SEISMIC QUALIFICATION UTILITY GROUP GUIDANCE: METHODS FOR CONVERTING FLOOR RESPONSE SPECTRA DAMPING

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THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

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NOTE

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Abstract

A response spectrum is a plot of the maximum responses of single-frequency oscillators over a range of frequencies to an excitation by a given input motion. The responses of the oscillators is a function of the oscillator frequency and selected damping. A response spectrum is developed by varying the frequency and plotting the maximum response (usually acceleration) at each frequency.

In some cases it is necessary to estimate a response spectrum with a different damping value than the one available. This paper summarizes methods for converting a response spectrum from one damping ratio to another, without regenerating the response spectrum from the original input motion.

Introduction

The purpose of this white paper is to summarize the methods for converting a floor response spectrum from one damping ratio to another, without regenerating the response spectrum from the original time history. The paper will investigate available methods and compare the results of using each method with the results from time history analysis, focusing on the application to narrow-banded floor response spectra.

Background

Response spectra are often used in seismic analysis. A response spectrum is the spectrum of the maximum responses of single-frequency oscillators over a range of frequencies to an excitation by a given base motion. The excitation is typically an acceleration time history (acceleration as a function of time) of the ground or a point in a structure. A single-frequency system is usually depicted as a single mass coupled to its support (ground or floor) by a single spring and a single damper. The motion (displacement, velocity, and acceleration) of the mass due to the input time history is calculated as a function of time, and the maximum value determined. The motion of the mass is a function of the frequency as defined by the mass and the spring stiffness) and damping (usually expressed as a percentage of critical damping). By varying the frequency and plotting the maximum response (usually acceleration) at each frequency, a response spectrum is obtained. This is useful in seismic analysis because if the modal frequencies of a system are known, the maximum response of each mode can easily be determined from the response spectrum without having to perform a time history analysis of the system. Modal responses can then be combined to obtain the total response. Often, the system can be conservatively evaluated by equivalent static analysis using the maximum spectral acceleration of the response spectrum without calculating the system modal frequencies.

The free vibration motion of a system, structure, or component (SSC) will decrease over time until the oscillation ceases. This decrease of oscillation is due to the energy of the system converting to heat or sound and is known as damping. The damping in the oscillator is expressed as a percentage of the critical damping of the SSC. The crticial damping is defined as the least amount of damping that will allow a displaced system to return to its original position without oscillation. The damping ratios for SSCs located in a nuclear power plants range from 0.5% to 15% of critical damping, depending on plant vintage and the SSC involved.

SSCs at existing nuclear power plants subject to USI A-46 [1] may be evaluated using the guidance provided in the Seismic Qualification Utility Group (SQUG) Generic Implementation Procedure (GIP) [2]. Application of the SQUG GIP requires use of the 5% damped floor response spectrum at the equipment location. This is used both in the capacity vs. demand screening and in the anchorage capacity verification.[1] Occasionally, the 5%-damped spectrum is not available and one must be calculated or estimated. One way to do this is to generate a 5%-damped spectrum using the time history originally used for the existing floor response spectra. This is easily done if the time history is available, but often it is not. If it is not,

[1] For some equipment types a response spectrum at a damping ratio different than 5% may be required.

then it is necessary to estimate the 5%-damped spectrum using the existing spectra.[2]

The following scenarios are possible:

1. Floor response spectra exist for two dampings, β_1 and β_2, and a spectrum is needed for a third damping, β_D
2. A floor response spectrum exists for one damping, β_A, and a spectrum is needed for a different damping, β_D

In the first scenario, an approximate spectrum can be estimated using either interpolation, if the desired damping is between the two existing dampings, or extrapolation if the desired damping is either greater than or less than both existing dampings. In the second scenario, only extrapolation is possible.

Various methods have been devised for the estimation of a floor response spectrum at a specific damping ratio based upon a response spectrum at a different damping ratio. These include linear interpolation, the American Society of Civil Engineers (ASCE) Standard 4 [3] methods (log interpolation and random vibration), NUREG/CR 6728 [4] method, and the SQUG GIP methods. The methods other than linear interpolation were derived and benchmarked against broad-banded response spectra. Their application to narrow-banded floor response spectra has not been examined. These methods are examined herein and benchmarked against actual narrow-banded floor response spectra in order to determine which method best approximates the response spectrum at a specific damping ratio based upon an existing response spectrum at a different damping ratio.

Approximate Methods for Scaling Spectra for Damping

Six methods for interpolating and/or extrapolating seismic response spectra to specific damping ratios are described and evaluated below. These six methods are linear interpolation, ASCE 4 logarithmic method, ASCE 4 random vibration method, NUREG/CR 6728 method, SQUG GIP Method 1 and SQUG GIP Method 2. The first three methods can be used for interpolation and all six methods can be used for extrapolation.

[2] Another option is to generate an artificial time history whose spectrum closely matches the known spectrum, and then use the artificial time history to generate a new spectrum at the desired damping. This is a tedious process and is seldom used.

Method 1 – Linear Interpolation

Linear interpolation is often used for estimating the desired spectral acceleration, S_D, at a damping ratio of β_D, which is between the known damping ratios β_1 and β_2 with spectral accelerations of S_1 and S_2, respectively. The equation is:

$$S_D = S_1 + (S_2 - S_1)\frac{(\beta_D - \beta_1)}{(\beta_2 - \beta_1)}$$

Clearly this is approximate, as response spectral accelerations are known to not vary linearly with damping. But the error may be acceptable considering various conservatisms in most floor response spectra.

Method 2 – ASCE 4 Logarithm Method

ASCE 4, Section 6.2.4, states that "in structure response spectra for damping ratios for which in structure response spectra were not explicity generated may be generated by linear interpolation for intermediate levels of damping, with the interpolation performed in terms of the natural logarithm of damping." This derives from the observation that ground response spectral accelerations in the amplified region tend to vary according to the log of the damping ratio. This method results in the following equation for estimation of the desired spectral acceleration, S_D, at a damping ratio of β_D, which is between the known damping ratios β_1 and β_2 with spectral accelerations of S_1 and S_2, respectively:

$$S_D = S_1 + (S_2 - S_1)\frac{ln\frac{\beta_D}{\beta_1}}{ln\frac{\beta_2}{\beta_1}}$$

ASCE 4 limits this method to interpolation; i.e., situations where the desired spectrum is located between two known response spectra.

Method 3 – ASCE 4 Random Vibration Method

ASCE 4, Section 6.2.4, allows for a second method to generate in structure response spectra which is based upon an analytical derivation using a stationary random vibration approach (EUR 11369, Chapter III, Appendix A [5]). Estimation of the desired spectral acceleration, S_D, at a damping ratio of β_D, between the known damping ratios β_1 and β_2 with spectral accelerations of S_1 and S_2 is performed via the following equation:

$$S_D = \sqrt{S_2^2 + (S_1^2 - S_2^2)\frac{\beta_1}{\beta_D}\left(\frac{\beta_D - \beta_2}{\beta_1 - \beta_2}\right)}$$

ASCE 4 also limits this method to interpolation, and contains a limit on the difference between the damping ratios of the two known spectra:

$$\beta_1 > \beta_D > \beta_2 \leq 3\beta_1$$

Method 4 – NUREG/CR-6728 Method

NUREG/CR 6728, Section 4.9.1, provides equations for accounting for damping through random vibration theory. The recommended procedure includes two different equations to be used within two frequency ranges. The spectral acceleration, SA(f,ξ) at frequency f and damping ξ is calculated using the strong motion duration, D, for frequencies between 1 Hz and 5 Hz with the following equation.

$$SA(f,\xi) = SA(f,0.05)\left[\frac{1 + 4.9\xi f D}{1 + 4.9 \times 0.05 f D}\right]^{-0.41}$$

At frequencies of 5 Hz and above, the following equation is recommended for use:

$$SA(f,\xi) = \left\{PGA^2 + [SA(f,0.05)^2 - PGA^2]\left[\frac{1 + 4.9\xi f D}{1 + 4.9 \times 0.05 f D}\right]^{-0.82}\right\}^{1/2}$$

NUREG/CR-6728 applies this method to ground response spectra.

Method 5 – SQUG GIP Method 1

The SQUG GIP, Section 4.4.3, provides two methods for estimating the response spectrum for one damping ratio based upon a known response spectrum at a different damping ratio. The first method (Method 1) is intended for in structure response spectra which have a shape similar to the Bounding Spectrum shown in the SQUG GIP, Figure 4 2. This method uses the following equation:

$$S_D = S_1\sqrt{\frac{\beta_A}{\beta_D}}, S_D \geq ZPA$$

GIP Method 1 can be derived from the random vibration method of EUR 11369 [5]. EUR 11369, Chapter III, Appendix A, equations A.7 and A.2 are:

$$S_D^2 - S_A^2 = \frac{\pi\omega\eta^2}{2}\Phi(\omega)\frac{\beta_A - \beta_D}{\beta_D\beta_A}$$

$$\Phi(\omega) = \frac{2\beta S_a^2}{\pi\omega\eta^2}$$

where:

S_D is the unknow spectral acceleration
S_A is the known spectral acceleration
β is the damping for a response spectrum
β_D is the damping for S_D
β_A is the damping for S_A
ω is the circular frequency
η is the peak-factor of the spectrum acceleration
Φ is the PSD of the ground excitation

Substituting Equation A.2 with $\beta = \beta_A$ and $Sa = S_A$ into A.7 and rearranging yields:

$$S_D = S_A\sqrt{\frac{\beta_A}{\beta_D}}$$

This equation is identical to the equation provided in the SQUG GIP, Section 4.4.3.

Method 6 – SQUG GIP Method 2

The second GIP method (Method 2) is for in structure response spectra which are based on 1.5 times the horizontal ground response spectrum, and applies to equipment which are mounted below about 40 feet (12.2 m) above the effective grade and have a fundamental natural frequency greater than about 8 Hz. Method 2 uses the same equation as Method 1 for frequencies less than or equal to 8 Hz. For frequencies greater than 8 Hz (but less than 20 Hz), Method 2 uses the following equations:

$$S_D = S_A \sqrt{\frac{\beta_A}{\beta_D}}, f \leq 8\ Hz$$

$$S_D = ZPA, f \geq 20\ Hz$$

$$S_D = 10^{\left[m \log\left(\frac{f}{8}\right) + \log(Sa_{8Hz,D})\right]}, \qquad 8\ Hz < f < 20\ Hz$$

$$m = \frac{\log\left(\frac{S_{20Hz,D}}{S_{8Hz,D}}\right)}{\log(20/8)}$$

This formulation assumes that the peak spectral acceleration occurs at 8 Hz and the rigid range begins at 20 Hz. If the peak and rigid range frequencies are different, those frequencies can be substituted for the frequencies in the above equations.

Benchmark Test Cases

The methods for interpolation and extrapolation described above were benchmarked against narrow-banded floor response spectra calculated from a floor time history. Two test cases were used for the benchmarking. Test Case 1 is a set of floor response spectra, shown in Figure 1, from a stick model using the El Centro earthquake time history as the base excitation. Spectra were generated for damping ratios of 0.5%, 1%, 2% and 5%.[3]

[3] The spectra are from projects that involved generating floor response spectra for two different nuclear power plants. One used a design basis lumped mass structure model and design basis input time history. The other used a more modern finite element structure model and a time history matched to a uniform hazard spectrum. Both projects generated spectra at various damping ratios from a floor time history. The damping ratios chosen were different for the two different projects. However, the spectra provide useful benchmarks for the interpolation/extrapolation methods.

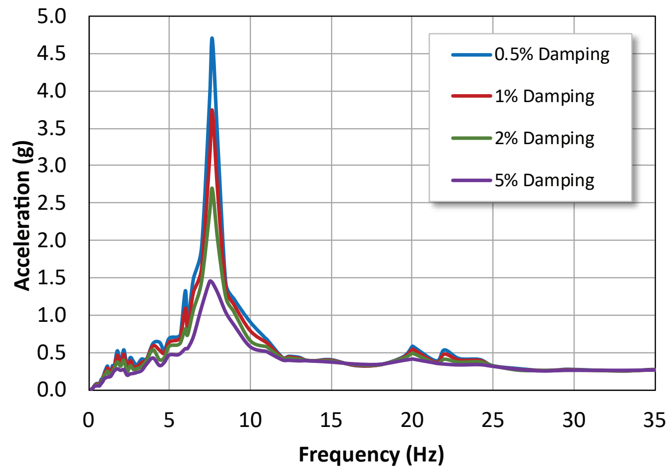

Figure 1 – Test Case 1 Response Spectra

Table 1 – Test Case 1 Peak Spectral Accelerations

Damping	Sa,peak
0.005	4.69
0.01	3.74
0.02	2.70
0.05	1.44

Test Case 2, shown in Figure 2, is a set of floor response spectra from a finite element model using a UHS-compatible time history as the base excitation. Spectra were generated for damping ratios of 0.5%, 3%, 4%, 5%, 7% and 10%.

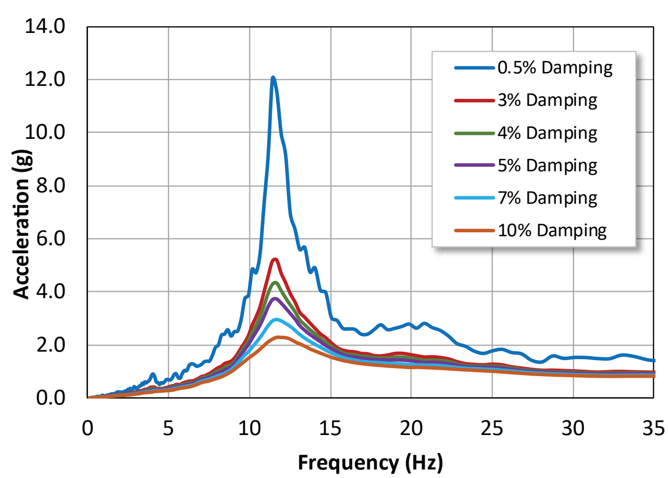

Figure 2 – Test Case 2 Response Spectra

Table 2 – Test Case 2 Peak Spectral Accelerations

Damping	Sa,peak
0.005	12.00
0.03	5.18
0.04	4.32
0.05	3.72
0.07	2.97
0.10	2.30

The two cases represent response spectra for a structure with a lower-frequency primary mode (Test Case 1) and a structure with a higher-frequency primary mode (Test Case 2), as well as lower-frequency input excitation (Test Case 1, El Centro earthquake) and higher-frequency input excitation (Test Case 2, UHS-compatible earthquake).

Two general scenarios are examined for each test case. The first scenario uses two known floor response spectra at two different damping ratios. Comparisons are performed using the linear interpolation method, and the ASCE 4 interpolation methods (log and random vibration). In addition, comparisons are performed using these methods for extrapolation.

The second scenario uses a single known floor response spectrum at one damping ratio. From this one spectrum, extrapolations are performed using the SQUG GIP methods (Methods 1 and 2) and the NUREG/CR 6725 method.

The floor response spectra are "raw" spectra; i.e., they have not been peak-broadened and smoothed, or enveloped from multiple time histories. The reason is to isolate the accuracy of the estimation methods from conservatisms involved in peak-broadening, smoothing and enveloping.

Benchmark Results

Interpolation Between Two Spectra

Four interpolation benchmark trials were run for the ASCE 4 logarithmic and random vibration methods as well as linear interpolation using the parameters in Table 3.

Table 3 – Interpolation Benchmarks

Trial	Test Spectra	Known Damping	Derived Damping
A	Case 1	0.5%, 2%	1%
B	Case 1	1%, 5%	2%
C	Case 2	3%, 7%	5%
D	Case 2	0.5%, 5%[4]	3%

Figures 3 through 6 show the results for interpolation methods between two spectra. Tables 4 through 7 show comparisons for the peak spectral accelerations and estimated error values, which are generally the worst case comparisons.

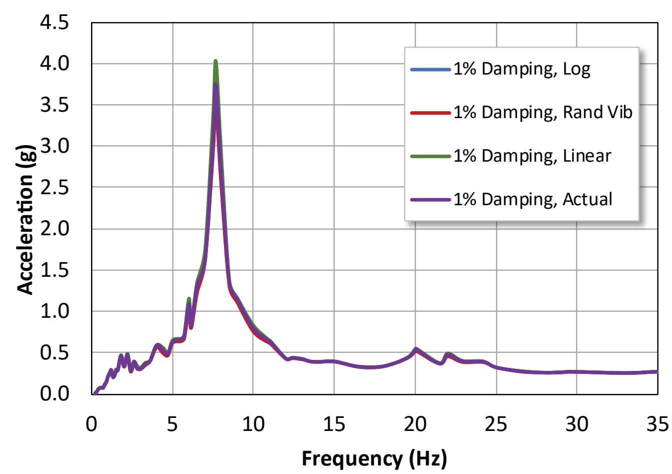

Figure 3 – Trial A Response Spectra

Table 4 – Trial A Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
Log	3.69	-1.3%
Rand Vib	3.49	-6.7%
Linear	4.03	7.6%
Actual	3.74	-

[4] Note: The difference between the damping ratios is greater than the limit in ASCE 4

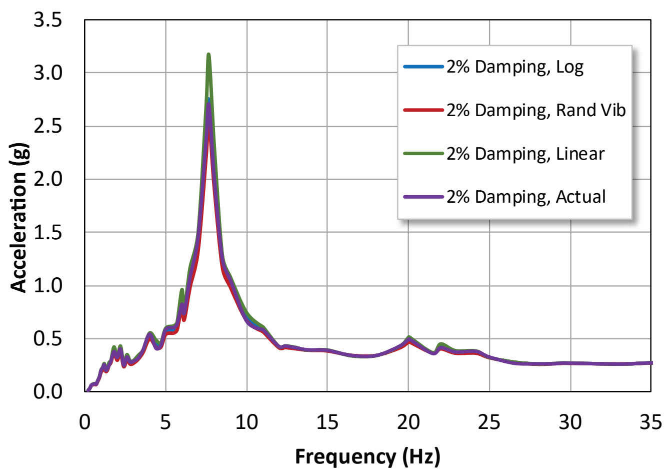

Figure 4 – Trial B Response Spectra

Table 5 – Trial B Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
Log	3.69	-1.3%
Rand Vib	3.49	-6.7%
Linear	4.03	7.6%
Actual	3.74	-

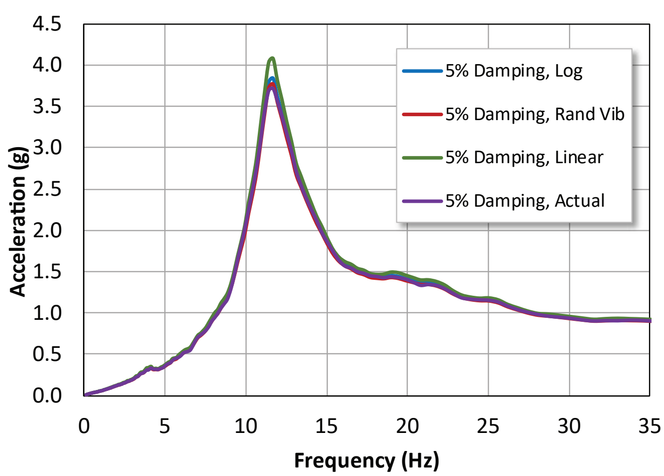

Figure 5 – Trial C Response Spectra

Table 6 – Trial C Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
Log	3.85	3.3%
Rand Vib	3.77	1.3%
Linear	4.07	9.4%
Actual	3.72	-

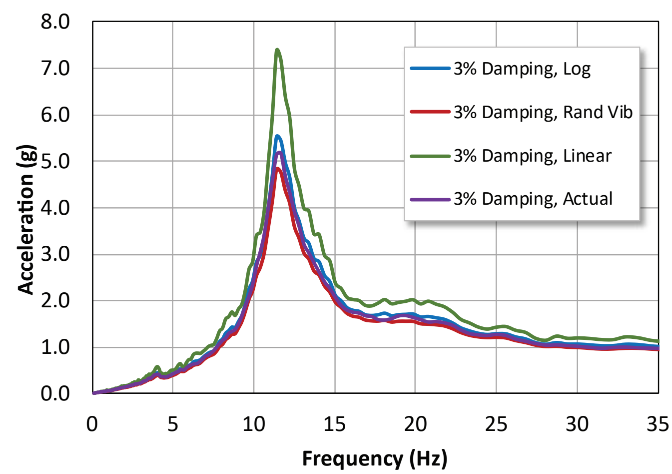

Figure 6 – Trial D Response Spectra

Table 7 – Trial D Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
Log	5.46	5.4%
Rand Vib	4.76	-8.0%
Linear	7.20	38.9%
Actual	3.72	-

The results show that the ASCE 4 log interpolation method performs well. The ASCE 4 random vibration method does not perform as well, especially if the damping range limit is exceeded. The linear method does not perform well, although it is conservative.

Extrapolation from Two Spectra

Four benchmark trials for extrapolation using two known spectra were run for the ASCE 4 logarithmic and random vibration methods as well as linear interpolation using the parameters in

Table 8. It should be noted that ASCE 4 does not allow extrapolation but it is included here for comparison.

Table 8 – Extrapolation from Two Spectra Benchmarks

Trial	Test Spectra	Known Damping	Derived Damping
E	Case 1	1%, 2%	5%
F	Case 1	2%, 5%	0.5%
G	Case 2	3%, 5%	7%
H	Case 2	5%, 7%	3%

Figures 7 through 10 and Tables 9 through 12 show the results for extrapolation for two spectra.

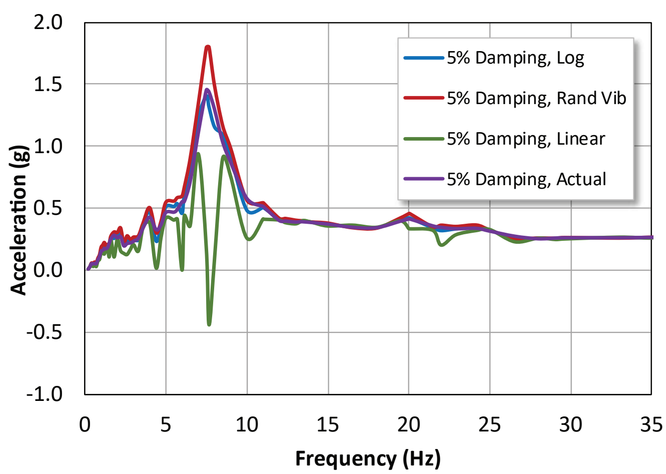

Figure 7 – Trial E Response Spectra

Table 9 – Trial E Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
Log	1.32	-8.6%
Rand Vib	1.80	25.0%
Linear	-0.44	-130.5%
Actual	1.44	-

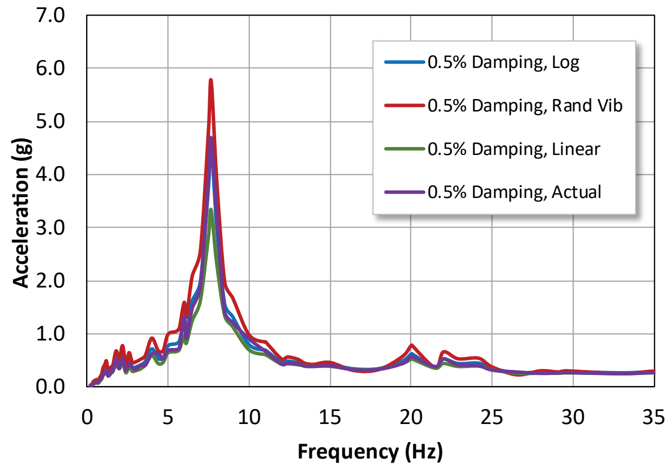

Figure 8 – Trial F Response Spectra

Table 10 – Trial F Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
Log	4.60	-1.9%
Rand Vib	5.77	23.0%
Linear	3.33	-29.1%
Actual	4.69	-

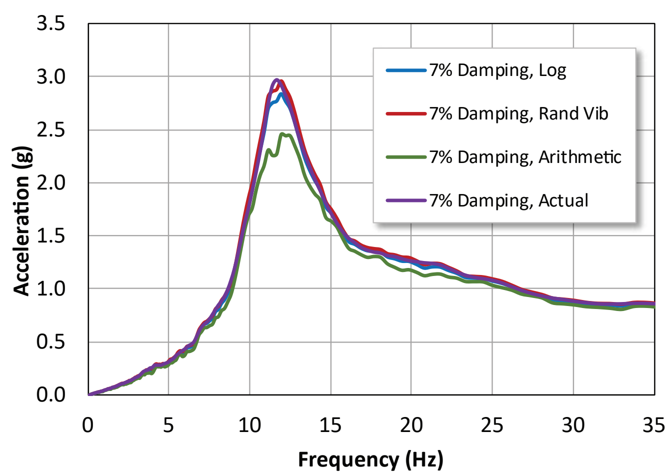

Figure 9 – Trial G Response Spectra

Table 11 – Trial G Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
Log	2.76	-6.9%
Rand Vib	2.88	-2.9%
Linear	2.27	-23.6%
Actual	2.97	-

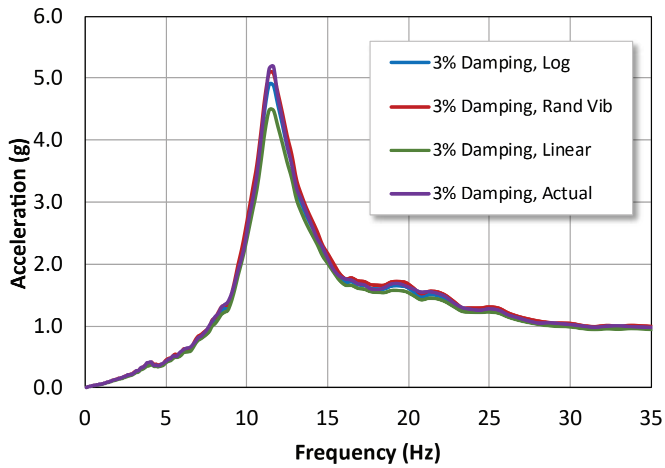

Figure 10 – Trial H Response Spectra

Table 12 – Trial H Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
Log	4.87	-6.0%
Rand Vib	5.07	-2.2%
Linear	4.48	-13.5%
Actual	5.18	-

Extrapolation from One Spectrum

Four benchmark trials for extrapolation using one known spectrum were run for the two SQUG methods and the NUREG/CR 6728 method using the parameters in Table 13. The linear method and the ASCE 4 methods are not considered because they require two known spectra.

As noted in the description of SQUG Method 2, the peak and rigid range frequencies can be adjusted to align with the input response spectrum. For Test Case 1 the peak frequency was changed from 8 Hz to 7.66 Hz and the rigid range frequency was changed from 20 Hz to 35.71 Hz. For Test Case 2 the peak frequency was changed from 8 Hz to 11.67 Hz and the rigid range frequency was changed from 20 Hz to 35.36 Hz.

Table 13 – Extrapolation from One Spectra Benchmarks

Trial	Test Spectra	Known Damping	Derived Damping
I	Case 1	5%	2%
J	Case 1	2%	5%
K	Case 2	5%	3%
L	Case 2	3%	5%

Figures 11 through 14 and Tables 14 through 17 show the results for extrapolation form one spectra.

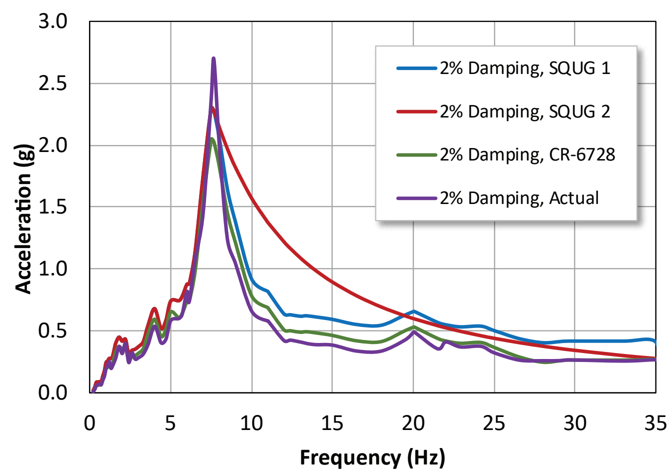

Figure 11 – Trial I Response Spectra

Table 14 – Trial I Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
SQUG 1	2.28	-15.7%
SQUG 2	2.28	-15.7%
CR-6728	2.03	-24.9%
Actual	2.70	-

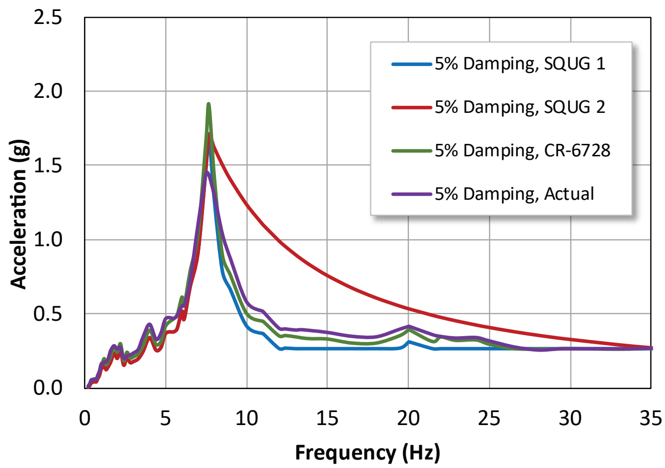

Figure 12 – Trial J Response Spectra

Table 15 – Trial J Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
SQUG 1	1.71	18.6%
SQUG 2	1.71	18.6%
CR-6728	1.91	32.7%
Actual	1.44	-

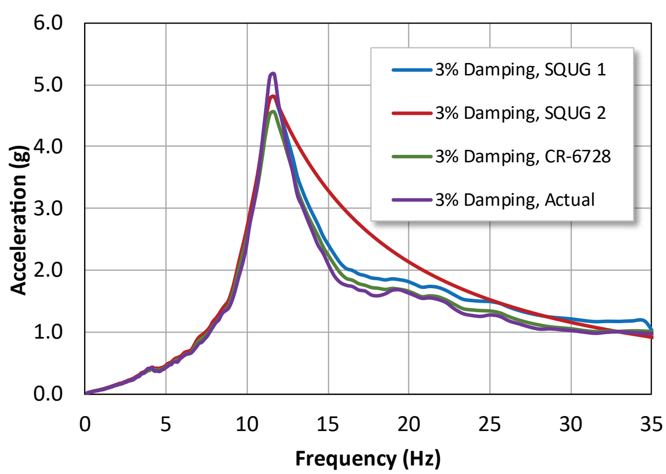

Figure 13– Trial K Response Spectra

Table 16 – Trial K Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
SQUG 1	4.81	-7.2%
SQUG 2	4.81	-7.2%
CR-6728	4.56	-12.0%
Actual	5.18	-

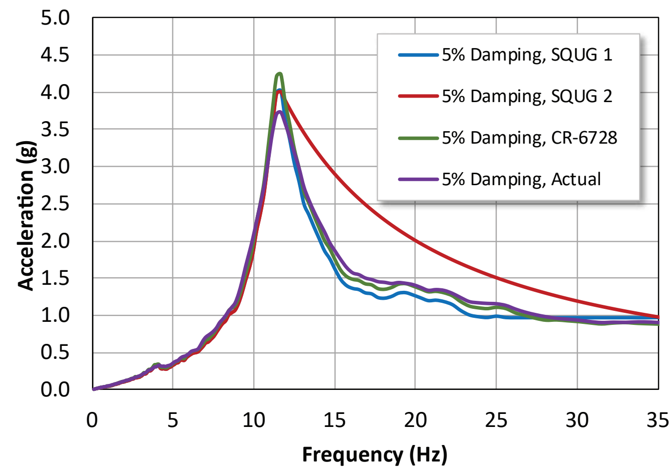

Figure 14– Trial L Response Spectra

Table 17 – Trial L Peak Spectral Accelerations

Method	Sa,peak	Est vs. Act
SQUG 1	4.01	7.7%
SQUG 2	4.01	7.7%
CR-6728	4.23	13.7%
Actual	3.72	-

Conclusions

Six methods for estimating a response spectrum at a desired damping from a response spectrum at a different damping or two response spectra at different dampings have been examined. These methods, except for the ASCE 4 methods, are intended to be used with broad-banded spectra such as ground response spectra. The ASCE 4 methods are intended to be used only for interpolation. This paper examined which methods work well with narrow-banded floor response spectra.

Interpolation Between Two Known Response Spectra

Both ASCE 4 methods (logarithmic and random vibration) perform well for interpolation of a response spectrum at a desired damping ratio between two response spectra at different damping ratios. The random vibration method works best if the known dampings are within the ASCE 4 acceptable range of three times the lower damping ratio. The linear interpolation method is conservative and therefore acceptable, but does not perform as well as the ASCE methods.

Extrapolation from Two Known Response Spectra

The logarithmic approach is the best alternative for extrapolation of older design basis spectra, which typically have peaks in the lower frequency range and which have two available response spectra at different damping ratios. The random vibration approach is the best alternative for extrapolation of spectra with peaks in the higher frequency range and which have two available response spectra at different damping ratios. The linear method does not perform well for extrapolation. For all methods, it is preferred to have the known response spectra damping ratio close to the desired damping ratio in order to minimize the inaccuracy of the extrapolation.

Extrapolation from One Known Response Spectrum

The SQUG GIP Method 1 is the best method for extrapolation from a single known response spectrum at one damping ratio to obtain a spectrum for a different damping ratio. This method produces an under-estimated spectrum when extrapolating to a lower damping ratio and produces an over-estimated spectrum when extrapolating to a higher damping ratio. The inaccuracy of the SQUG method increases with the difference between the known and desired damping ratios. For Test Case 1, when extrapolating from 5% damping to 2% damping, which is a fairly large difference, the under-estimation was about 16%. While this may seem significant, it needs to be judged against other conservatisms such as the conservativism in the ground response spectrum enveloping for the ground time history, peak-broadening and smoothing, and enveloping. These, as well as other conservatisms, often add more than 100% to floor response spectral[5] amplitudes. Thus, the under-estimation is seen to be relatively small in comparison.

The NUREG/CR 6728 method produces estimated spectra which are less accurate than those estimated by the SQUG GIP methods when compared to actual response spectra calculated from the time history. SQUG GIP Method 2 is not recommended for in structure spectra with narrow peaks since the extrapolation results are very conservative at frequencies away from the peak. For all methods, it is preferred to have known response spectra damping ratios close to the desired damping ratio in order to minimize the inaccuracy of the extrapolation method.

[5] This was established by SQUG during the justification of use of SQUG Method A for demand vs. capacity at plants whose floor response spectra exceeded 1.5 times the ground response spectra.

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