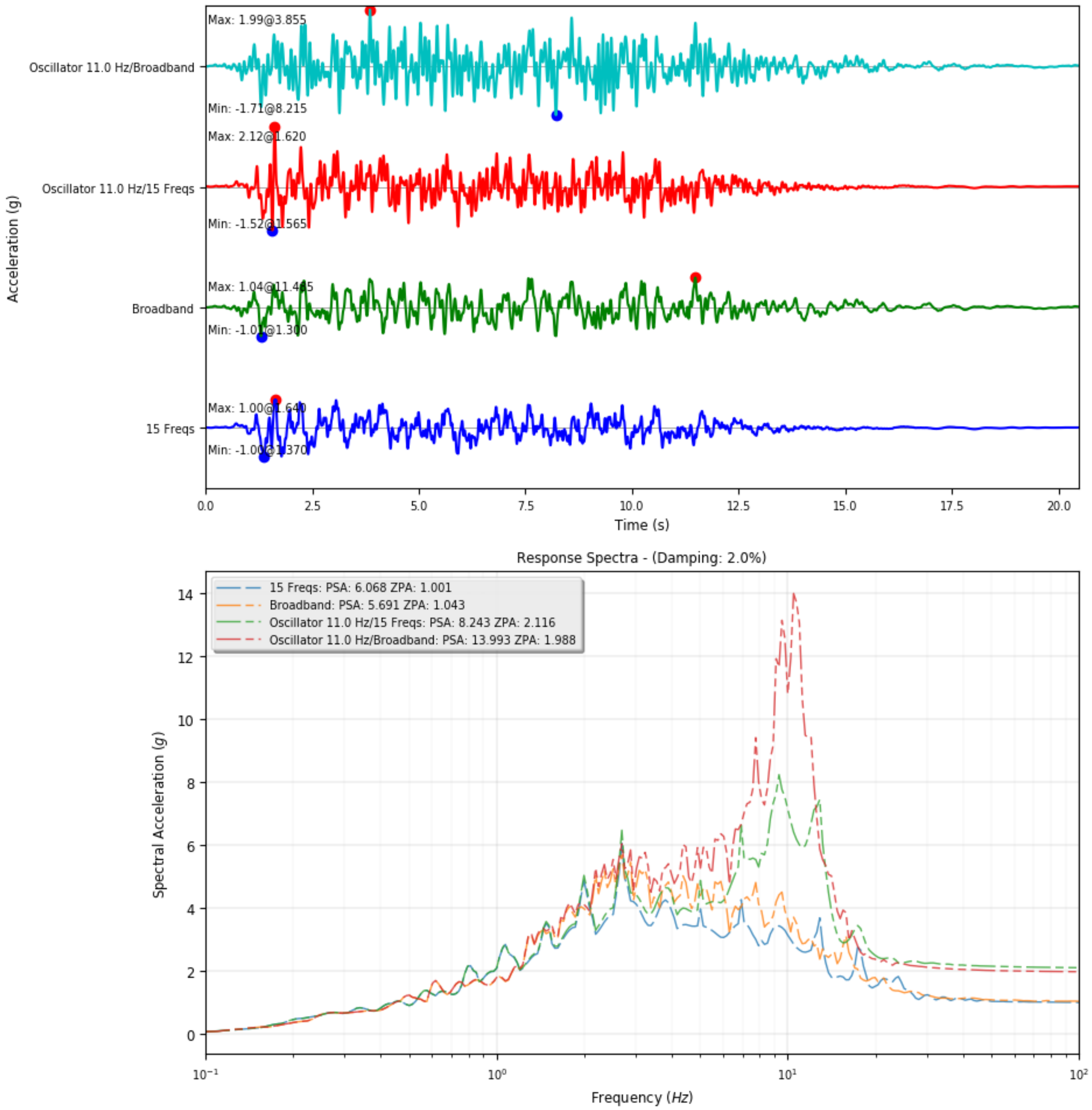


Figure 2-40 Time histories and the 2-percent damped RS and ISRS for the 11.0-Hz SDOF structure with a 10-percent damping ratio

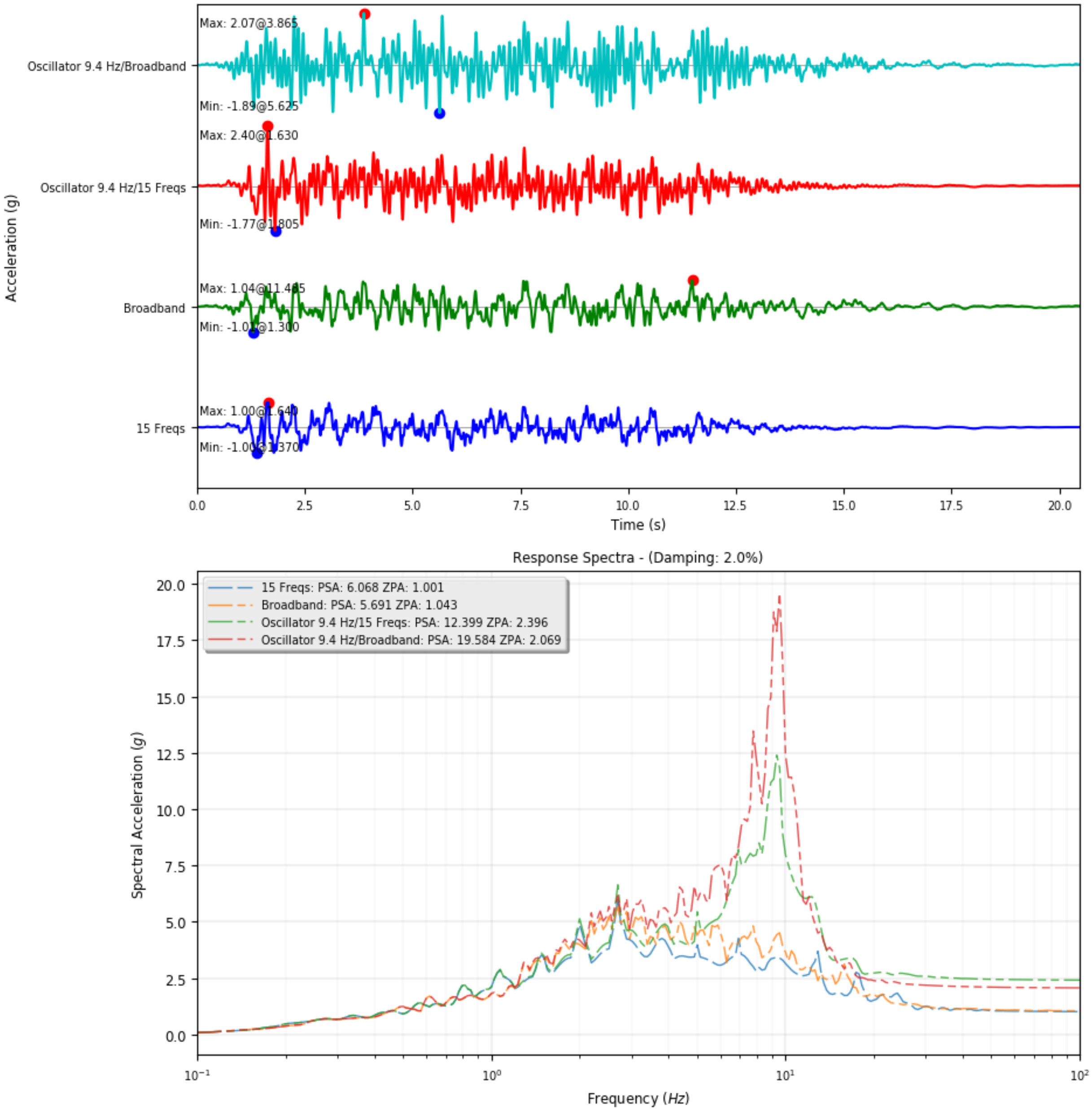


Figure 2-41 Time histories and the 2-percent damped RS and ISRS for the 9.4-Hz SDOF structure with a 10-percent damping ratio

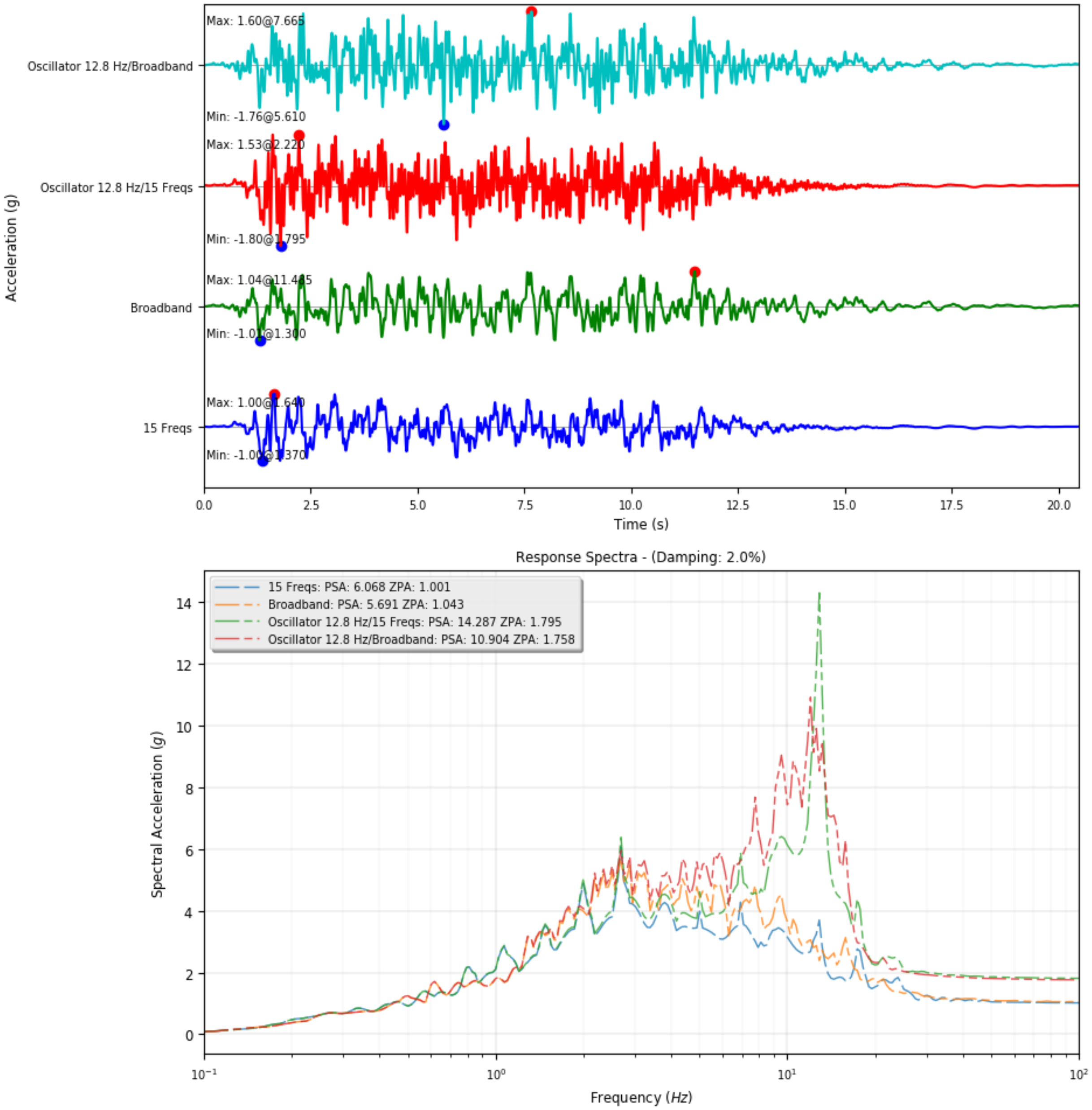


Figure 2-42 Time histories and the 2-percent damped RS and ISRS for the 12.8-Hz SDOF structure with a 10-percent damping ratio

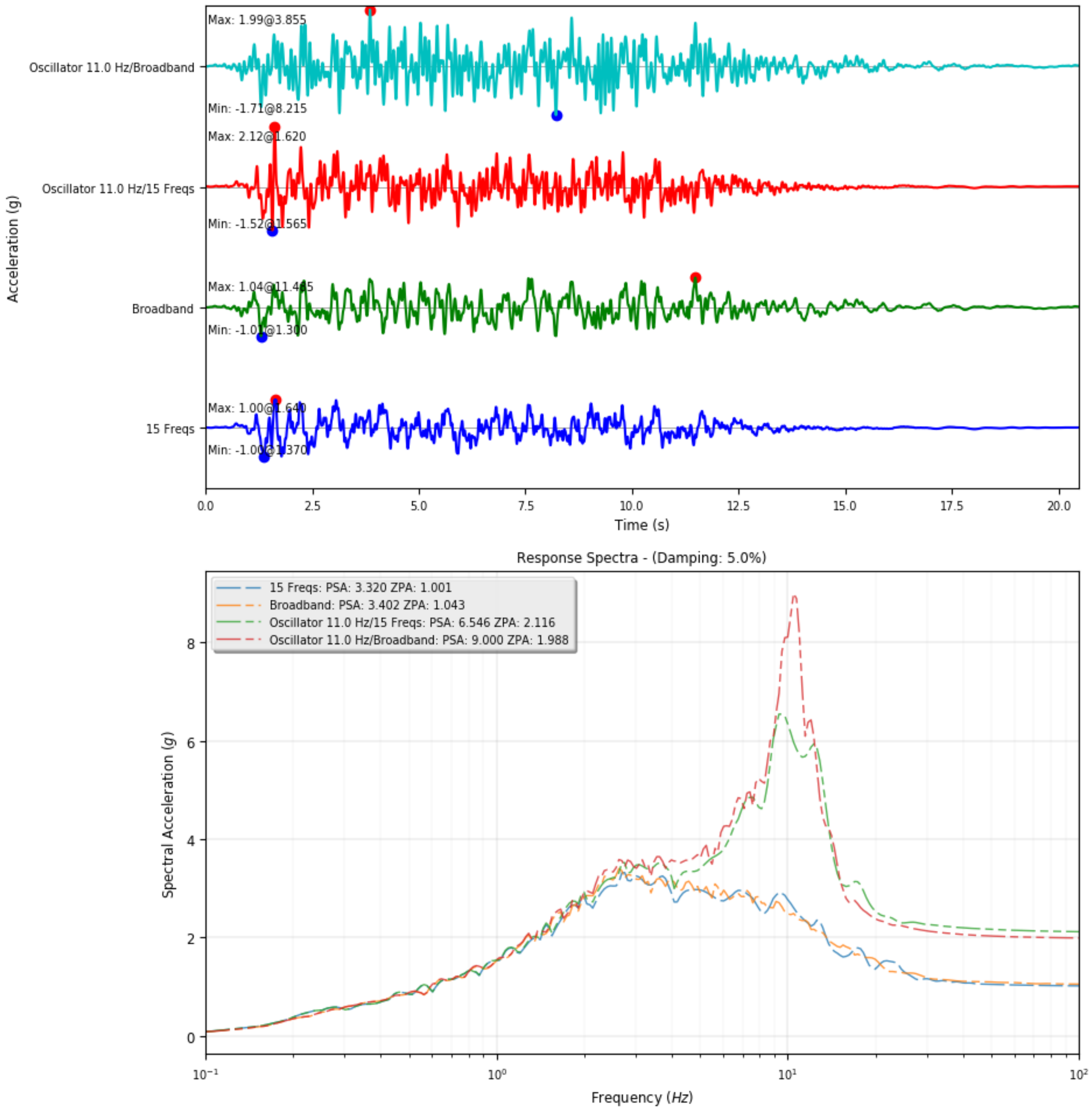


Figure 2-43 Time histories and the 5-percent damped RS and ISRS for the 11.0-Hz SDOF structure with a 10-percent damping ratio

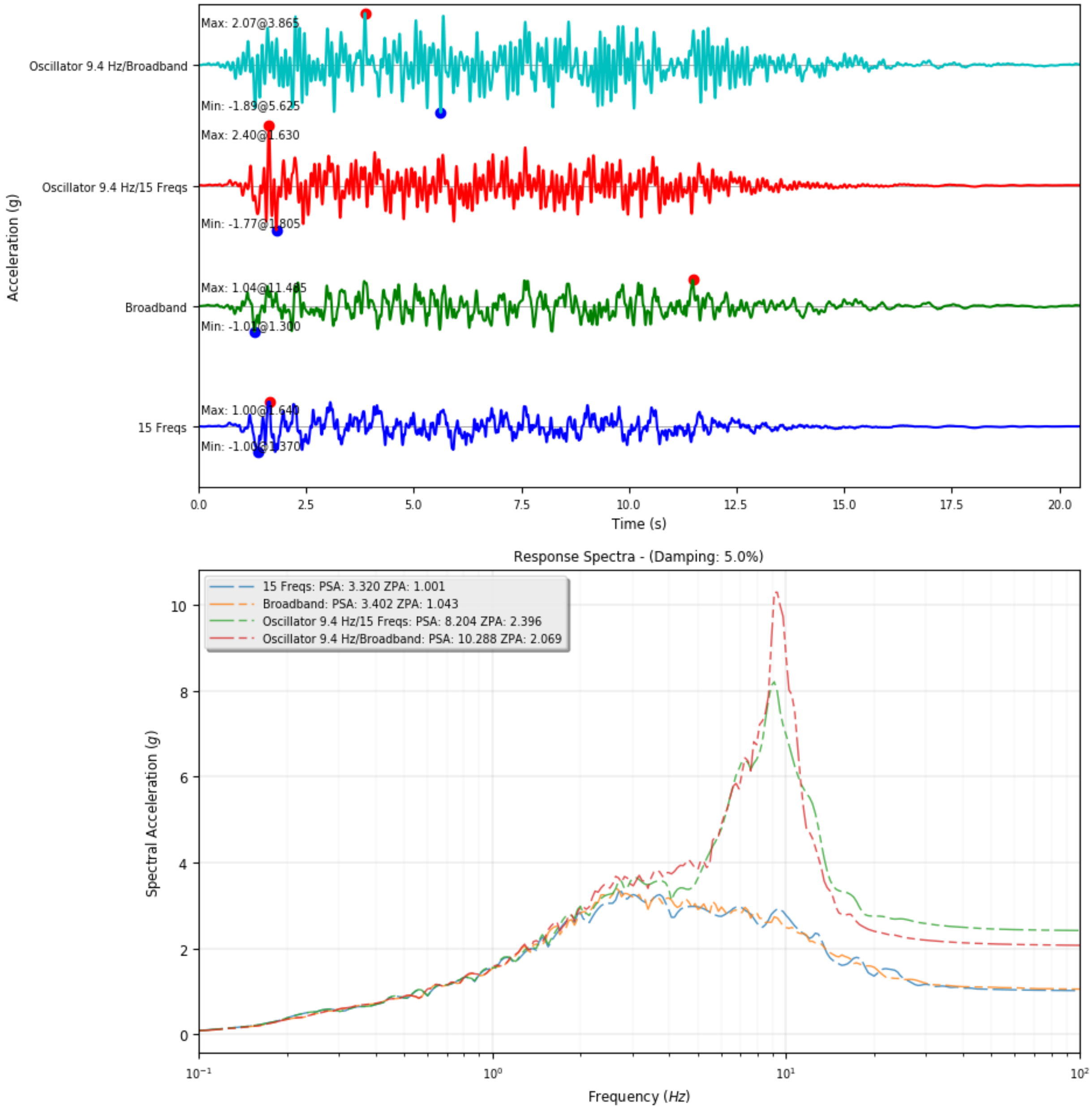


Figure 2-44 Time histories and the 5-percent damped RS and ISRS for the 9.4-Hz SDOF structure with a 10-percent damping ratio

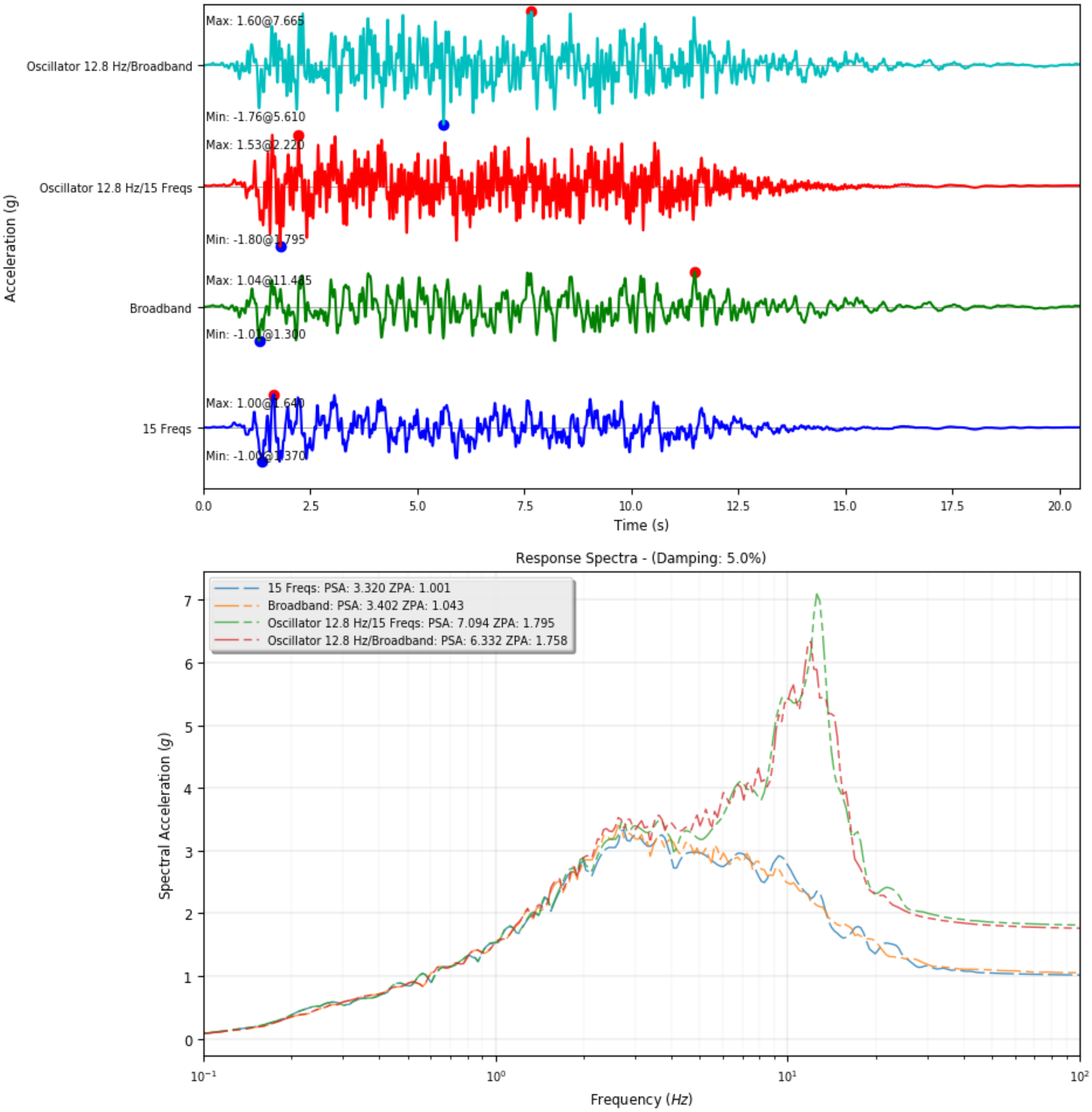


Figure 2-45 **Time histories and the 5-percent damped RS and ISRS for a 12.8-Hz SDOF structure with a 10-percent damping ratio**

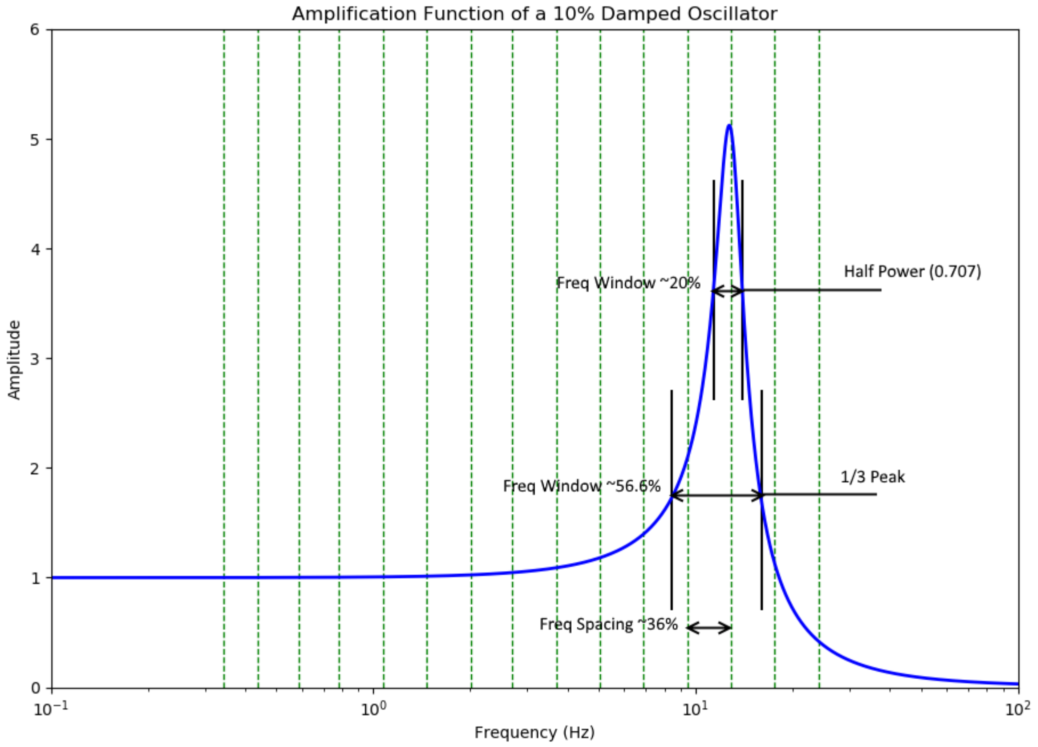


Figure 2-46 An illustration of frequency windows on the amplification function of a 10-percent damped oscillator

2.4.2.3 Conclusion

Based on the literature review and discussion in this section, it can be concluded that power deficiency at very low frequencies or high frequencies can be significant to structures and components with important modes in those frequency ranges. Because Option 1 uses a single set of time histories as a surrogate for the input ground motion, which is specified as the DRS, power-deficient time histories are not able to authentically serve that role. Therefore, the staff should not accept power-deficient time histories unless the applicant provides an adequate technical justification to show that the corresponding power deficiencies are not important to the affected structures and equipment supported by the structures. The applicant may use other methods (e.g., RSA- or RVT-based method) or time histories without power deficiencies to justify its use of power-deficient time histories.

A comparison of the responses of SDOF structures showed that the broadbanded, power-sufficient time history and the power-deficient time history with only 15 major frequencies can differ significantly in PSA (by as much as 90 percent (broadbanded/15 major frequencies) at a 5-percent damping ratio) while maintaining about the same ZPA.

The study by Houston et al. (2010) is the only realistic example that the RES staff found in its review to indicate that power deficiencies in time histories can have a significant effect on structural responses. To gain further insights for real SSCs, a variety of real structural and component models can be analyzed. The analyses should consider multiple different methods, including time histories adequately enveloping the DRS, some with power deficiencies and some without such deficiencies. A technical difficulty is to develop time histories that meet the RS enveloping criteria but have power deficiencies in a specific frequency range at which the models are sensitive. However, since these analyses require more resources, such analyses are recommended as a future endeavor. RES does not expect that these proposed analyses will affect the conclusions stated above.

3 ISSUES RELATED TO SEED TIME HISTORIES

Issues 2 and 4 are related to seed time histories that are used as the starting point to generate the artificial acceleration time histories. Revisions of SRP Section 3.7.1 before Revision 3 do not provide specific provisions for seed time histories. Revision 3 states that artificial time histories that are not based on recorded seed time histories should not be used. Revision 4 allows both recorded and artificial seed time histories. The two issues addressed in this section are related to the provisions in SRP Section 3.7.1, Revision 4. Because these two issues are closely related, this section addresses them together.

3.1 Issue 2 and Issue 4—Seed Time Histories

3.1.1 Issue 2: Criteria for Recorded Seed Time Histories

The SRP recommends the use of recorded time histories as seeds for the generation of artificial time histories. The SRP also allows the use of random generation routines to generate artificial seed time histories as an alternative. SRP Section 3.7.1, Revision 4, provides some guidance on the selection of recorded seed time histories. The specific challenges in the staff's review of applications are as follows:

- how to determine that a seed record is *similar* in shape to the DRS
- how to determine that the phasing characteristics are not *significantly* changed

The issue concerns the acceptance criteria for seed time history records.

The following excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B:

> When the seed time histories are selected from earthquake records, the response spectra corresponding to the seed record should be similar in shape to the target spectra across the frequency range of interest to the analysis (e.g., Houston et al., 2010) and phasing characteristics of the earthquake records should not change significantly.

3.1.2 Issue 4: Criteria for Randomly Generated Seed Time Histories

The SRP does not provide specific guidance on the randomly generated seed time histories and states that their acceptability will be reviewed on a case-by-case basis. The issue concerns acceptance criteria for review of submittals using artificial seed time histories.

The following excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B:

> Alternatively, an artificial time history may be developed using random generation routines or through the use of multiple time history techniques. If a random time history generator technique is used to develop the seed time histories, then acceptability of the seed will be reviewed on a case-by-case basis. For generated time histories, it should be demonstrated that acceleration, velocity, and displacement are compatible and do not result in displacement's baseline drift.

3.2 Technical Rationale and Basis

3.2.1 Spectrum Shape of the Seed Time History

Although SRP Section 3.7.1, Revision 4, cites the work by Houston et al. (2010), that work did not specifically mention the criteria for recorded seed time histories, as discussed in SRP Section 3.7.1, Acceptance Criterion II.1.B. The affected SRP description was actually consistent with the description in NUREG/CR-5347, Appendix A. In this reference, Dr. Kennedy indicated that his preferred method was to generate an artificial time history based on an actual earthquake record. This method involves two steps: (1) select an actual earthquake time history that produces a spectrum shape close to the DRS (and has an appropriate strong motion duration) and (2) retain the Fourier phase spectrum and iteratively adjust the Fourier amplitudes until the RS of the time history closely envelop the DRS. He also indicated that the resultant artificial time history is like a real earthquake record except that the resulting RS is smooth. Dr. Kennedy did not provide any acceptance criteria for determining the closeness of a spectrum shape to the DRS; however, he did indicate that many records have an appropriate strong motion duration and spectrum shape so that they can be used as the seed record for RG 1.60 or the NUREG/CR-0098 DRS. ASCE/SEI 4-16 provides similar criteria.

The Pacific Earthquake Engineering Research Center (PEER) ground motion database has been widely used in selecting real earthquake records for seismic analysis. These records are either used as seeds to generate time histories or used directly in seismic analysis with or without linear scaling. Records can be retrieved from the PEER ground motion database as scaled records by minimizing the weighted mean squared error (MSE) at periods (frequencies) that the user provides. Many records (e.g., more than 100) can be retrieved from the PEER database, and the user can rank and then select the ones with a very small MSE.

In its literature review, RES did not identify references that support any numerical criteria for selecting a seed record based on how close its spectrum shape is to the DRS. This finding is consistent with the following statement from NIST GCR-11-917-15:

> Apart from qualitative recommendations in the RspMatch2005 documentation and the anecdotal suggestion to select appropriate seed ground motions to ensure that required changes are minimal, there are no quantitative studies investigating the effect that large changes can have on nonlinear structural response prediction. In practice, spectrum-matched motions are generally assessed by visually comparing the traces of acceleration, velocity, displacement, and possibly Arias Intensity, before and after matching, and making a judgment as to whether introduced changes should be considered significant.

Although the SRP guidance aims to minimize the modification of the seed records by requiring seed records to have a shape similar to the DRS, staff experience indicates that the shape of the spectrum is not so crucial for a successful RS enveloping. For example, seed records with frequency content up to only about 9 Hz could still lead to satisfactory artificial time histories that were power sufficient up to 50 Hz. Therefore, RES does not currently recommend strict numerical criteria for the seed spectrum shape compared to the DRS. More effort is required to investigate the significance of such numerical criteria (e.g., based on an MSE measure) to seismic analysis and how such criteria can be applied. Such an effort should also be balanced with other practical issues, such as the implementation of such criteria in the PEER database and other databases and the richness of records in these databases that can meet such criteria. Nevertheless, the SRP guidance on the seed spectrum shape criterion should remain because it has been widely used in the nuclear industry and other building industries and because the intent of the guidance is to discourage large modifications to the seeds during the RS enveloping process so that, although subjective, the generated artificial time histories are like real earthquake records.

For a randomly generated seed time history, its initial spectrum shape can be selected through techniques such as SIMQKE developed by Gasparini and Vanmarcke (1976). This may speed up the iteration process; however, staff experience suggests that, without such initialization, a seed of uniformly modulated white noise usually leads to a sufficient artificial time history without problem.

3.2.2 Phase Spectrum of the Seed Time History

As for the phase spectrum, the current SRP guidance states that the “phasing characteristics of the earthquake records should not change significantly” during the time history generation process when recorded seed time histories are used. For randomly generated seed time histories, the SRP provides no specific guidance other than indicating that such random seeds should be reviewed on a case-by-case basis. Although randomly generated seed time histories became explicitly acceptable in Revision 4 of SRP Section 3.7.1, Revision 3 is the only revision that does not allow random phases.

For randomly generated seed time histories, both NUREG/CR-3509 and NUREG/CR-5347 provide the same equations for generating artificial time histories based on random phase angles uniformly distributed between 0 and 2π. NUREG/CR-3509 shows that using different sequences of random phase angles does not result in significant differences in the artificial acceleration histories, PSD functions, and RS.

The study by Houston et al. (2010) also investigated the effect of the earthquake magnitude and distance on the variation of the structural response, based on the results of SSI analyses using hundreds of synthetic time histories that were developed based on recorded seed records. This study concluded that, although earthquake magnitude and distance parameters are important components for development of the UHRS in probabilistic seismic hazard assessment (PSHA), once the shape and amplitude of the RS are established, the computed response of elastic systems to time histories fit to the UHRS is not significantly correlated to the magnitude and distance parameters. Of more significance is the relation of the phase of the response of the structural system to the phase of the time history used in the analysis. However, these conclusions in the paper are confusing because the computed responses do not significantly correlate to the magnitude and distance parameters, but in the meantime, they do correlate to the phases of the time histories. Step 2 in Section 2, “Background,” of the paper by Houston et al. (2010) states that “these synthetic time histories are usually developed by modifying recorded earthquake records that have magnitude, distance, and site class characteristics similar to the characteristic event(s) identified in the PSHA from which the UHS is obtained.” The intent of such a selection of recorded earthquake records (seeds) is to retain any potential but unidentified significance of the phase information of the records, which is commonly believed to reflect the magnitude, distance, and site class characteristics, because the Fourier amplitudes have been modified to envelop the DRS. Therefore, assuming there is a strong relation between the earthquake parameters (magnitude and distance) and the phases, it is reasonable to infer that the structural responses should be insignificantly correlated to the phases of the time histories as well, because the structural responses are found insignificantly correlated to earthquake magnitude and distance parameters.

Ohsaki (1979) studied several earthquake ground acceleration records and one example of a modulated phase wave to investigate the phase characteristics. A phase wave has a unit Fourier amplitude for all frequencies and a phase spectrum uniformly distributed between 0 and 2π. He concluded that the phase spectra seem to be uniform and that the phase difference spectra appear to have a normal or normal-like distribution. The nonuniform distribution of the phase difference resembles the shape of the acceleration envelop function (i.e., intensity function). An intensity function controls the rise, strong motion, and decay durations of a synthetic acceleration time history. Nigam (1982, 1984) developed a theoretical basis for these findings based on a uniformly modulated Gaussian process, which may be appropriate for modeling earthquake ground motions (Sargoni et al., 1980; Rasco'n and Cornell, 1969). Specifically, Nigam determined that strong motion accelerograms recorded on firm ground and at a moderate distance from the epicenter can be modeled adequately by a uniformly modulated white noise. The Fourier phase of a uniformly modulated white noise is uniformly distributed between 0 and 2π, and its phase derivative (phase difference in terms of finite digitalized records) has a nonuniform distribution that depends on the ratios of the first three moments of the squared intensity function.

RES considers that the phase difference distribution is less important than phase distribution because phase difference distribution is related to the intensity function. A Gaussian white noise process with a uniform intensity function can simulate a proper phase difference distribution, and references such as NUREG/CR-5347 conclude that the intensity function is not critically important in the RS enveloping process. Therefore, RES recommends that the SRP guidance should not include the phase difference distribution until further evidence indicates its importance.

As for the phase distribution, RES recommends removing the current provision for the recorded seed records (i.e., “phasing characteristics of the earthquake records should not change significantly”) from the SRP guidance. The “phasing characteristics” can be well preserved if a frequency domain method is used to generate artificial time histories, but they can be significantly changed if a time domain method is used. In this context, the following fundamental questions are important:

- How do the phasing characteristics of the seed records affect the seismic analysis and design?
- When many seed records can be considered to have spectral shapes similar to the DRS, why is one seed record considered better than other seed records for a particular design, in terms of their phase information?
- What measures can be used to identify the phasing characteristics of the seeds and assess their effect on the final time histories?

These questions currently have no immediate answer. Therefore, instead of the above-quoted criterion in the SRP, RES recommends a check of the phase distribution on the final artificial time history that is generated from either a recorded or random seed time history to ensure that the Fourier phase spectrum demonstrates a uniform distribution. The staff should review such a demonstration on a case-by-case basis. Although the Fourier phase spectra of real earthquake records generally demonstrate a uniform distribution over 0 to 2π, the RES literature review did not find information on their degree of conformance to a uniform distribution, and the effect of the degree of conformance on structural responses has yet to be determined.

As a general observation, randomly generated seed time histories with sufficiently long strong motion durations would apparently be convenient and adequate for standard designs and site-specific designs. Random seed time histories may be conceptually more appropriate than recorded seed time histories in the context of seismic design, which targets a wide range of potential earthquakes. Any preference for a particular set of recorded seed time histories would be difficult to justify based on their phase spectra.

3.3 Clarification and Recommendation

3.3.1 Near-Term Recommendations

RES recommends that the SRP guidance retain the criterion for the spectral shape of the recorded seed time histories (i.e., the RS corresponding to the seed record should be similar in shape to the target spectra across the frequency range of interest to the analysis).

RES recommends removal of the SRP criterion “phasing characteristics of the earthquake records should not change significantly.” Instead, RES recommends that the Fourier phase spectrum of the final artificial time history, based on either a recorded or random seed time history, should be demonstrated to have a uniform distribution over 0 to 2π.

3.3.2 Long-Term Recommendations

RES recommends a future investigation of the feasibility of establishing numerical criteria for how close to the DRS the spectral shape of the seed records should be for the purpose of seed selection. This investigation may need to study many real earthquake records to determine the significance of the shape similarity between the seed RS and DRS on structural responses, which the RES literature review did not identify. The investigation will also need to determine whether the available earthquake databases can provide a sufficient number of seed records that meet the spectral shape based criteria.

RES also recommends an investigation to study the significance of phase spectra (in particular their uniformity) for structural responses and to determine whether a PSD check can replace the check of phase spectra.

4 ISSUE RELATED TO MULTIPLE SETS OF ACCELERATION TIME HISTORIES

4.1 Issue 7—Enveloping Criteria for Multiple Sets of Time Histories

4.1.1 The Issue and Affected SRP Text

SRP Section 3.7.1, Option 2, provides acceptance criteria for the use of multiple sets of acceleration time histories in the seismic analysis of SSCs. To demonstrate the adequacy of multiple sets of time histories, Option 2 allows the use of the Option 1, Approach 2, procedure to ensure the time histories envelop the DRS and contain sufficient power. The existing guidance appears to be adequate because the Option 1, Approach 2, procedure is applied using the average RS and average PSD functions. In Option 2, an individual time history is not required to meet the Option 1, Approach 2, criteria, but the average RS and average PSD function are required. This issue involves checking whether the Option 2 guidance still applies if Option 1, Approach 2, is changed based on the resolution of other issues in this RIL. Issue 7 aims to ensure that the same RS matching and PSD criteria continue to apply for multiple time histories.

The following excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B, Option 2:

> The response spectra calculated for each individual time history may not envelop the design response spectra. However, the multiple time histories are acceptable if the average calculated response spectra generated from these time histories envelop the design response spectra. An acceptable method to demonstrate the adequacy of a set of multiple time histories, in terms of enveloping criteria and having sufficient power over the frequency range of interest, is to follow the procedures described for Approach 2 presented in Subsection II.1.B.ii of this SRP. When implementing Approach 2, the criteria in paragraphs (a) and (b) of this approach should be satisfied for each of the time histories. The criteria in paragraphs (c) and (d) of this approach can be satisfied by utilizing the results for the average of the suite of multiple time histories.

4.1.2 Technical Rationale and Basis

RES reassessed the current Option 2 provisions based on resolutions of other issues and did not find a need for any change to Option 2. The essence of the SRP acceptance criteria for multiple sets of time histories is that each individual time history does not need to satisfy all the Option 1, Approach 2, criteria, but the average RS and the average PSD function of the multiple time histories need to meet the Option 1, Approach 2, acceptance criteria. The goal of such a criterion is to prevent situations in which systematic biases may occur in the multiple sets of design time histories, such as using the same RS matching program or procedure, taking seeds recorded at seismometers with similar applicable frequency range, and filtering the records using the same method and parameters.

A general concern is whether a single set of time histories should be allowed at all in seismic analysis and design of NPP SSCs. A single set of time histories enveloping the DRS may not represent the potential seismic scenarios resulted from the deaggregation procedure in RG 1.208. A single set of time histories enveloping a broadband DRS may be perceived as overly conservative because the DRS consists of both low- and high-frequency events. However, the apparent overconservativeness of a single set cannot be easily justified because of other effects. For example, a single set includes only one sequence of phase angles that can represent only a single scenario of modal combination and, therefore, lacks the capability of the multiple sets that allow a more thorough modal combination. In addition, modes at low frequencies and modes at high frequencies may not always combine because they may occur at completely different parts of the structure, rendering the effects of the low- and high-frequency contents in the single set of time histories independent of each other.

From a historical perspective, the practice of using a single set of time histories has been in place since the first issuance of SRP Section 3.7.1, and this method apparently was widely accepted before 1975 when this SRP section was initially issued. The NRC did not develop guidance on the use of multiple time histories in SRP Section 3.7.1 until Revision 2 in 1989. Given the advanced power of modern computers, the NRC staff may need to assess the appropriateness of the current approach that allows a single set of time histories. Conversely, the mathematical models used in current analyses are significantly larger and more complicated than they were in the 1970s; therefore, requiring more than one set of time histories may be less favorable because of the time needed to conduct typical SSI analyses (particularly when time domain methods are used).

4.1.3 Clarification and Recommendation

Option 2 does not need a revision because of the recommended revision of Option 1. Minor editorial changes may be needed to ensure consistency.

5 ISSUES RELATED TO OTHER ACCEPTANCE CRITERIA FOR A SINGLE SET OF ACCELERATION TIME HISTORIES

5.1 Issue 5, Part B—Number of Frequencies and Damping Ratios in Response Spectra Enveloping

5.1.1 The Issue and Affected SRP Text

Issue 5 covers aspects related to the different number of frequencies and the different number of RS between Approach 1 and Approach 2 and the different frequency ranges for the PSD check. Item 3 and the first part of Item 2 of Issue 5 are related to PSD functions and have been addressed in Section 2.3 in the context of the PSD check. Item 1 and the second part of Item 2 of this issue are not related to the PSD check and are addressed in this section. Items 1 and 2 of Issue 5 are as follows:

(1) Option 1, Approach 1, uses fewer frequency points than does Approach 2 in RS enveloping.

(2) Option 1, Approach 1, uses more damping ratios than does Approach 2 in RS enveloping.

The issue indicates a need to clarify these differences and determine a basis if such differences will remain in the guidance.

For Item 1, the following excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B.i, Option 1, Approach 1:

> When spectral values (e.g., spectral accelerations) are calculated from the design time history, the frequency intervals at which spectral values are determined are to be sufficiently small. Table 3.7.1-1 (below) provides an acceptable set of frequencies at which the response spectra may be calculated.

SRP Section 3.7.1, Table 3.7.1-1, specifies 80 frequencies between 0.2 Hz and 50 Hz and 97 frequencies up to 100 Hz. The minimum number of frequencies required in Option 1, Approach 2, is significantly more than the minimum in Approach 1 (e.g., at least 301 frequencies from 0.1 Hz to 100 Hz), as indicated in the following affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B.i, Option 1, Approach 2:

> …(b) Spectral acceleration at 5 percent damping should be computed at a minimum of 100 points per frequency decade, uniformly spaced over the log frequency scale from 0.1 Hz to 50 Hz or the Nyquist frequency. The comparison of the response spectrum obtained from the design ground motion time history with the target response spectrum should be made at each frequency computed in the frequency range of interest.

For Item 2, the following excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B.i, Option 1, Approach 1:

> The spectrum from the design ground motion time history should envelop the free-field design response spectra for all damping values used in the seismic response analysis.

The following excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B.i, Option 1, Approach 2:

> …(c) The computed 5 percent damped response spectrum of the acceleration time history should not fall more than 10 percent below the target response spectrum at any one frequency. To prevent response spectra in large frequency windows from falling below the target response spectrum, the response spectra within a frequency window of no larger than ±10% centered on the frequency should be allowed to fall below the target response spectrum.
>
> …(d) The computed 5 percent damped response spectrum of the acceleration time history should not exceed the target response spectrum at any frequency by more than 30 percent (a factor of 1.3) in the frequency range of interest.

5.1.2 Technical Rationale and Basis

5.1.2.1 Item 1—Difference in the Number of Frequency Points for Response Spectra Enveloping

Option 1, Approach 1, requires fewer frequency points than Approach 2 in the RS calculation and comparison. The allowable frequency points in SRP Section 3.7.1, Table 3.7.1-1, have not changed since its first release in 1975. The smaller number of frequencies required in the RS calculation in Approach 1 can be partially attributed to the high computational cost when this approach was first proposed. Given today's wide access to advanced computational capability, Approach 1 can now use denser frequency points such as those provided in Approach 2. In addition, the frequencies linearly spaced on the log scale can be implemented more conveniently in practice than those frequency points in SRP Section 3.7.1, Table 3.7.1-1.

Figure 5-1 shows a comparison of the frequency points in SRP Section 3.7.1, Table 3.7.1-1 (Approach 1); the frequencies from 0.1 Hz to 100 Hz as a minimum requirement in Option 1, Approach 2; and the frequencies for a fast Fourier transform (FFT) of a typical time history with a time increment of 0.005 seconds and 4,096 data points. The top plot is on the linear scale, and the bottom plot is on the log scale. Figure 5-1 shows that Approach 2 uses many more frequencies than Approach 1 does. The frequencies used in Approach 1 appear to be sufficiently fine for frequency ranges of 1 Hz to 18 Hz and above 60 Hz for the computation and comparison of RS. Below 1 Hz, Approach 1 uses only eight frequencies, which are apparently too few to represent a sufficient frequency coverage. In this frequency range, Approach 2 uses at least 100 frequencies, which are apparently too many because even the FFT of a typical time history (dt = 0.005 seconds and N = 4,096) has only 18 frequencies. Calculating and comparing RS at more frequencies than those of the Fourier spectrum may not provide much benefit. Based on this assessment, RES developed the new frequency series described below.

A series of frequencies may be developed by starting with the list of frequencies required as a minimum in Approach 2, skipping three frequencies for every four frequencies below 1 Hz and skipping one for every two frequencies between 1 Hz and 10 Hz. The resultant series has a total of 176 frequencies. Table 5-1 and Figure 5-2 show this series designated as "25/50/101." This series is denser than Approach 1. It is similar to the FFT frequencies below 1 Hz, similar to Approach 1 between 1 Hz and 10 Hz, and the same as Approach 2 above 10 Hz. However, this series does not have a smooth transition at 1 Hz and 10 Hz, and the procedure used to create the frequency points is not straightforward. To create a frequency series that is similar to the "25/50/101" series in terms of frequency coverage and that varies smoothly on the log scale, the following simple log-power rule can be used:

$$\log F_i = 3\left(\frac{i}{n-1}\right)^p - 1, \qquad i = 0, 1, \cdots, n-1 \tag{5-1}$$

where *n* is the total number of frequency points between 0.1 Hz and 100 Hz (inclusive), and *p* is the power parameter that determines how the frequency series is distributed on the log scale. This rule is very flexible. When *p* = 1 and *n* = 301, Equation (5-1) gives the minimum number of frequencies used in Approach 2 (i.e., 100 frequencies per frequency decade). Table 5-1 and Figure 5-2 compare log_sqrt (*p* = 1/2 and *n* = 176) and log_power (*p* = 0.6 and *n* = 151) with "25/50/101," FFT, Approach 1, and Approach 2. From this comparison, it appears that log_power (*p* = 0.6 and *n* = 151) uses fewer points than "25/50/101" and can achieve the same effect in all three frequency ranges (0.1–1 Hz, 1–10 Hz, and 10–100 Hz). Therefore, RES recommends it as a replacement for the frequency specifications for both Approach 1 and Approach 2.

Of course, when the number of frequencies increases, the RS enveloping criteria should be updated accordingly. First, the RES staff examined the current RS enveloping criteria in Approach 2 to see if they could be borrowed for use in Approach 1. However, this examination indicated a need to improve Approach 2 by imposing a limit on the total number of points that are allowed below the DRS. Although the example in Figure 5-3 is unlikely to occur in reality, the figure shows that the RS enveloping criteria in Steps (a) through (d) in Approach 2 allow the computed RS to have a consecutive pattern of nine points at 90 percent of the DRS and one point at the DRS; this obviously shows an unacceptable and unconservative time history. This example shows a case in which the average ratio of the spectral acceleration over the DRS is about 0.9, which contradicts the following general objective achievable by Steps (a) through (d) in Approach 2:

> The general objective is to generate a modified recorded or artificial accelerogram which achieves approximately mean based fit to the target response spectrum; that is, the average ratio of the spectral acceleration calculated from the accelerogram to the target, where the ratio is calculated frequency by frequency, is only slightly greater than 1.

Even by imposing this general objective as part of the criteria (i.e., ensuring the average spectral ratio to be slightly larger than 1), Approach 2 can still allow cases in which significant portions of the computed RS are below the DRS, as shown in Figure 5-4 and Figure 5-5. In summary, Approach 2 does not prevent an unconservative RS enveloping situation (i.e., a series of ±10-percent frequency windows below the DRS connected by one or a few frequency points above the DRS). A limit on the total number of spectral points below the DRS can avoid this unconservative situation for Approach 2, similar to the current requirement in Approach 1.

The study also examined Approach 1 RS enveloping criteria. Approach 1 requires at most five points below the DRS, corresponding to 5/74 ≈ 6.8 percent for a DRS with a ZPA frequency of 33 Hz. For a DRS with a ZPA frequency of 50 Hz, which has been used in some applications, this ratio decreases to 5/80 ≈ 6.3 percent. A ratio of 6.3 percent applied to the current Approach 2 minimum list of frequencies leads to 17 points up to 50 Hz (i.e., about two allowable windows in Approach 2). In Approach 1, if all five points fall below the DRS in a single-frequency window, this window can be much larger than the ±10-percent frequency window allowed in Approach 2 in some frequency ranges. For example, from 20 Hz to 33 Hz, Approach 1 has five points; this frequency window is about ±25 percent. This window is even wider than the PSD smoothing window (±25 percent) allowed in the SRP. In the frequency range of 0.2 Hz to 0.6 Hz in which there are also five points, this window becomes ±50 percent. Of course, Approach 1 does not use a frequency series linearly distributed on the log scale; therefore, comparing it to the frequency window size is not a completely fair comparison. Nevertheless, it appears reasonable to restrict the allowable five points in Approach 1 from occurring in any window that covers a large frequency range.

For the proposed frequency series log_power (*p* = 0.6 and *n* = 151), an allowable ratio of 6 percent (slightly rounded down from the above ratios) leads to a total number of seven frequencies that are allowed to fall below the DRS for a ZPA frequency of 33 Hz and eight points for a ZPA frequency of 50 Hz. Based on the above discussion, RES recommends that 6 percent of the total points in the frequency range of interest be allowed to fall below the DRS for the proposed log_power series of frequencies. For this frequency series, the ±10-percent frequency window corresponds to a varying window size in terms of frequency points, from one point at 0.1 Hz to five points at 1 Hz and to seven points from 6.8 Hz through 100 Hz. This series reaches and stays at the maximum window size of seven points at 6.8 Hz.

Table 5-1 Statistics of frequency points for RS computation and comparison

Series (Total Frequency Points)	Number of Frequency Points in Different Frequency Ranges*				
	[0.1, 1) Hz	[1, 10) Hz	[10, 100] Hz	[0.1, 33] Hz	[0.1, 50] Hz
FFT (2,049)	18	184	1,844	673	1,022
Approach 2 (301)	100	100	101	252	270
25/50/101 (176)	25	50	101	127	145
Log_sqrt (176)	20	58	98	124	142
Log_power (151)	25	52	74	113	126
Approach 1 (97)	8	47	42	74	80

* *A square bracket indicates an inclusive (closed) endpoint of a frequency range, whereas a parenthesis indicates a noninclusive (open) endpoint.*

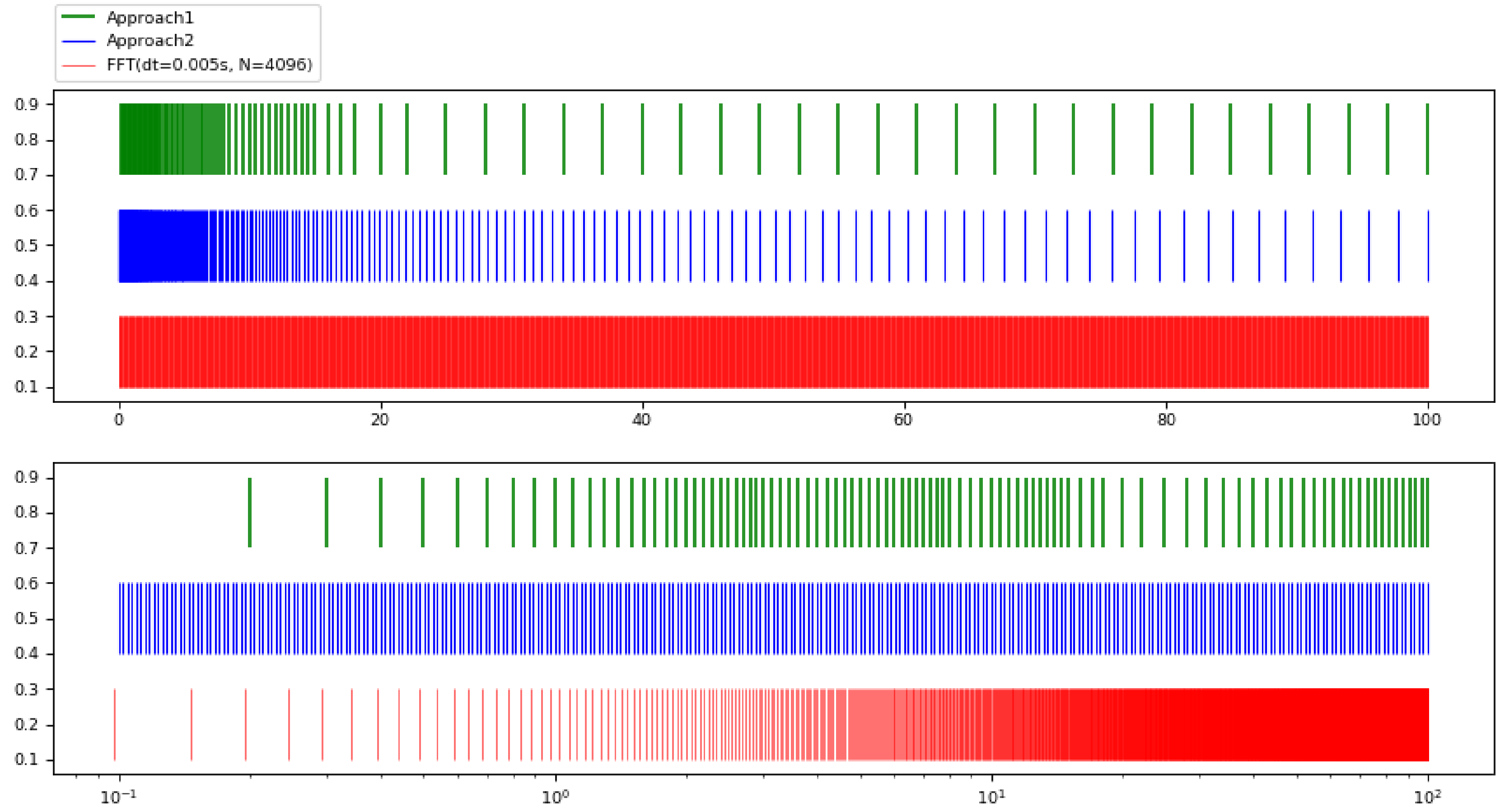


Figure 5-1 A comparison of frequencies for Approach 1, Approach 2, and the FFT for a typical time history

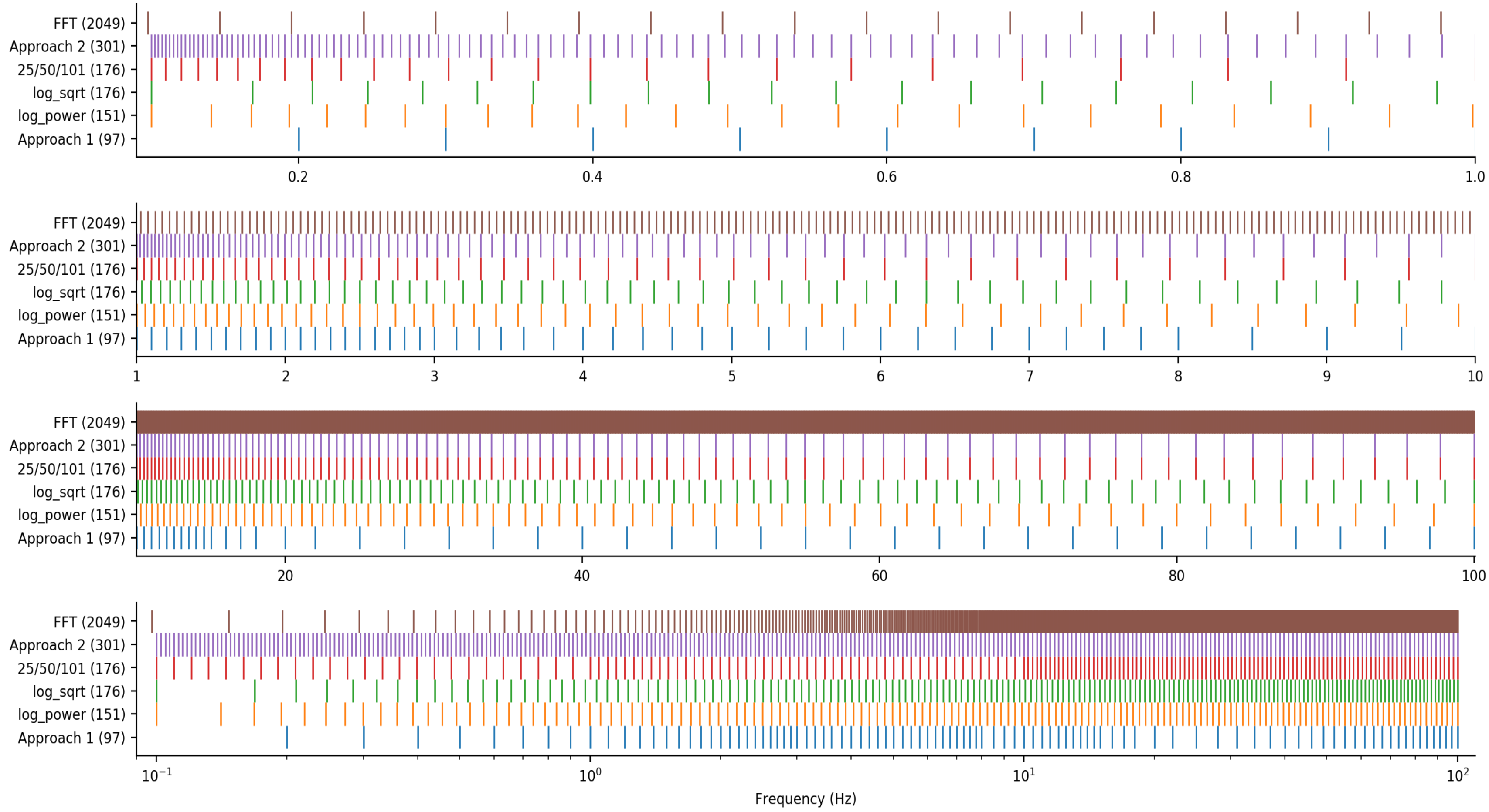


Figure 5-2 The development of a new series of frequencies for RS comparison

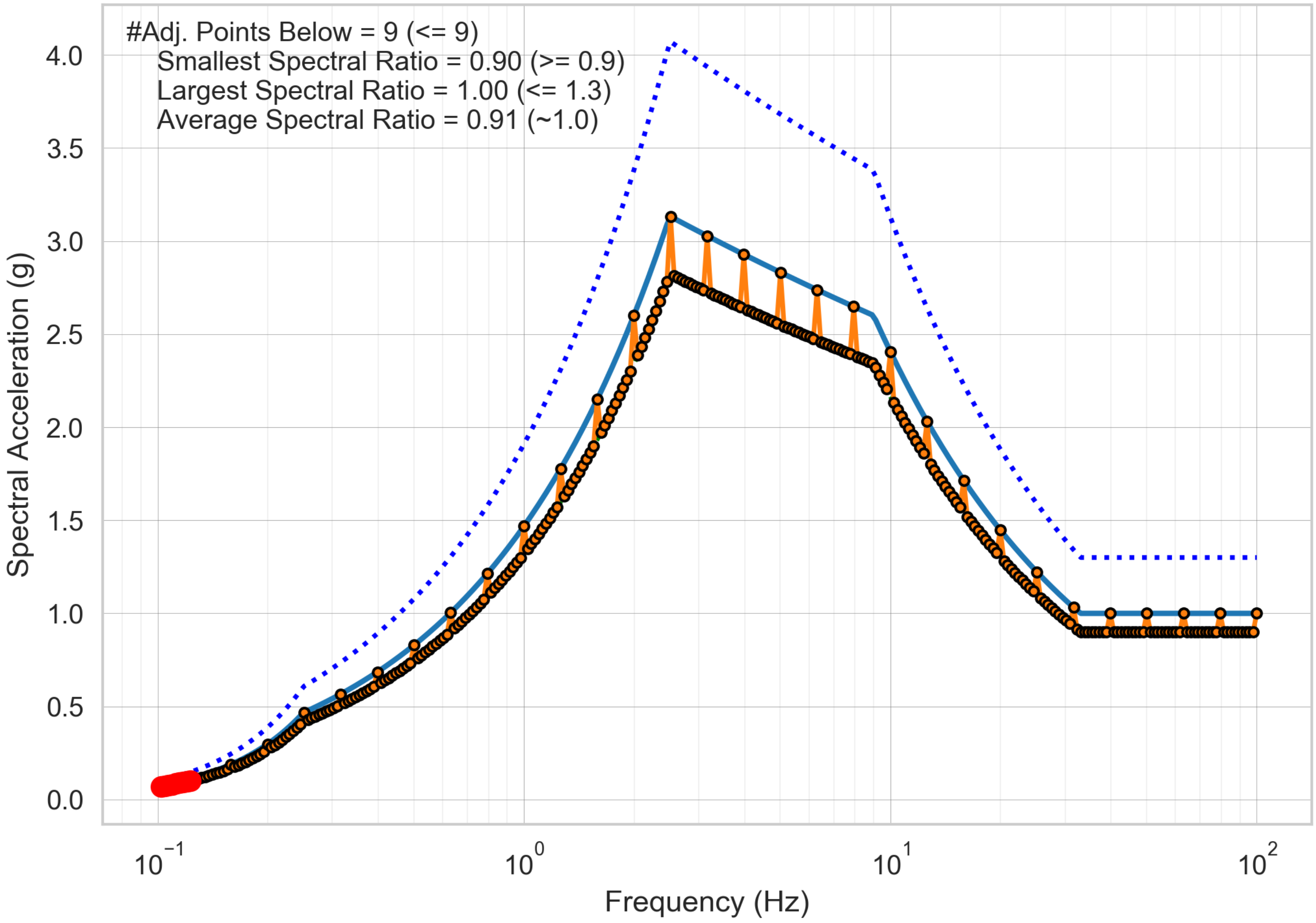


Figure 5-3 An RS (circles) with nine points at 90 percent of the DRS and one point at the DRS (other piecewise smooth curves showing the criteria)

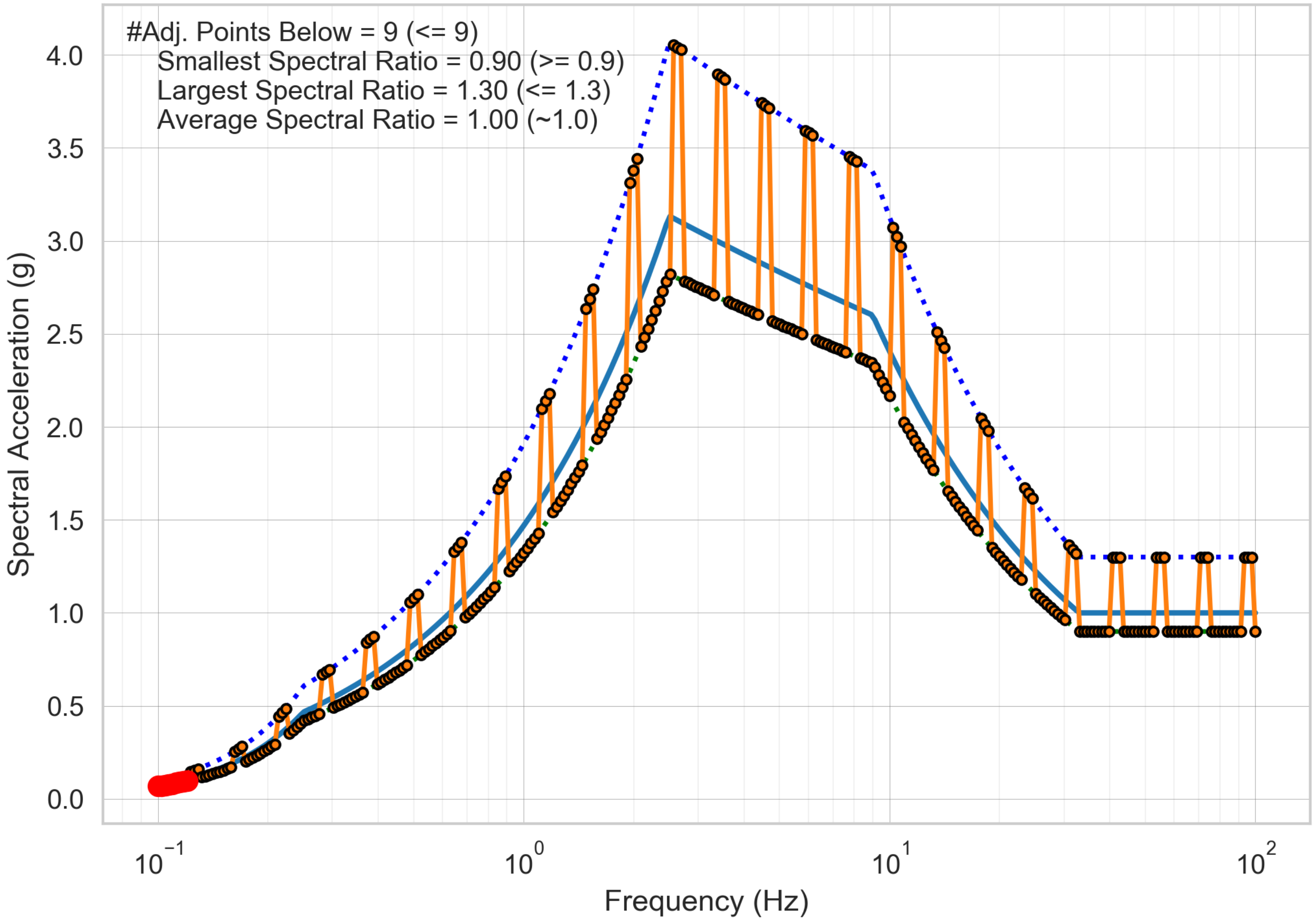


Figure 5-4 An RS (circles) with nine points at 90 percent of the DRS and three points at 130 percent of the DRS (other piecewise smooth curves showing the criteria)

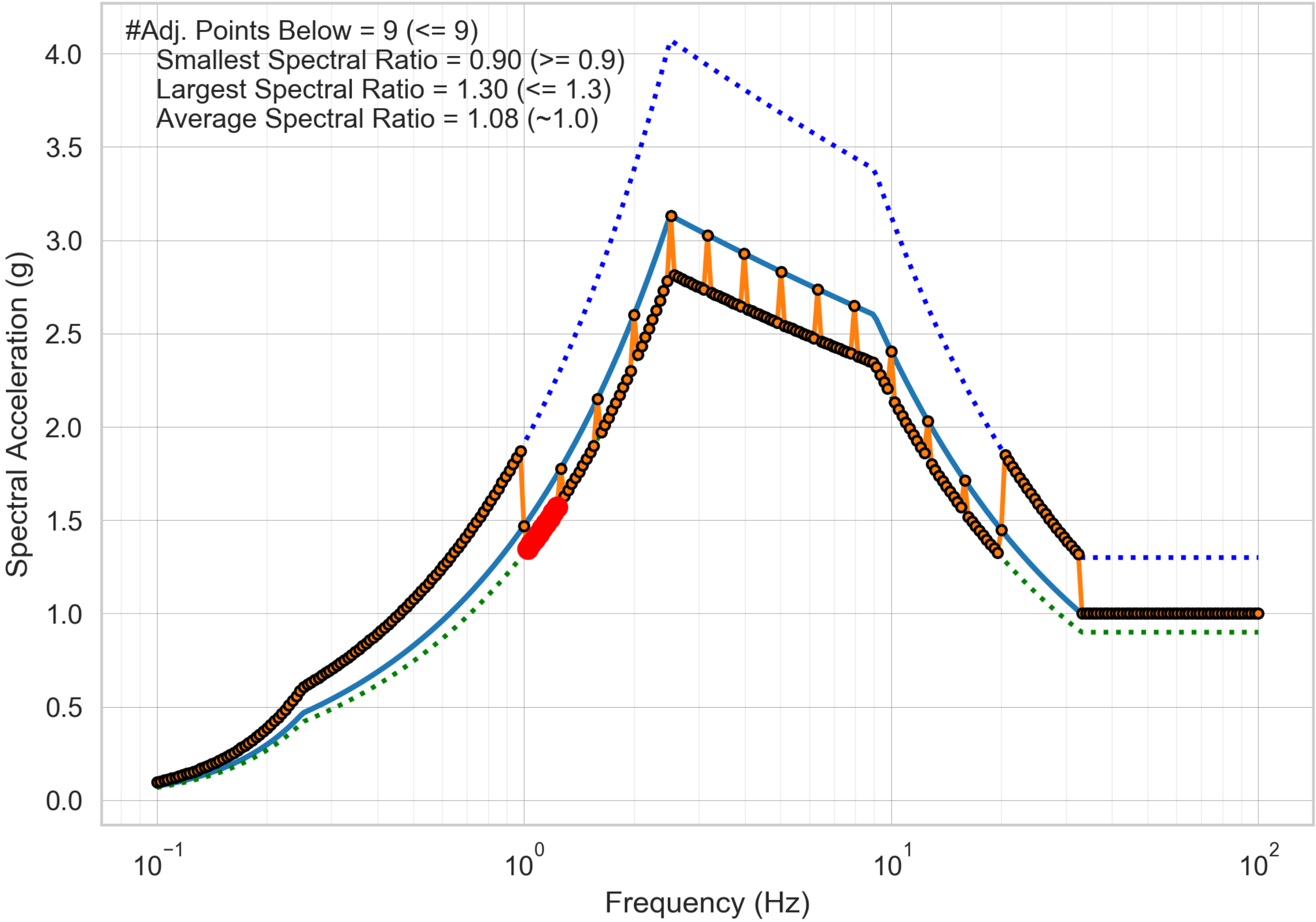


Figure 5-5 An RS (circles) with nine points at 90 percent of the DRS and one point at the DRS between 1 Hz and 20 Hz (other piecewise smooth curves showing the criteria)

5.1.2.2 Item 2—Difference in the Number of Design Response Spectra for Response Spectra Enveloping

This item concerns the difference in the number of DRS between Option 1, Approach 1, and Approach 2. Option 1, Approach 1, requires several DRS curves at different damping ratios, whereas Approach 2 requires only the 5-percent damped DRS. Multiple DRS with different damping ratios in RS enveloping criteria usually lead to more conservative design time histories than does a single DRS. Staff experience shows that multiple DRS may govern the RS enveloping process at different frequency ranges, partially because of the lack of consistency among some of the DRS. Because a lower damped oscillator amplifies the input motion more significantly in a smaller frequency window around the fundamental frequency of the oscillator, the lower damped RS fluctuates more and tends to govern in more cases.

For further demonstration of the effect of damping ratios in assessing RS, the three DRS shown in Figure 2-19 are used in the examples below to remove the potential influence of the nonconsistency issue that occurs for some DRS. The DRS shown in Figure 2-19 are consistent because they were developed from the same time histories. Figure 5-6 shows the assessment of the RS of an acceleration time history following the Option 1, Approach 1, RS enveloping criteria for damping ratios of 2 percent, 5 percent, and 10 percent. Figure 5-6 illustrates that this time history can pass the 5-percent damped DRS criteria but not the 2-percent and 10-percent DRS. The acceleration time history was developed following the criteria in SRP Section 3.7.1, Revision 4, Option 1, Approach 2 (Steps (a) through (d)).

Figure 5-7 shows similar comparisons based on the Option 1, Approach 2, criteria. These figures appear to have many fewer dots than they should because only those points beyond the 90- to 130-percent DRS range are marked with dots. Despite the difference in the number of frequencies used to calculate and compare RS, comparisons based on the Approach 1 criteria (Figure 5-6) and the Approach 2 criteria (Figure 5-7) show a similar trend in the points that fall below the DRS and below the 90-percent DRS. In other words, using more frequencies can identify more details in the computed RS but does not significantly change the overall resolution of the RS.

Figure 5-8 shows an assessment of the same time history following Option 1, Approach 1, but it uses the proposed frequency series log_power (p = 0.6 and n = 151). There are nine calculated maximum allowed points below the DRS (i.e., 6 percent of 151). Similar to the above assessments, the time history meets the RS enveloping criteria for the 5-percent damped DRS but not for the other two DRS at 2-percent and 10-percent damping ratios. A comparison of Figure 5-6 through Figure 5-8 shows that the new frequency series is similar to Approach 2 in the high-frequency range (greater than 10 Hz) and similar to Approach 1 in the midfrequency range (1 Hz to 10 Hz). In the low-frequency range (0.1 Hz to 1 Hz), the new frequency series identifies more points below the DRS than does Approach 1 because it has more frequencies (25 versus 8). In this frequency range, the new frequency series is similar to those used in the FFT, but it has many fewer points than in Approach 2.

Overall, although the above comparison indicates that a time history generated to envelop the 5-percent damped DRS cannot pass either of the approaches using 2-percent and 10-percent damped DRS, the differences between the computed RS and the DRS at 2 percent and 10 percent are not particularly large in an engineering sense. The computed RS are still generally conservative as compared to the DRS at the 2-percent and 10-percent damping ratios. The dip below the 90-percent DRS around 9 Hz at 2-percent damping can probably be seen in the PSD check, especially through the raw PSD curve.

The following three conclusions are based on the above assessment:

(1) The frequency series does not appear to be a significant factor in a successful judgment of the adequacy of a time history. The new frequency series, “log_power,” is flexible, convenient, and sufficient, and it does not have an excessive number of frequencies as compared to the Fourier spectrum.

(2) RS enveloping criteria that use multiple DRS (if so specified in an application) are more conservative than those using a single DRS.

(3) When a 5-percent damped DRS is the only RS provided (i.e., as a result of the PSHA), a 5-percent damped DRS may be used. DRS at other damping ratios can be developed consistently (e.g., by generating many time histories). RES considers enveloping the DRS at a 5-percent damping ratio in conjunction with a PSD check to be adequate. Other options are available in these situations (e.g., using the 2-percent damped DRS instead of the 5-percent damped DRS or using multiple DRS that are developed based on the 5-percent damped DRS).

Item 3 above requires further discussion for a consensus on the appropriateness of using the 5-percent damped DRS only, or the SRP should include other alternatives because of the lack of sufficient technical information. Analyses with more time histories may lead to additional insights on the level of conservativeness of the computed RS compared to the DRS at damping ratios other than 5 percent.

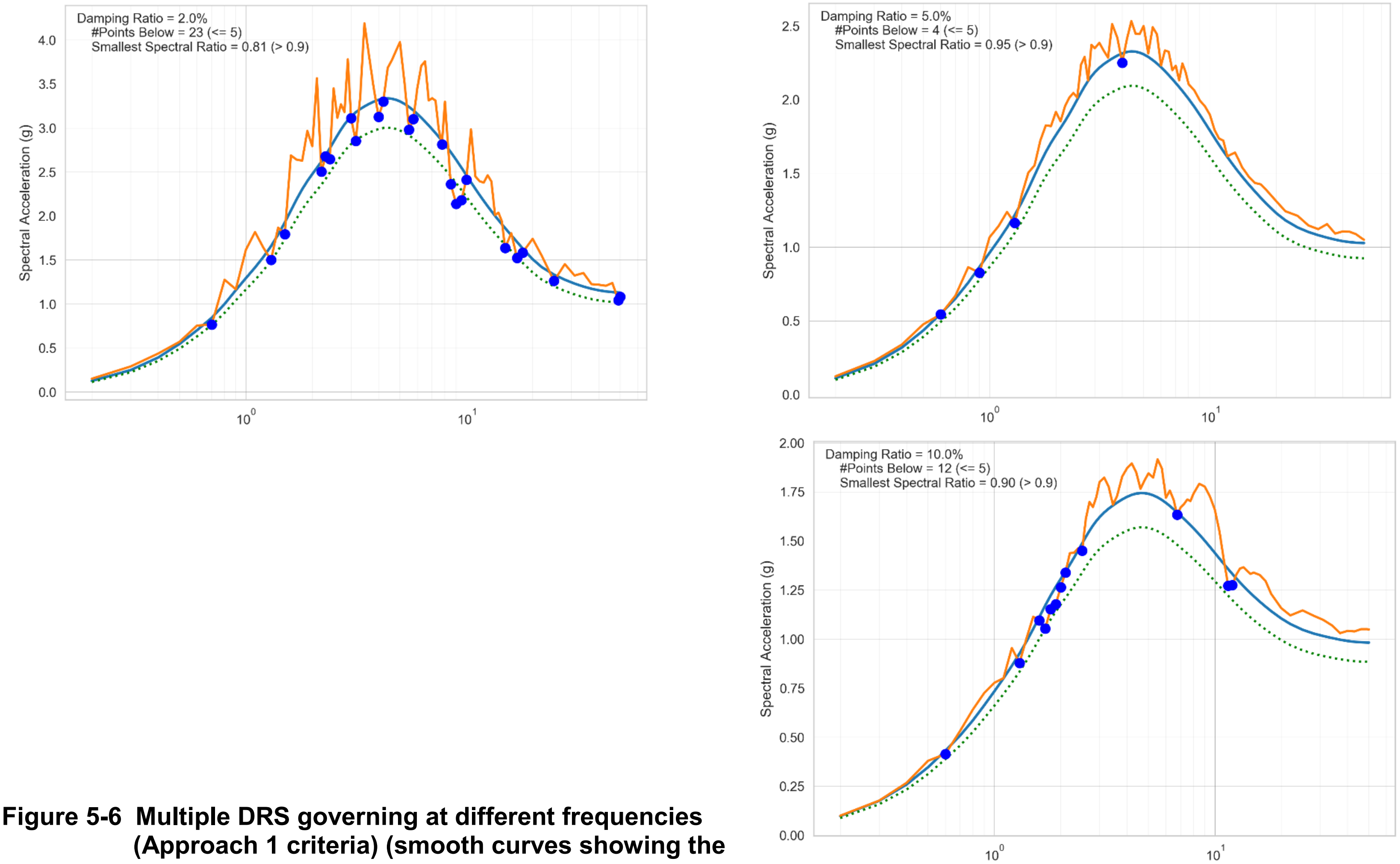


Figure 5-6 Multiple DRS governing at different frequencies (Approach 1 criteria) (smooth curves showing the criteria)

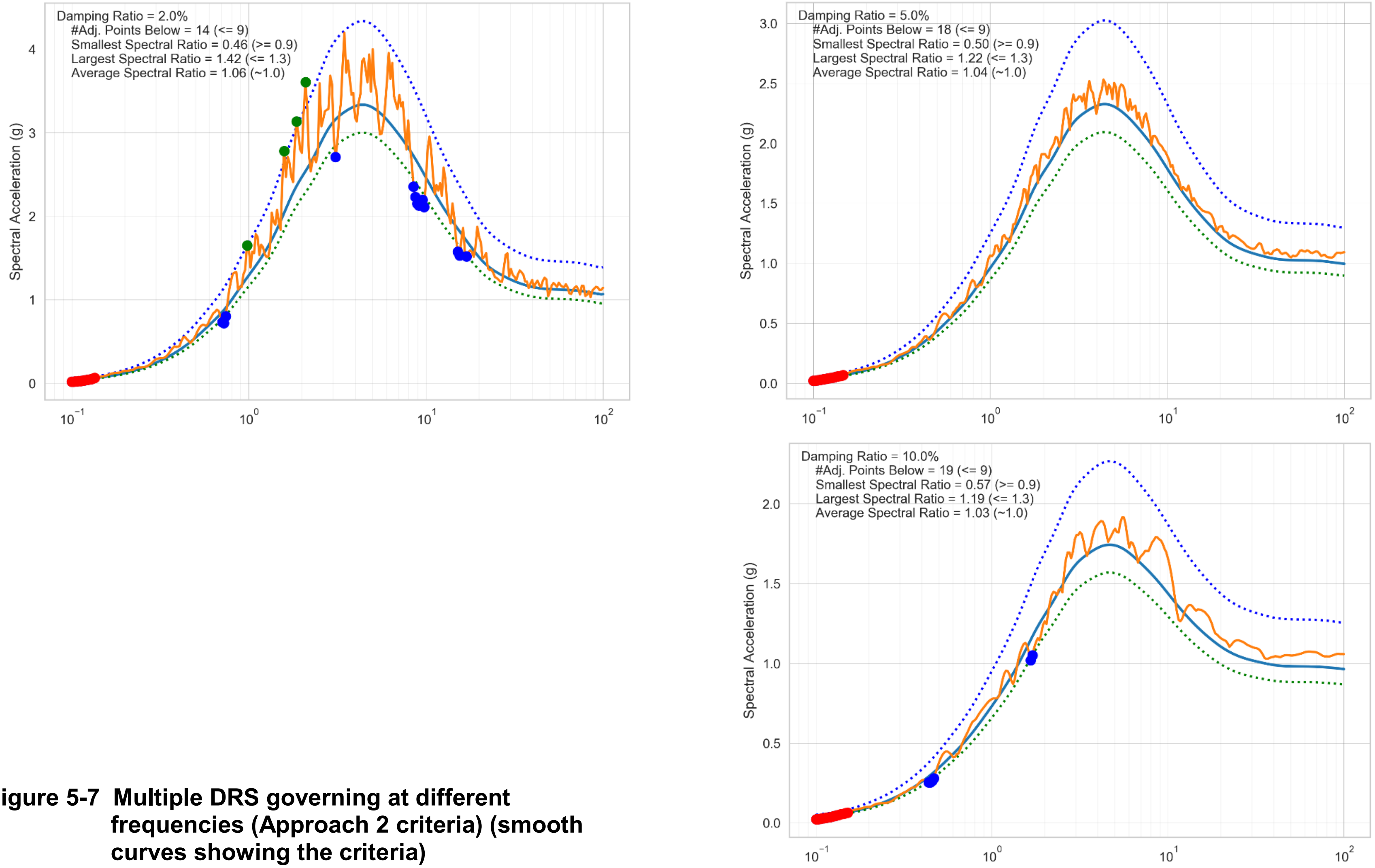


Figure 5-7 Multiple DRS governing at different frequencies (Approach 2 criteria) (smooth curves showing the criteria)

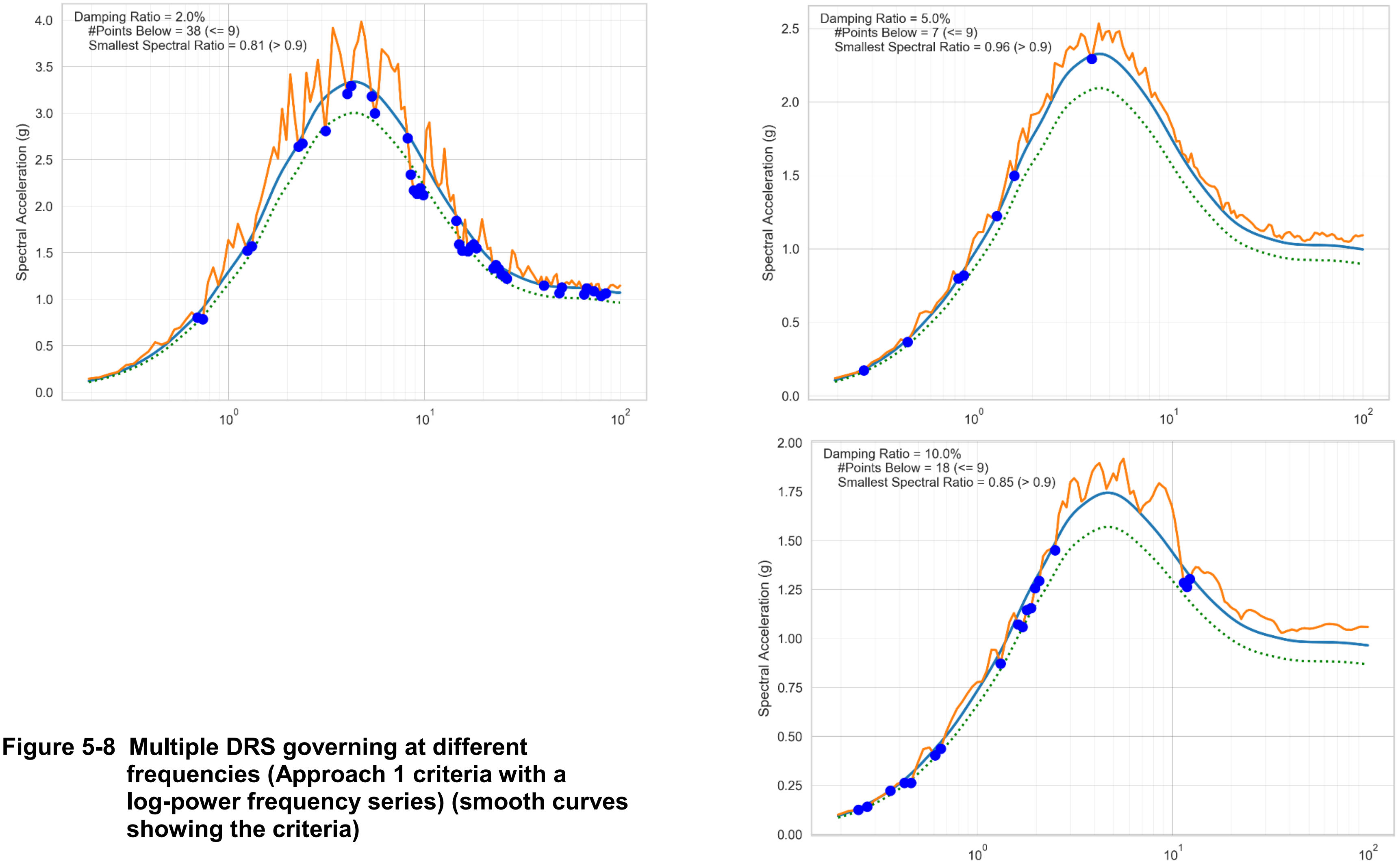


Figure 5-8 Multiple DRS governing at different frequencies (Approach 1 criteria with a log-power frequency series) (smooth curves showing the criteria)

5.1.3 Clarification and Recommendation

An assessment of the frequency points currently used in Option 1, Approach 1, and in Approach 2 indicates that the two frequency series can be unified and replaced by a newly proposed series, log_power (p = 0.6 and n = 151). The new frequency series is similar to Approach 2 at high frequencies (great than 10 Hz) and similar to Approach 1 at midfrequencies (1 Hz through 10 Hz). At low frequencies (less than 1 Hz), the new frequency series has 25 frequency points, as compared to 8 points for Approach 1 and 100 points for Approach 2, and is close to those for the Fourier spectrum of a typical time history (dt = 0.005 seconds, N = 4,096). The assessment concludes that the log_power frequency series is flexible, convenient, and sufficient.

The RES assessment of the Approach 2 RS enveloping criteria indicates that these criteria can allow unconservative RS enveloping situations. Therefore, the RS enveloping criteria in Approach 2 may be enhanced to limit the total number of spectral points that are allowed to fall below the DRS. RES proposes that no more than 6 percent of the total frequency points in the frequency range of interest should be allowed, which translates to 16 points up to 50 Hz using the current Approach 2 minimum frequency series (i.e., 100 points per frequency decade). For Approach 1, if the allowable five points occur in the same frequency range, they can cover a frequency window larger than that allowed in Approach 2. Therefore, RES recommends an enhancement to Approach 1 requiring a check to ensure that the points below the DRS do not fall in frequency windows larger than ±10 percent. These conclusions and recommendations only indicate the defects in the current criteria but do not suggest that these situations occur in practice. The goal of the proposed enhancement of both approaches is to improve regulatory efficiency by avoiding potential unfavorable cases in the future.

As for the number of DRS at different damping ratios, the RES assessment reaffirmed that using multiple DRS in RS enveloping is more conservative than using a single DRS, even at a 2-percent damping ratio. DRS curves tend to govern at different frequency ranges, although DRS at lower damping values generally govern more than DRS at higher damping values. However, the RES staff notes that, in situations where only the 5-percent damped DRS is available (e.g., as a result of PSHA), instead of generating and using DRS at other damping ratios, using the DRS at a 5-percent damping ratio is acceptable. This conclusion is based on (1) the degree to which the RS enveloping criteria at other damping ratios are exceeded is considered insignificant in an engineering sense, (2) other DRS can be generated consistently, and (3) a PSD check against the target PSD function helps identify the unsatisfactory frequency ranges in RS enveloping at lower damping values.

5.2 Issue 6—Time Increment and Total Duration of Time Histories

5.2.1 The Issue and Affected SRP Text

SRP Section 3.7.1, Option 1, Approach 2, provides guidance on the minimum Nyquist frequency, time increment, and total duration of time histories, but Approach 1 does not have similar criteria. The issue indicates a need for clarification as to the applicability of these criteria to Approach 1.

The following excerpt is the affected text from SRP Section 3.7.1, Acceptance Criterion II.1.B.i, Option 1, Approach 2:

> The time history should have a sufficiently small time increment and sufficiently long duration. Records should have a Nyquist frequency of at least 50 Hz, (e.g., a time increment of at most 0.010 seconds) and a total duration of at least 20 seconds. If frequencies higher than 50 Hz are of interest, the time increment of the record should be suitably reduced to provide a Nyquist frequency ($N_f = 1/(2\Delta t)$, where Δt = time increment) above the maximum frequency of interest. The total duration of the record can be increased by zero packing to satisfy these frequency criteria.

5.2.2 Technical Rationale and Basis

Recent practices commonly meet the SRP acceptance criteria for minimum Nyquist frequency, time increment, and total duration of time histories currently provided in Option 1, Approach 2. Staff experience indicates that achieving these technical aspects in synthetic acceleration time histories is not difficult. Therefore, imposing these criteria on Approach 1 apparently is not a problem.

The SRP guidance states that the total duration of the time history should be at least 20 seconds, which is consistent with the recommendation in NUREG/CR-5347 that the total duration should be between 10 and 25 seconds. This is also consistent with Trifunac and Brady (1975), who concluded the following:

> For low Modified Mercalli intensity (II and III) the average duration of strong-motion acceleration is about 45 sec and one standard deviation on either side of this mean is about 15 sec. With increasing intensity, duration decreases and becomes on the average 20 to 25 sec for intensity VIII.

In this study, Trifunac and Brady defined the duration of strong motion acceleration to be the time for the cumulative Arias Intensity to rise from 5 percent to 95 percent, which was a very subjective choice as the authors indicated.

NUREG/CR-5347 recommends that the strong motion duration should be between 6 and 15 seconds, which is consistent with the current SRP position that the strong motion duration should be at least 6 seconds. In practice, applications seldom, if ever, use time histories that have a strong motion duration longer than 15 seconds.

5.2.3 Clarification and Recommendation

The provisions in Step (a) of Option 1, Approach 2, can be relocated to the general criterion of Option 1, thus making them applicable to both approaches.

6 CONCLUSIONS AND RECOMMENDATIONS

This RIL covers an evaluation of eight issues related to the SRP acceptance criteria for artificial acceleration time histories and has clarified or developed technical bases for various staff positions. SRP Section 3.7.1, Acceptance Criterion II.1.B, provides these acceptance criteria. In this RIL, the RES staff reviewed NUREG reports and other references to identify technical bases to address the issues. For technical areas in which the RES staff did not find a sufficient technical basis in its literature review, it performed limited and targeted analyses to develop the required technical basis.

The results of the RES work described in this RIL have identified opportunities for enhancement in several technical areas in the current SRP guidance and have provided the necessary technical bases. Enhancement of SRP guidance on this topic can reduce the possibility of using unacceptable time histories in seismic analysis. The research results associated with this effort can also help the staff and the industry align better on certain critical aspects in the development of acceleration time histories for seismic analysis and design of NPP SSCs.

This section summarizes the major conclusions for these issues and presents recommendations for SRP enhancement. Previous sections of this RIL discuss these issues in more detail. RES has reached the following four major conclusions that are condensed from the proposed resolution of each of the eight issues:

(1) The current criterion of demonstrating the power sufficiency of artificial acceleration time histories by a comparison to target PSD functions, as provided in Option 1, Approach 1, of SRP Section 3.7.1, should remain. Guidance for Option 1, Approach 2, should be enhanced to require such a demonstration by a comparison to target PSD functions. The RES review and analysis showed that RS enveloping alone does not ensure power sufficiency and that a PSD assessment without a comparison to a target PSD function is not conclusive.

(2) Power deficiency at very low frequencies or high frequencies can be significant to structures and components with important modes in those frequency ranges. Both a literature review and a staff analysis showed that a power-deficient time history could lead to significant underprediction of ISRS. Houston et al. (2010) found that power deficiencies could underpredict the PSAs in ISRS by as much as 70 percent. Similarly, this study found that a broadband acceleration time history and an acceleration time history with 15 major frequencies, both satisfying the same RS enveloping criteria, led to about a 90-percent difference (broadband compared to 15 major frequencies) in the PSAs of the 5-percent damped ISRS. Therefore, power-deficient time histories should not be accepted unless an adequate technical justification is provided to show that the power deficiencies are not important to the affected structures and components for the particular application.

(3) The PSD check should cover a frequency range that is consistent with the shape of the input RS.

(4) The use of a new frequency series developed in this RIL can enhance and unify the frequency points used for RS calculations and comparisons. For RS enveloping, acceptance criteria should include criteria that no more than 6 percent of the total

number of frequency points are allowed to be lower than the design RS and that the cluster of these points should not exceed a frequency window of ±10 percent.

The sections below summarize the conclusions and recommendations for each technical issue addressed in this RIL.

6.1 Issues Related to Power Spectral Density Functions

6.1.1 Issue 1—Necessity of Target Power Spectral Density Functions

In addition to ensuring the estimated RS enveloping the DRS, SRP Section 3.7.1, Revision 2, introduced a PSD check as a secondary, yet necessary, check to ensure the power sufficiency of the acceleration time history. Based on a recommendation in NUREG/CR-6728, SRP Section 3.7.1, Revision 3, adopted Option 1, Approach 2, which requires, as a substitute for a PSD check, the computed RS to be below 130 percent of the DRS. However, NUREG/CR-6728 and other references reviewed do not identify a technical basis for such a substitution. SRP Section 3.7.1, Revision 4, makes the PSD assessment in Option 1, Approach 2, unconditional on the result of RS enveloping but does not require a comparison to a target PSD function. Section 2.1 of this RIL provides the results of the RES staff's literature review, technical discussion, and examples. Based on these results, the RES staff concluded the following:

- RS enveloping alone does not ensure power sufficiency. Houston et al. (2010) found that power deficiencies could underpredict the PSAs in ISRS by as much as 70 percent. This study showed that a broadband time history produced an ISRS that differed by 90 percent from that of a time history with 15 major frequencies.

- A PSD assessment without a comparison to a target PSD function is not conclusive.

- The PSD check should also include a check of the raw PSD curve to determine whether the ±20-percent frequency window for smoothing adequately produces a mean PSD curve that follows the trend of the raw PSD curve.

- For practical purposes, a target PSD function can be developed for a given practical DRS, and methods are available for developing such target PSD functions.

Therefore, RES recommends that Option 1, Approach 2, include a criterion that the estimated PSD function of the acceleration time history be computed and shown to be higher than the minimum target PSD function to ensure that there are no significant gaps in power at any frequency over the frequency range that is described in Step (a) of Approach 2.

Alternatively, Approach 1 and Approach 2 may be combined to simplify the SRP criteria for the acceptance of acceleration time histories based on the resolution of all issues addressed in this RIL. With the newly proposed frequency series and newly recommended RS enveloping criteria (Issue 5) and the proposed addition of a comparison to the target PSD function in Approach 2, these two approaches differ only in the number of DRS curves. The combined approach can easily accommodate this difference.

6.1.2 Issue 3—Strong Motion Durations

SRP guidance recommends the strong motion duration T_D as defined in SRP Section 3.7.1, Appendices A and B. In particular, the use of T_{5-75} in SRP Section 3.7.1, Revision 4, Acceptance Criterion II.1.B, requires a check of the uniformity of the growth of the cumulative Arias Intensity, which is often overlooked in practice. Even when it is checked, the determination of uniformity can be subjectively biased because of the predetermined T_{5-75}. In addition, when the uniformity of the growth of the cumulative Arias Intensity is checked, T_D becomes readily available, thus eliminating the need to compute T_{5-75}.

6.1.3 Issue 5, Part A—Frequency Range and Damping Considerations for a Power Spectral Density Check

Issue 5 has three items:

(1) Option 1, Approach 1, uses fewer frequency points than those in Approach 2 in RS calculations and comparisons.

(2) Option 1, Approach 1, uses more damping ratios than those in Approach 2 in RS enveloping.

(3) For the PSD check, SRP Section 3.7.1, Appendix A, requires a frequency range of 0.3 Hz to 24 Hz, whereas Appendix B requires a frequency range of 0.3 Hz to an unspecified upper bound frequency to be consistent with the RS shape.

Of these three items, Item 3 and part of Item 2 are related to PSD functions. Items 1 and 2 are related to RS enveloping and are summarized in Section 6.4 of this RIL.

For the upper bound frequency in a PSD check, the current guidance in SRP Section 3.7.1, Appendix B, on the frequency range for a PSD check should remain because the upper bound frequency for the PSD check depends on the shape of the DRS. In addition, Section 2.3 of this RIL demonstrates that the development of a criterion based on the cumulative PSD function is not feasible as it becomes flat at high frequencies.

The lower bound frequency for a PSD check, which is currently set at 0.3 Hz, may need to be removed from both Appendices A and B to SRP Section 3.7.1, because low frequencies close to this frequency can be important for SSI phenomena at some deep soil sites and for sloshing in large tanks. As a replacement, the lower bound frequency for a PSD check should be consistent with the DRS and stated similarly to the upper bound frequency. The same single set of time histories is often used in different analyses, such as SSI analyses of major buildings or storage tanks installed on the ground surface.

The upper bound frequency of 24 Hz in SRP Section 3.7.1, Appendix A, may remain; this RIL demonstrates that the power above this frequency has minimal effort on RS. However, it could be removed from Appendix A, and the same guidance in Appendix B for upper bound frequency could be used in Appendix A. The practical impact of such a revision is considered minimal.

As for damping ratios in the context of PSD assessment, if the DRS can be demonstrated to be consistent with each other, the use of the 5-percent damped DRS is appropriate for developing the target PSD function. Otherwise, the target PSD function should take the envelope of the target PSD functions developed for the DRS at all damping ratios.

6.1.4 Issue 8—Effect of Power Deficiency in Very Low Frequencies or High Frequencies

Power deficiency at very low frequencies or high frequencies can be significant to structures and components with important modes in those frequency ranges. Both a literature review and the RES staff's analysis showed that a power-deficient time history can lead to a significant underprediction of ISRS. The RES staff's analysis showed that, except for ZPAs, ISRS reflect the power distribution of the input time history more than the input RS does. Other structural responses sensitive to frequency content, such as fatigue, should be affected similarly. Because Option 1 uses a single set of time histories as a surrogate to the input ground motion, which is specified as the DRS of three spatial components, power-deficient time histories are not able to authentically serve that role (as a surrogate). Therefore, power-deficient time histories are not acceptable unless the applicant provides an adequate technical justification to show that the corresponding power deficiencies are not important to the affected structures and components for the particular application. One may use other methods (e.g., an RSA- or RVT-based method) or time histories without power deficiencies to justify the use of power-deficient time histories.

6.2 Issues Related to Seed Time Histories

This category includes two issues: Issue 2 (criteria for recorded seed time histories) and Issue 4 (criteria for randomly generated seed time histories). Because these two issues are closely related, this section addresses them together. Before the issuance of SRP Section 3.7.1, Revision 3, the SRP did not include provisions for seed time histories. Revision 3 states that artificial time histories that are not based on recorded seed time histories should not be used. Revision 4 allows both recorded and artificial seed time histories.

RES recommends the following based on its literature review:

- The SRP guidance on the shape of the recorded seed time histories should remain (i.e., the RS corresponding to the seed record should be similar in shape to the target spectra across the frequency range of interest to the analysis). The intent of this guidance is to encourage minimal modification to the seed time histories so that the resultant artificial time histories are more like real earthquake ground motions.

- The SRP guidance should remove the criterion "phasing characteristics of the earthquake records should not change significantly" because time domain methods often change phase characteristics significantly.

- Instead, Fourier phase spectra of the final artificial time history, based on either recorded or random seed time histories, should be demonstrated to have a uniform distribution over 0 to 2π. This recommendation is based on both empirical and theoretical research results in the literature.

6.3 Issue Related to Multiple Sets of Time Histories

To demonstrate the adequacy of multiple sets of time histories, Option 2 indicates that the average RS and average PSD function should meet the Option 1, Approach 2, criteria; each individual time history does not need to satisfy these criteria. The goal of such a criterion is to prevent situations in which systematic biases may occur in the multiple sets of design time histories. Using the same RS matching program or procedure, using seeds recorded at seismometers with similar applicable frequency range and filtering records may cause systematic biases.

The intent of this issue was to check whether the Option 2 guidance still applies if Option 1, Approach 2, is changed based on the resolution of other issues. RES concludes that Option 2 does not need to be changed based on the recommended revisions of Option 1 (except for probable minor editorial changes to ensure consistency).

6.4 Other Issues

6.4.1 Issue 5, Part B—Number of Frequencies and Damping Ratios in Response Spectra Enveloping

Items 1 and 2 in Issue 5 concern the differences between Approach 1 and Approach 2 in terms of the number of frequencies and damping ratios used in RS enveloping.

An assessment of the frequency points currently used in Option 1, Approach 1, and in Approach 2 indicates that the two frequency series can be unified and be replaced by a newly proposed series, log_power ($p = 0.6$ and $n = 151$). The new frequency series is similar to Approach 2 at high frequencies (greater than 10 Hz) and similar to Approach 1 at midfrequencies (1 Hz through 10 Hz). In the low-frequency range (0.1 Hz to 1 Hz), the new frequency series has 25 frequency points, as compared to 8 frequency points for Approach 1 and 100 frequency points for Approach 2, and is close to those for the Fourier spectrum of a typical time history (dt = 0.005 seconds, N = 4,096). The assessment concludes that the log_power frequency series is flexible, convenient, and sufficient.

The RES staff's assessment of the Approach 2 RS enveloping criteria indicates that these criteria can allow unconservative RS enveloping situations. Therefore, the RS enveloping criteria in Approach 2 may need to be enhanced to limit the total number of spectral points below the DRS. RES proposes that no more than 6 percent of the total frequency points in the frequency range of interest should be allowed, which translates to 16 points up to 50 Hz using the current Approach 2 minimum frequency series (i.e., 100 points per frequency decade). For Approach 1, if the allowable five points occur in the same frequency range, they can cover a frequency window larger than that allowed in Approach 2. Therefore, RES recommends that Approach 1 should be enhanced to require a check that ensures that the points below the DRS do not fall in frequency windows larger than ±10 percent. The RES staff notes that these conclusions and recommendations only indicate the potential deficiencies in the current criteria but do not suggest these situations occur in practice. The goal of the proposed enhancement is to improve regulatory efficiency by avoiding potential unfavorable cases in the future.

As for the number of DRS at different damping ratios, the RES assessment reaffirmed that the use of multiple DRS in RS enveloping is more conservative than the use of a single DRS, even at a 2-percent damping ratio. DRS curves tend to govern at different frequency ranges, although DRS at lower damping values generally govern more than DRS at higher damping values. However, for situations in which only the 5-percent damped DRS is available (e.g., as a result of the PSHA), instead of generating and using DRS at other damping ratios, the use of the DRS at a 5-percent damping ratio is acceptable. This conclusion is based on (1) the degree to which the RS enveloping criteria at other damping ratios are exceeded is considered insignificant in an engineering sense, (2) other DRS can be generated consistently, and (3) the PSD check against the target PSD function helps identify the unsatisfactory frequency ranges in RS enveloping at lower damping values.

6.4.2 Issue 6—Time Increment and Total Duration of Time Histories

Recent practices commonly meet the SRP acceptance criteria for minimum Nyquist frequency, time increment, and total duration of time histories currently provided in Option 1, Approach 2. RES staff experience indicates that achieving these technical aspects in synthetic acceleration time histories is not difficult. Therefore, imposing these criteria on Approach 1 presents no practical problem, and the provisions in Step (a) of Option 1, Approach 2, can be relocated to the general criterion of Option 1, thus making them applicable to both approaches.

6.5 Recommendations for Future Research

The RES work described in this RIL also identified the following six technical areas for future research, which can provide further insights to enhance technical positions in the SRP guidance that relate to the proposed resolution of the issues identified for the generation of ground motion acceleration time histories for seismic design. Such work would address, for example, issues that might arise in a possible implementation of the proposed resolutions.

6.5.1 Development of an Automated Method To Determine the Strong Motion Duration

The cumulative Arias Intensity curve (also referred to as Husid plot) is used to determine the strong motion duration, during which the acceleration time history reaches near maximum and nearly stationary power. The cumulative Arias Intensity curve usually shows a shape similar to a log-sigmoid function, with the strong motion portion nearly a straight-line segment. Therefore, a log-sigmoid function or other similar functions can be used to determine a best fit to the cumulative Arias Intensity curve, and the parameters of the fitted curve can then be used to calculate the strong motion duration. This process can be implemented as an automated procedure and consequently can be standardized to avoid ambiguity. The relationship between T_D and the parameters of the fitted curve needs to be determined based on the analysis of many real and synthesized acceleration time histories.

6.5.2 Study of Power Spectral Density Effects Using Realistic Models

The study by Houston et al. (2010) is the only example that the RES staff found using realistic models to show that power deficiencies in time histories can have a significant effect on structural responses (ISRS in particular). That study compared the results of SSI analyses using hundreds of artificial time histories that were developed based on recorded seed time histories to meet the Option 1, Approach 2, criteria in SRP Section 3.7.1. Analysis of a variety of other realistic structural and component models would provide further insights into real SSCs and other response parameters (such as fatigue). The analyses would consider different methods, such as RSA and RVT analysis, and time histories that adequately envelop the DRS but may or may not envelop the minimum target PSD functions. One of the technical difficulties is to develop time histories with power deficiencies in specific frequency ranges that affect the adequacy of the calculated response of the models. The results of this effort would provide further insights into the development of target PSD functions and related PSD checks based on the effects of power deficiency on realistic SSCs.

6.5.3 Spectral Shape and Phase Spectrum of Recorded Seed Time Histories

A future effort would investigate the feasibility of establishing quantitative criteria for adequate similarity between the spectrum shape of the seed record and that of the DRS. Many real earthquake records would be examined to determine the metrics of the significance of the shape similarity between the RS of the seed records and DRS in predicting structural responses. RES staff review did not find such studies in the literature.

A related effort would study the significance of the phase spectra, particularly their uniformity, for structural response and confirm the view in the literature that phase spectra do not have a significant impact on structural responses (beyond the known variation that has been accounted for in practice by meeting the RS enveloping criteria, PSD check, ground motion specification, and factors in design equations). This would also involve development of a procedure or numerical criteria to determine the uniformity of the phase angle distribution.

6.5.4 Single Set versus Multiple Sets of Time Histories

There is a general question whether a single set of time histories should be allowed in seismic analysis and design of NPP SSCs. A single set of time histories enveloping the DRS may not represent the potential seismic scenarios resulted from the deaggregation procedure in RG 1.208. A single set of time histories enveloping a broad band DRS may be overly conservative as the DRS consists of both low spectral frequency events and high spectral frequency events. On the other hand, a single set may be less conservative than multiple sets as it includes only a single set of phase sequences. From a historical perspective, the practice of using a single set of time histories has been in place since the first issuance of SRP Section 3.7.1 in 1975, and this method apparently was widely accepted before then. In 1989, SRP Section 3.7.1, Revision 2, introduced the use of multiple time histories.

This research would involve a working group of staff from various offices and specialties to establish whether the use of a single set of time histories continues to be justified or adequate, or if future guidance should concentrate on the use of multiple sets of time histories. The research would consider the added clarity associated with the use of multiple sets of time histories, the improvements in computational power and the complexity of methods of seismic response analysis, and new design refinements and criteria that may be more sensitive to the randomness in the time histories.

6.5.5 Development of a Regulatory Guide on Acceptable Criteria and Methods for Generating Acceleration Time History

As Section 1.2.1 of this RIL indicates, the content of SRP Section 3.7.1 has grown significantly, and much of that growth relates to the acceptance criteria for artificial time histories. The discussion of time histories and the associated acceptance criteria in the main text of SRP Section 3.7.1 and its two appendices has reached a level of technical detail much greater than that in other typical technical areas in SRP Sections 3.7 and 3.8. By itself, this imparity with other SRP sections would warrant the development of a standalone technical report (NUREG) or regulatory guide that can be referred to by SRP Section 3.7.1. The simplified SRP Section 3.7.1 would then require less revision and could focus on guidance that is more specific to the NRC review processes.

This standalone document would allow more technical discussion to be included as needed. For example, it could include a critical appraisal of common methods for generation of time histories to identify issues that may be important to the safety of NPP SSCs but do not need to be included in the SRP guidance. The literature and practice offer many methods for generating artificial time histories. The resulting artificial time histories may have characteristics that can differ significantly from method to method.

To achieve a broader, more stable review practice in the program offices, this work would preferably be integrated with activities in the current Structural, Geotechnical, and Seismic Research Plan. These are the plans for the joint review of the updated consensus standard for seismic analysis of nuclear facilities. This review can integrate with the update of a set of existing NRC guidance documents for seismic analysis currently dispersed over various parts of SRP Sections 3.7 and 3.8, RGs, and ISG documents in a risk-informed manner. The consensus standard of interest is the ASCE/SEI 4-16 for the seismic analysis of nuclear facilities. Examples of relevant NRC guidance documents are RG 1.92, “Combining Modal Responses and Spatial Components in Seismic Response Analysis”; RG 1.122, “Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components”; RG 1.208, “A Performance-Based Approach To Define the Site-Specific Earthquake Ground Motion;” DC/COL-ISG-17, “Interim Staff Guidance on Ensuring Hazard-Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses”; and DC/COL-ISG-01, “Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications.”

6.5.6 Development of Software Tools To Support Staff Review

To support technical reviewers assessing the adequacy of artificial time histories, RES recommends the development of computer tools for use in the review activities. These tools are expected to quickly and objectively determine the adequacy of the time histories. Since the acceleration time histories include thousands of data points and not all of their important technical aspects are observable directly from the data, the success of staff review without using computer tools would largely depend on what is described in the applications. RES staff experience indicates that given the technical complexity of the issues related to acceleration time histories, application documents may be unable to address such complexity effectively, and many requests for additional information and other costly regulatory actions such as audits are often needed. To this end, staff confirmatory analysis using computer tools can be much more efficient and effective. Even more effectively, these tools may be developed, validated, and maintained through a worldwide consortium drawn from academia, industry, and regulators.

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