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Scaling Acceleration Response Spectra From One Damping to Another

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Background

- Ground motion predication equations (GMPEs) are almost all formulated for 5% spectral damping, as a result the site-specific design motion are always developed at 5% spectral damping.
- For application to SSCs, depending on the SSC and state of stress, input motion at other spectral damping is often required ranging from 0.50% to over 30% damping.
- Similarly, when ISRS is developed, some equipment may need input at other damping levels for qualification.
- Even when time histories are developed matching the design response spectra, it is desirable to evaluate the time history adequacy against the spectra at other damping levels pertinent to the SSC model.
- The subject of spectral damping ratio has been the subject of study and contentious debate for many years.
- Many codes and standards provide approximate method for conversion of spectral values with unknown accuracy.
- The presentation provides the most up to date approach for spectral scaling from one damping to other.

Abstract

This study focuses on the development of CEUS-like project-specific estimates of design ground motions at spectral dampings other than the conventional 5% critical damping. Given the wealth of recorded earthquake time histories in active tectonic regions, most published damping scaling factor [DSF] models used for estimating response spectra at other damping levels are readily applicable to such seismically active areas, such as WUS. Cameron and Green (2007) utilizes the sets of time histories useful for nuclear power plant design analyses in either general WUS or CEUS tectonic environments – NUREG/CR-6728 -- and finds differences worth considering. The approach of Cameron and Green is adapted here to estimate project site- and hazard-specific DSFs.

Response Spectra and Damping Values

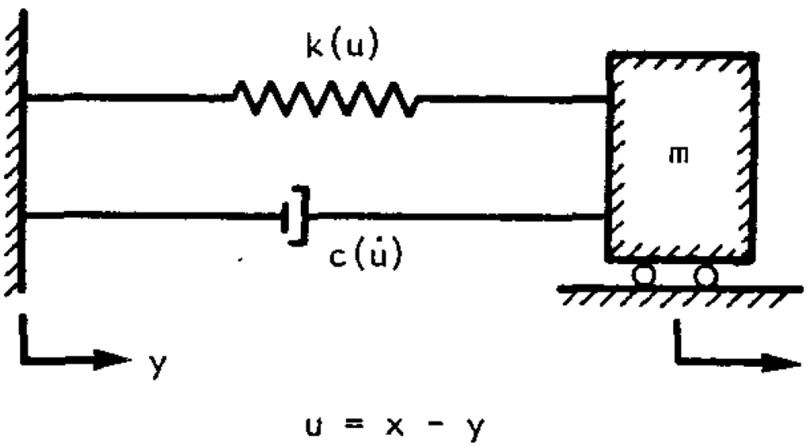


Figure 1. Simple Damped Mass-Spring Syster

Source: Newmark and Hall (1982)

TABLE 3. RECOMMENDED DAMPING VALUES

Stress Level	Type and Condition of Structure	Percentage Critical Damping
Working stress, no more than about ½ yield point	• Vital piping	1 to 2
	• Welded steel, prestressed concrete, well reinforced concrete (only slight cracking)	2 to 3
	• Reinforced concrete with considerable cracking	3 to 5
	• Bolted and/or riveted steel, wood structures with nailed or bolted joints	5 to 7
At or just below yield point	• Vital piping	2 to 3
	• Welded steel, prestressed concrete (without complete loss in prestress)	5 to 7
	• Prestressed concrete with no prestress left	7 to 10
	• Reinforced concrete	7 to 10
	• Bolted and/or riveted steel, wood structures, with bolted joints	10 to 15
	• Wood structures with nailed joints	15 to 20

Reg. Guide 1.60 DRS and DSFs

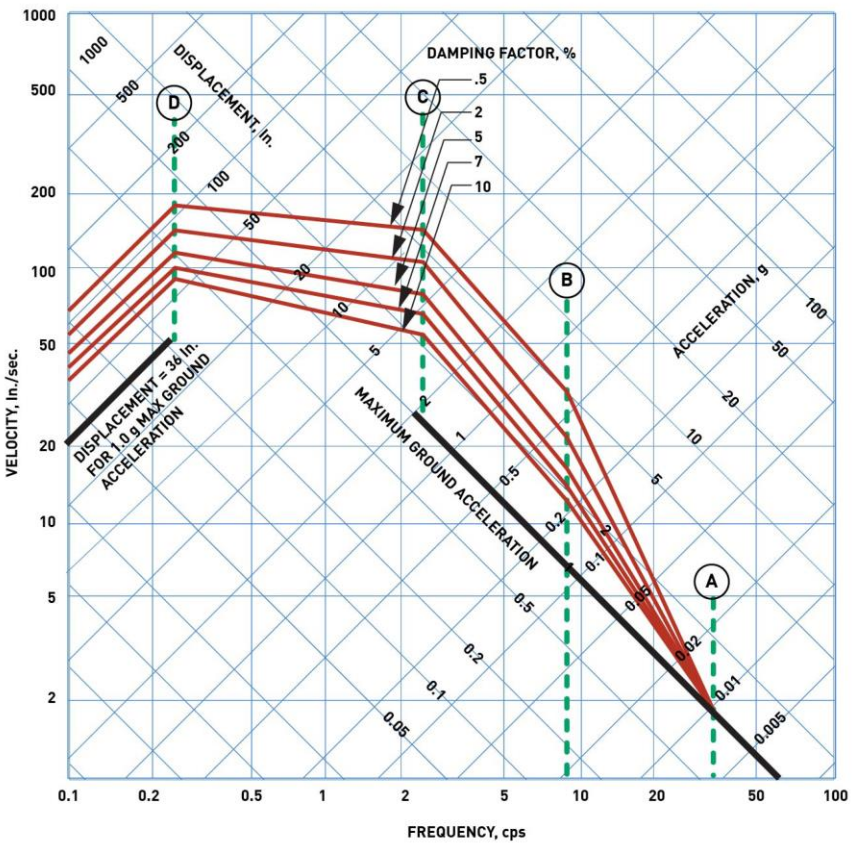


Figure 1. Horizontal Design Response Spectra Scaled to 1 g Horizontal Ground Acceleration

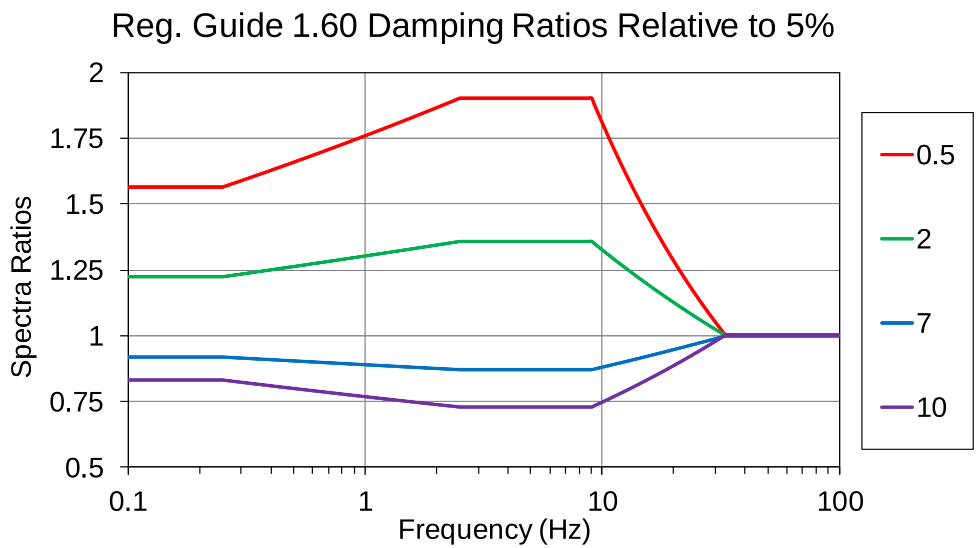
Table 1. Horizontal Design Response Spectra

Relative Values of Spectrum Amplification Factors for Control Points

Percent of Critical Damping	Amplification Factors for Control Points			
	Acceleration[a,b]			Displacement[a,b]
	A (33 cps)	B (9 cps)	C (2.5 cps)	D (0.25 cps)
0.5	1.0	4.96	5.95	3.20
2.0	1.0	3.54	4.25	2.50
5.0	1.0	2.61	3.13	2.05
7.0	1.0	2.27	2.72	1.88
10.0	1.0	1.90	2.28	1.70

a. Maximum ground displacement is taken proportional to maximum ground acceleration, and is 36 in. for ground acceleration of 1.0 gravity.

b. Acceleration and displacement amplification factor are taken from recommendations given in Reference 9.



DSF (f, β) = PSA$_{\beta\%}$ (f) / PSA$_{5\%}$ (f)

Concerns about Reg. Guide 1.60 DSFs

There are several issues with the DSFs from Reg. Guide 1.60:

- In the 1970's there were few earthquake recordings to get response spectra

- The records used were mostly from California: Note: Typical western US earthquake [WUS] characteristic of peak ground acceleration [PGA] occurring at ~33 Hz and its impact on high frequency DSF.

- No explicit dependence on earthquakes source characteristics as are known to affect 5%-damped response spectra and may, in turn, affect DSF:
  - Magnitude
  - Distance
  - Duration
  - Intensity
  - Tectonic environment
    - WUS vs. CEUS vs. Large Subduction Region [e.g., Cascadia]
    - Fault type: strike-slip, reverse, normal

- No explicit dependence on site conditions: rock, soil, Vs30

Published Studies of DSFs

Numerous DSF studies have now been published considering the greater global availability of earthquake records:

- Particularly from active tectonic regions

- Just as ground motion prediction equations [GMPEs], DSFs show some variability regarding:
    - earthquake source characteristics
    - source-to-site path, and
    - site conditions

Rezaeian and others (2012) is a notable study from the PEER on damping scaling factors, taking advantage of the significant database of earthquake recordings from the PEER NGA-West2 study:

- Again, focused on shallow crustal active tectonic regions, like WUS.

- An appendix to this report is a tabulated summary of 26 DSF relationships, as well as 7 additional DSF relationships explicit or implicit within building codes. Only one was specific to CEUS

Published Studies of DSFs

Sample of Published DSFs Listed in Rezaeian and others (2012) Appendix:

MODEL	DEPENDENCE ON:			
	Magnitude	**Distance**	**Tectonic Setting**	**Site Conditions**
Newmark and Hall (1982)	No	No	Active [WUS]	undifferentiated
Idriss (1993)	No	No	Active [WUS]	undifferentiated
Abrahamson and Silva (1996)	Yes	No	Active [WUS]	undifferentiated
Eurocode 8	No	No	? [Europe]	undifferentiated
Cameron and Green (2007)	Yes	Yes	CEUS, WUS	rock, soil
Rezaeian and others (2012)	Yes	Yes	Active [WUS]	undifferentiated

Published Studies of DSFs

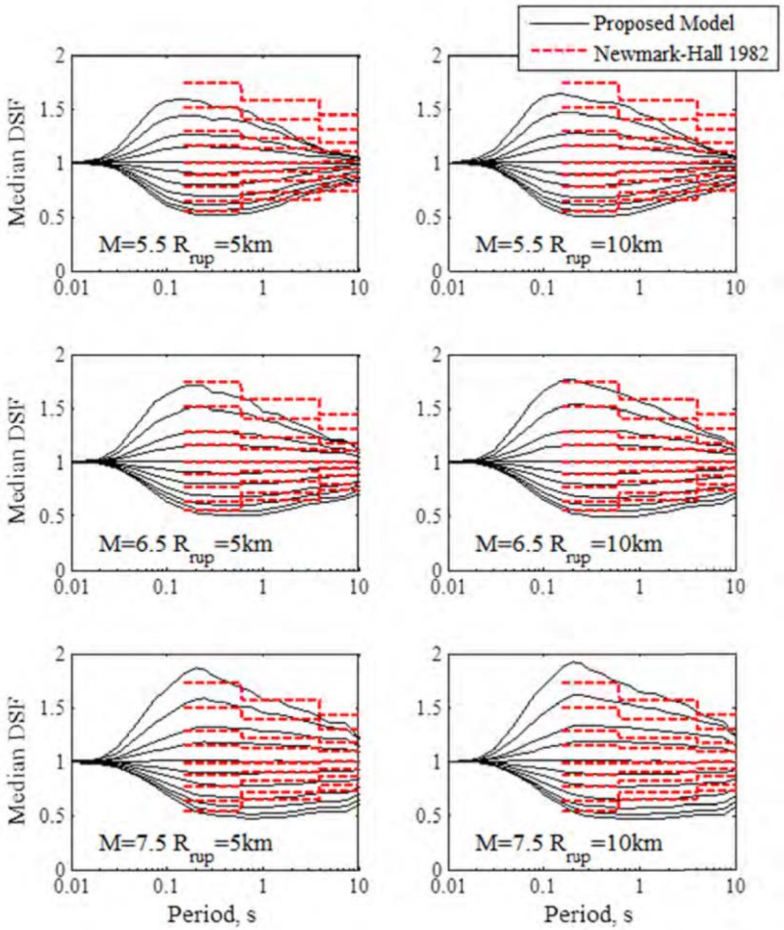


Figure 5.4 The proposed model is plotted for all 11 damping ratios from 0.5% to 30%. Newmark and Hall [1982] is applicable for $\beta \leq 20\%$ and T = 0.125–10 sec. It is plotted for β = 0.5, 1, 2, 3, 5, 7, 10, 15, and 20%, and is a not a function of M or R_{rup}.

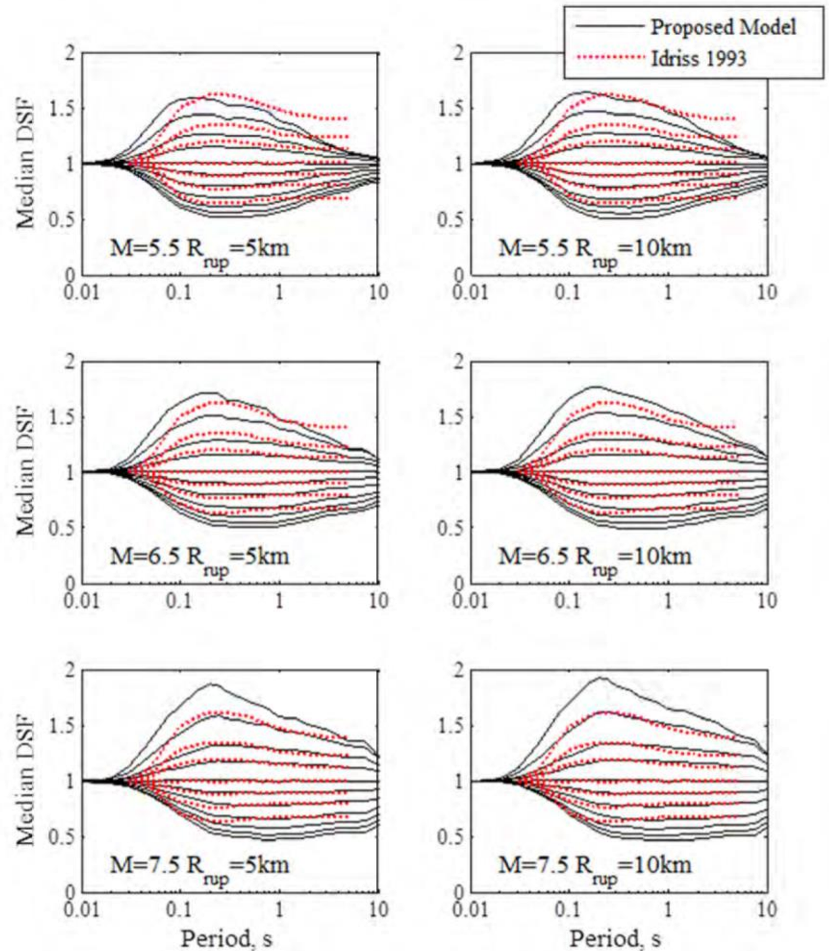


Figure 5.2 The proposed model is plotted for all 11 damping ratios from 0.5% to 30%. Idriss [1993] is plotted for β = 1, 2, 3, 5, 7, 10, 15%. It is applicable to T = 0.03–5 sec, and is not a function of M or R_{rup}.

"Proposed": Rezaeian and others (2012)

Published Studies of DSFs

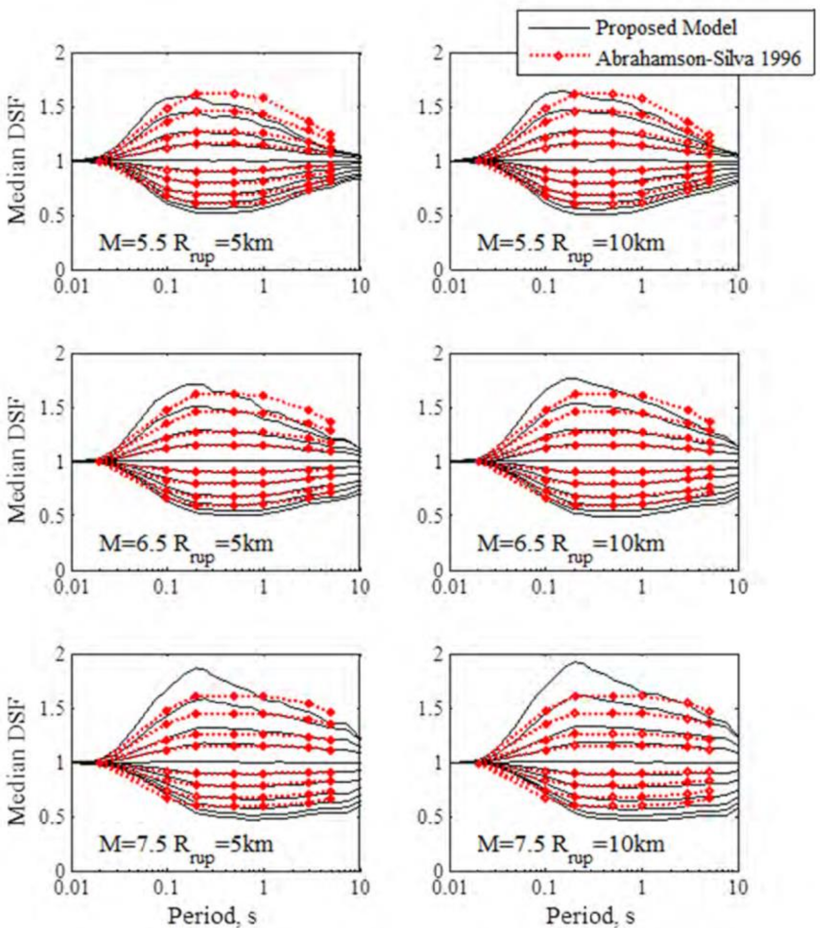


Figure 5.3 The proposed model is plotted for all 11 damping ratios from 0.5% to 30%. Abrahamson and Silva [1996] is plotted for β = 0.5, 1, 2, 3, 7, 10, 15, 20% at select periods and interpolated in-between. It is applicable to T = 0.02–5 sec, and is a function of M but not R_{rup}.

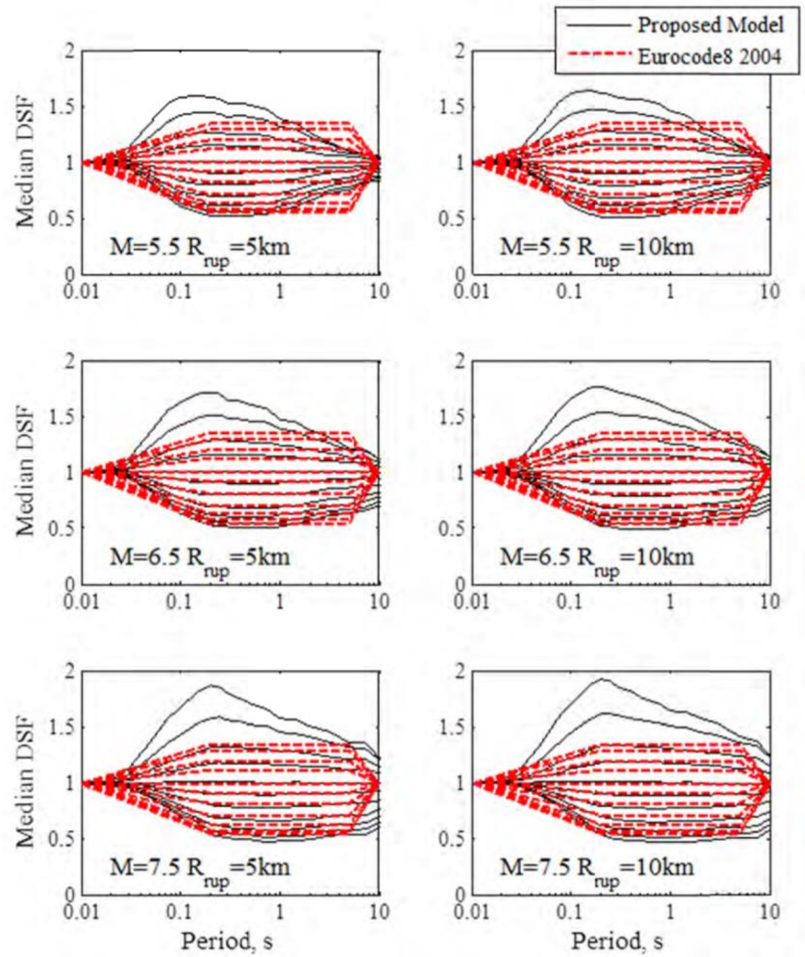


Figure 5.5 The proposed model and the model by Eurocode 8 [2004] are plotted for all 11 damping ratios from 0.5% to 30%. The model by Eurocode 8 [2004] is not a function of M or R_{rup}. This figure assumes very low and very high periods, where the model by Eurocode 8 is equal to unity, are 0.01 and 10 sec (10 sec is the value used by Bommer and Mendis [2005]).

“Proposed”: Rezaeian and others (2012)

Cameron and Green (2007)

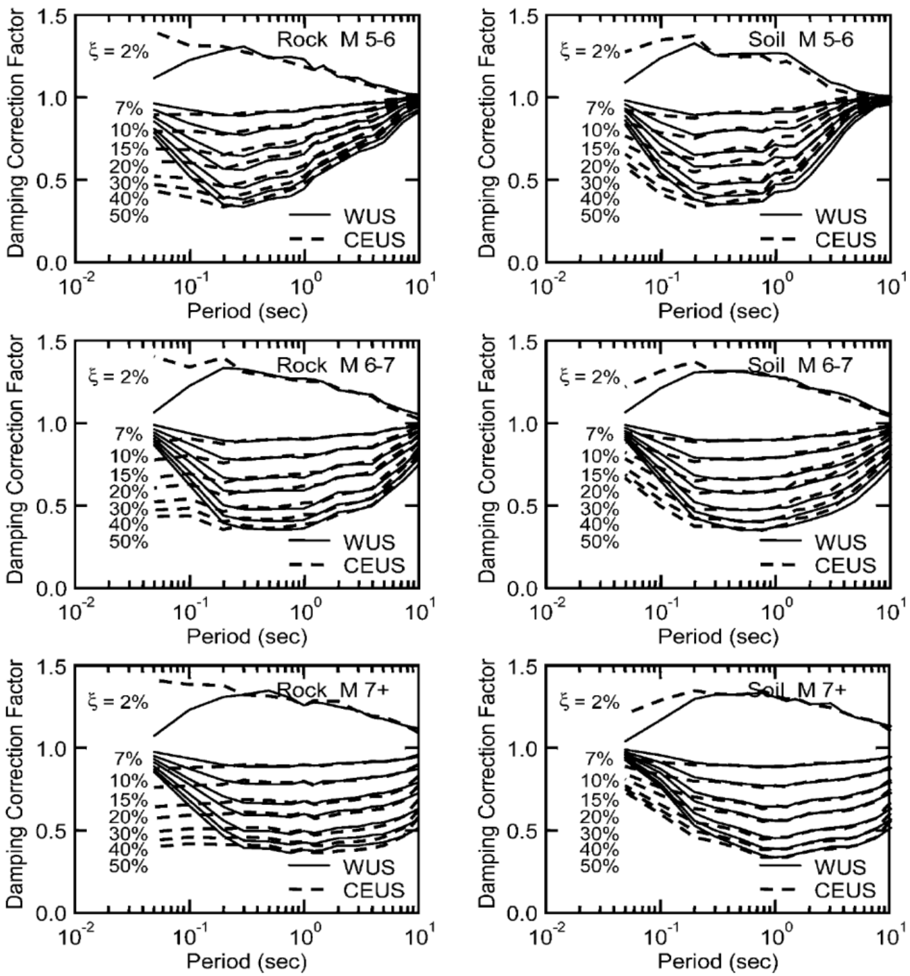


Figure 9. Median DCFs for ξ = 2, 7, 10, 15, 20, 30, 40, and 50% for *M* 5–6, *M* 6–7, and *M* 7+ for the WUS and CEUS for rock and soil site conditions (i.e., a replot of the data presented in Fig. 8 to facilitate a comparison of DCFs for CEUS and WUS motions).

Cameron and Green (2007)

DSFs as a function of:

- Magnitude
- Distance (ξ or β < 2%)
- WUS vs. CEUS
- Rock vs. Soil

Uses database of magnitude- and distance-binned WUS and CEUS earthquake time histories from NUREG/CR-6728

Cameron and Green (2007)

DSF(1%)	DSF(2%) to DSF(50%)
M5-6, 0-50 km	M5-6 only, no distance dependence
M5-6, 50-100 km	
M6-7, 0-50 km	M6-7 only, no distance dependence
M6-7, 50-200 km	
M7+, 0-50 km	M7+ only, no distance dependence
M7+, 50-200 km	

Unfortunately, the Cameron and Green paper does not present DSF functions for:

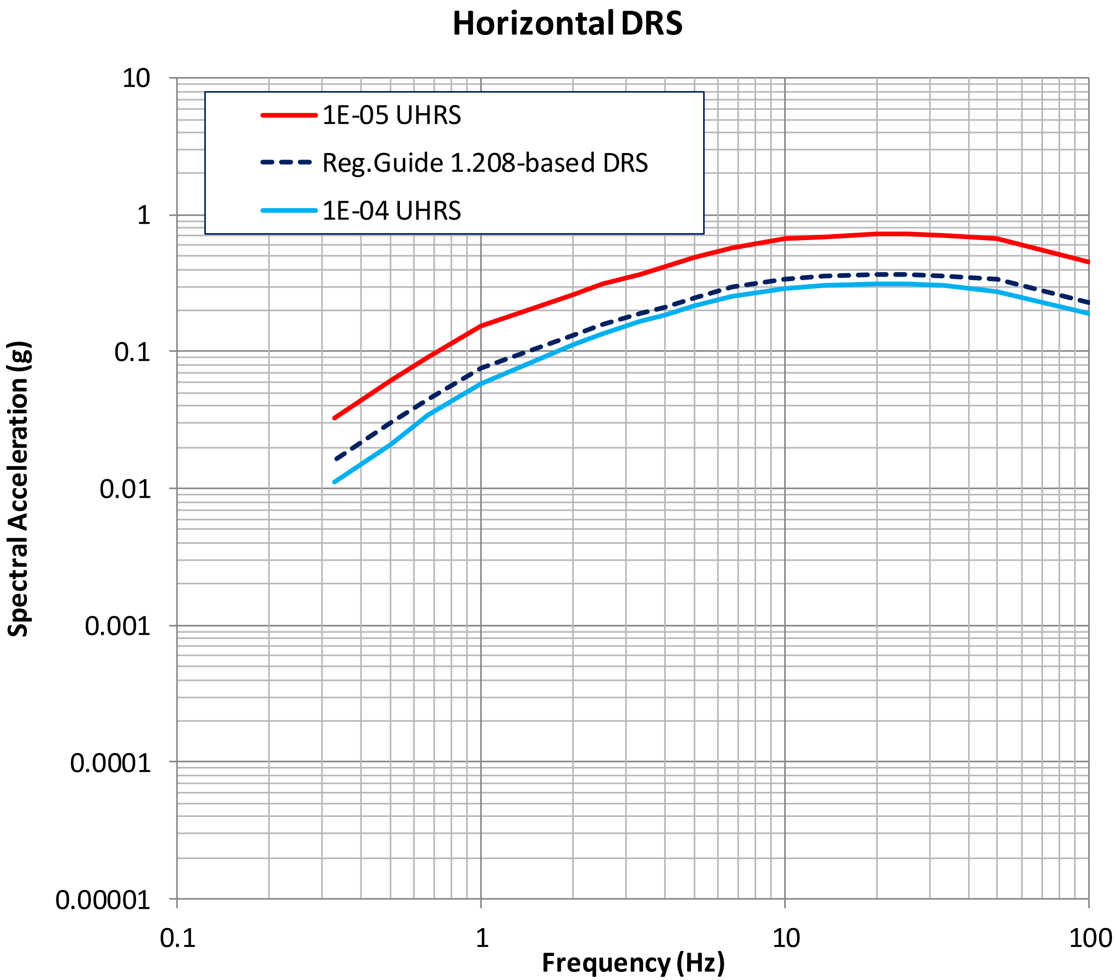
- Spectral frequencies greater than 20 Hz
- Specific damping levels required for our project, or
- DSF functions for vertical response spectra.

However, for our CEUS-like rock site, we use CG approach to process site hazard-specific M-D bins of NUREG time histories, addressing the elements not covered by CG paper.

Project Requirements

- Magnitudes and distances should be consistent with the controlling earthquakes from the project PSHA and the design response spectrum [DRS]
- Project site is a rock site in a stable continental region, like CEUS
- Both horizontal and vertical DSF functions should be considered
- DSFs should consider spectral frequencies of 0.1 to 100 Hz
- Explicit DSFs required: 1%, 2%, 3%, 4%, 7%, and 10%

Choice of NUREG Time Histories



From deaggregation analysis of the project PSHA, controlling earthquakes were determined as associated with the DRS:

10-4, LF: Mag 6.2 at 130 km
10-4, HF: Mag 5.7 at 25 km
10-5, LF: Mag 6.3 at 36 km
10-5, HF: Mag 5.8 at 18 km

NUREG/CR-6728 M&D-binned time histories initially considered in this calculation are:

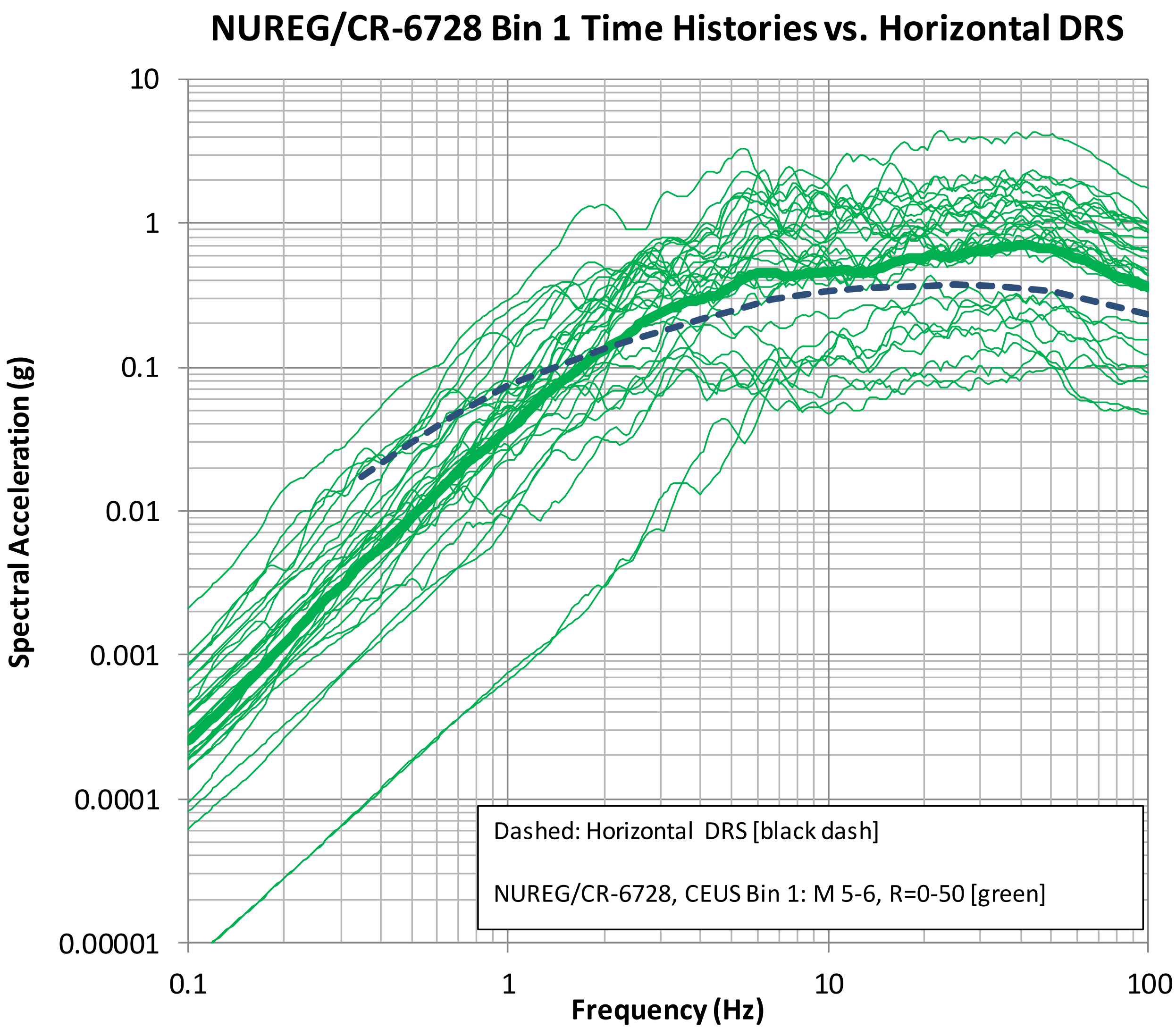
- Bin 1: M 5-6, R = 0-50 km
- Bin 2: M 6-7, R = 10-50 km
- Bin 3: M 6-7, R = 100-200 km

NUREG/CR-6728 Time Histories

NUREG/CR-6728 Time History Database: CEUS, M5-6, R0-50km, Rock [**Bin 1**]

Earthquake	**Year MMDD**	**Mag**	**Recording Station**	**Dist (km)**
Lytle Creek	1970 0912	5.4	Devil's Canyon	21.9
Lytle Creek	1970 0912	5.4	Wrightwood - 6074 Park Dr	15.4
Fruili, Italy	1976 0911	5.5	San Rocco	17.9
Santa Barbara	1978 0813	6.0	Cachuma Dam Toe	36.6
Livermore	1980 0127	5.4	APEEL 3E Hayward CSUH	31.0
Livermore	1980 0127	5.4	San Ramon - Eastman Kodak	17.6
Mammoth Lakes	1980 0611	5.0	USC Convict Lakes	9.1
Coalinga	1983 0709	5.2	Anticline Ridge Free-Field	11.0
Coalinga	1983 0709	5.2	Anticline Ridge Pad	11.0
Coalinga	1983 0709	5.2	Oil City	10.0
Coalinga	1983 0709	5.2	Transmitter Hill	10.4
Coalinga	1983 0722	5.8	Oil City	8.2
Coalinga	1983 0722	5.8	Palmer Ave	12.2
N. Palm Springs	1986 0708	6.0	Hurkey Creek Park	34.9
Whittier Narrows	1987 1001	6.0	Garvey Res. - Control Bldg	12.1

NUREG/CR-6728 Time Histories

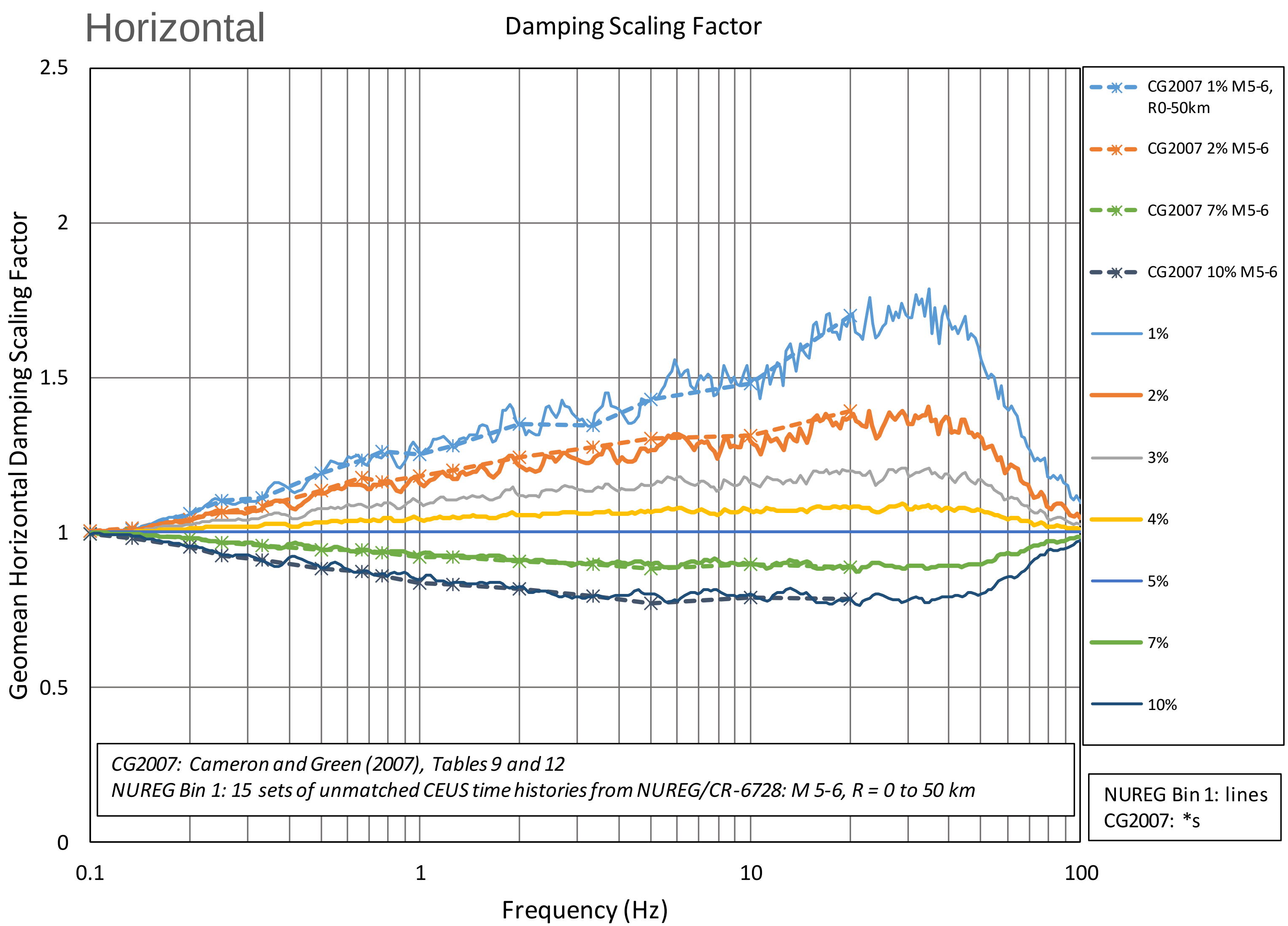


5% critical damping
No scaling applied

Similar comparisons for other bins suggested only two Bin sets of time histories needed further consideration:

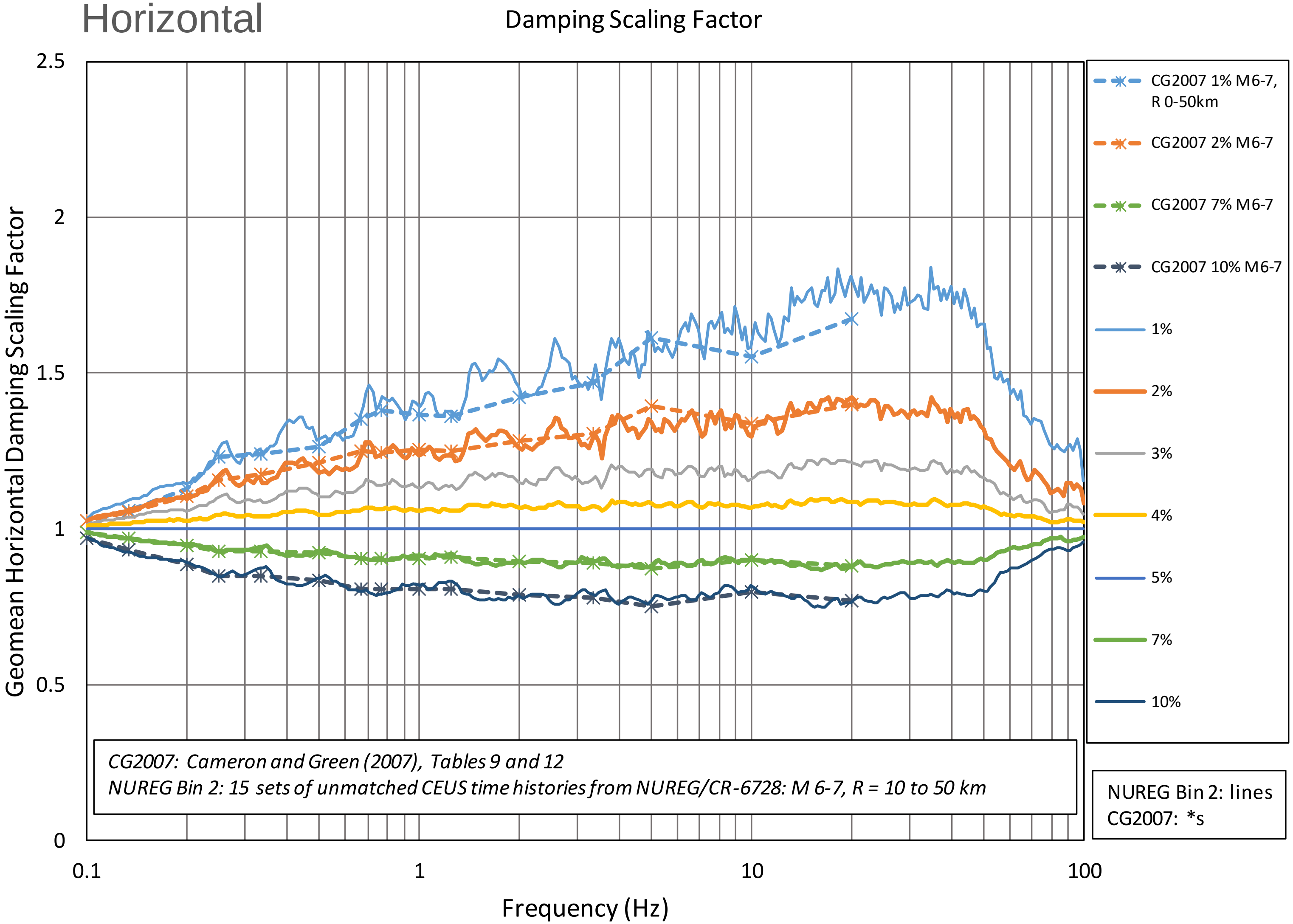
- Bin 1: M 5-6, R = 0-50 km
- Bin 2: M 6-7, R = 10-50 km

Bin 1: NUREG/CR-6728 Time Histories

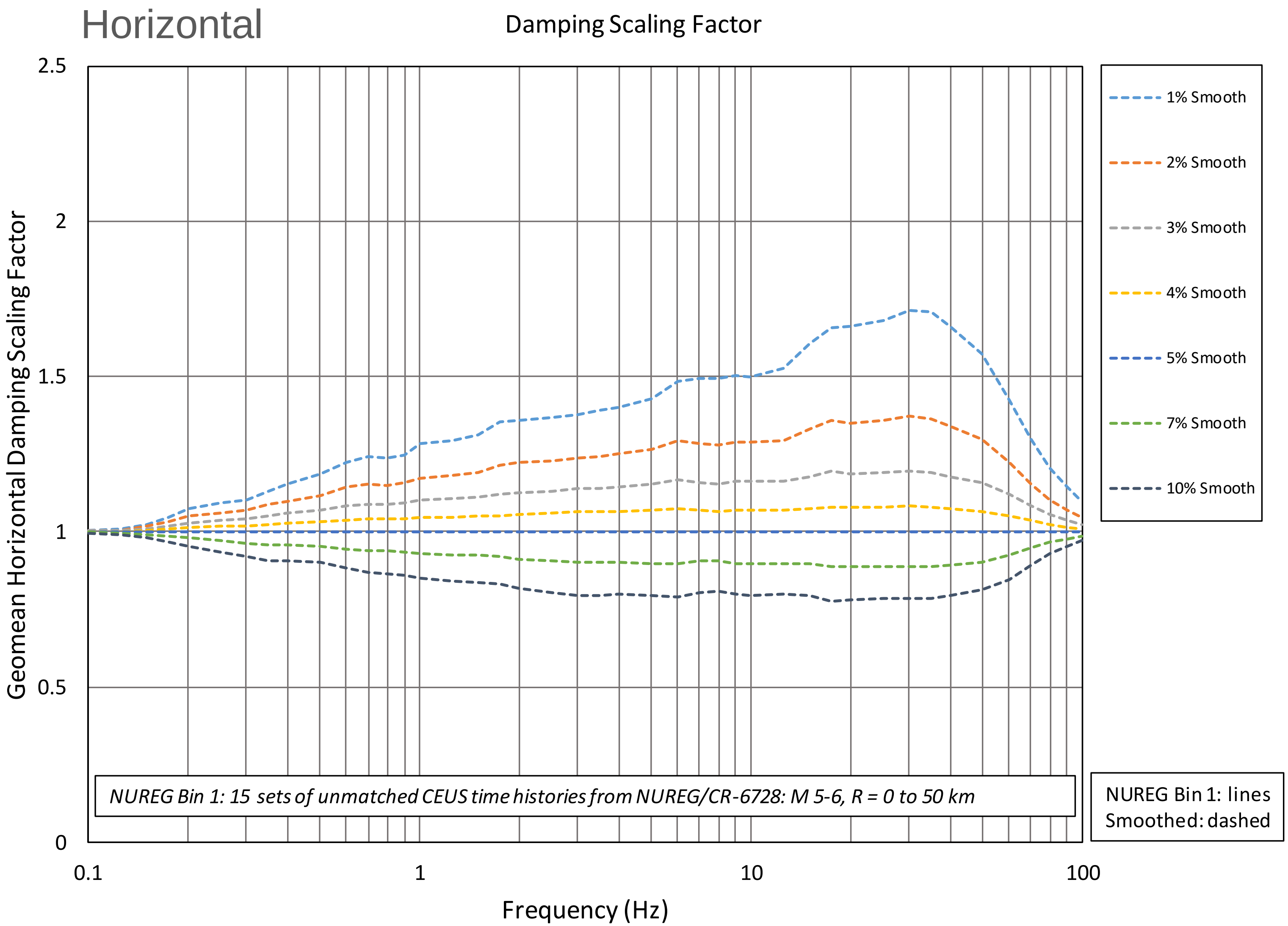


Bin 2: NUREG/CR-6728 Time Histories

Horizontal

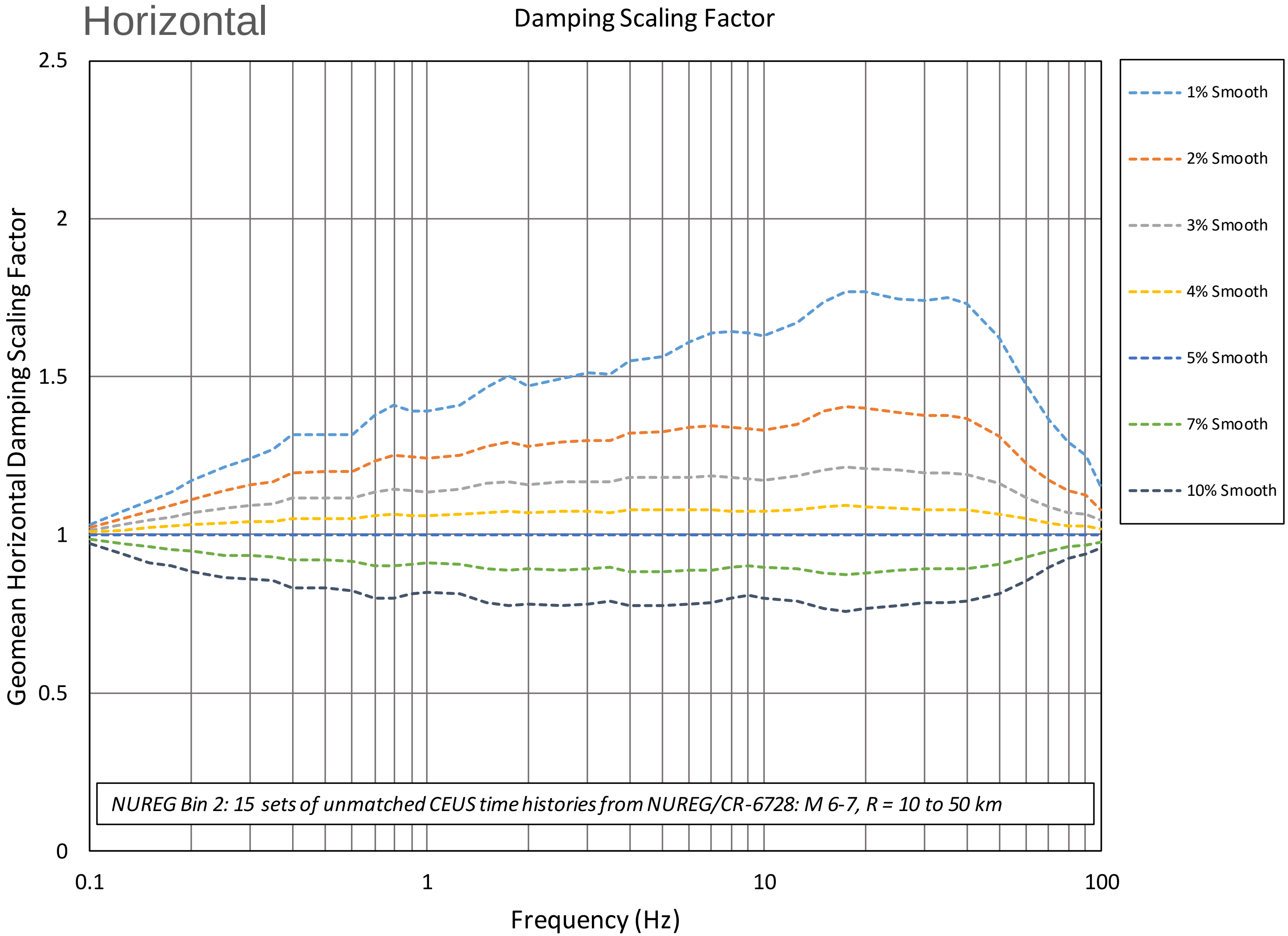


Bin 1: Initial Smoothed DSFs

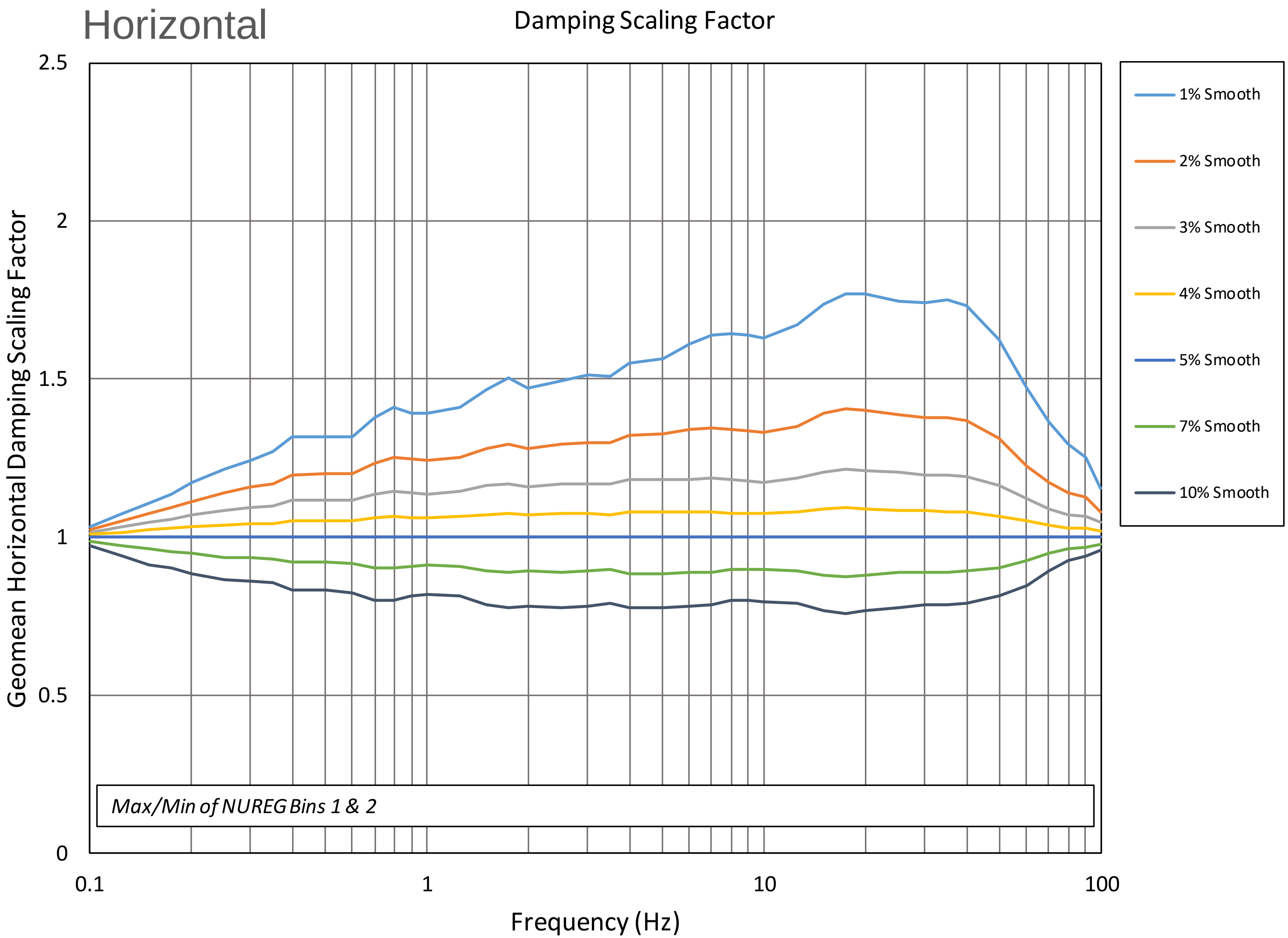


Bin 2: Initial Smoothed DSFs

Horizontal

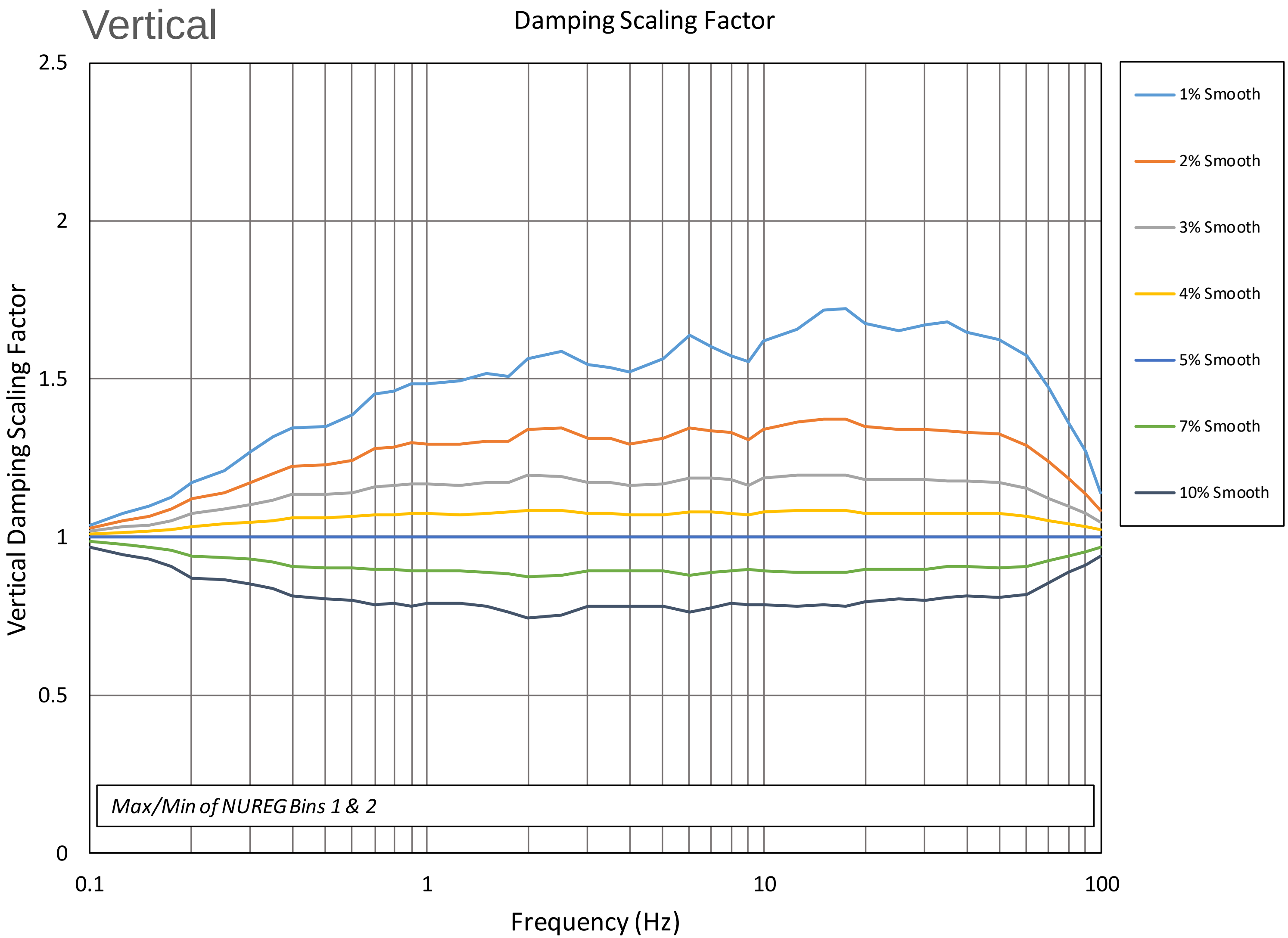


Smoothed DSFs: Min/Max Envelope

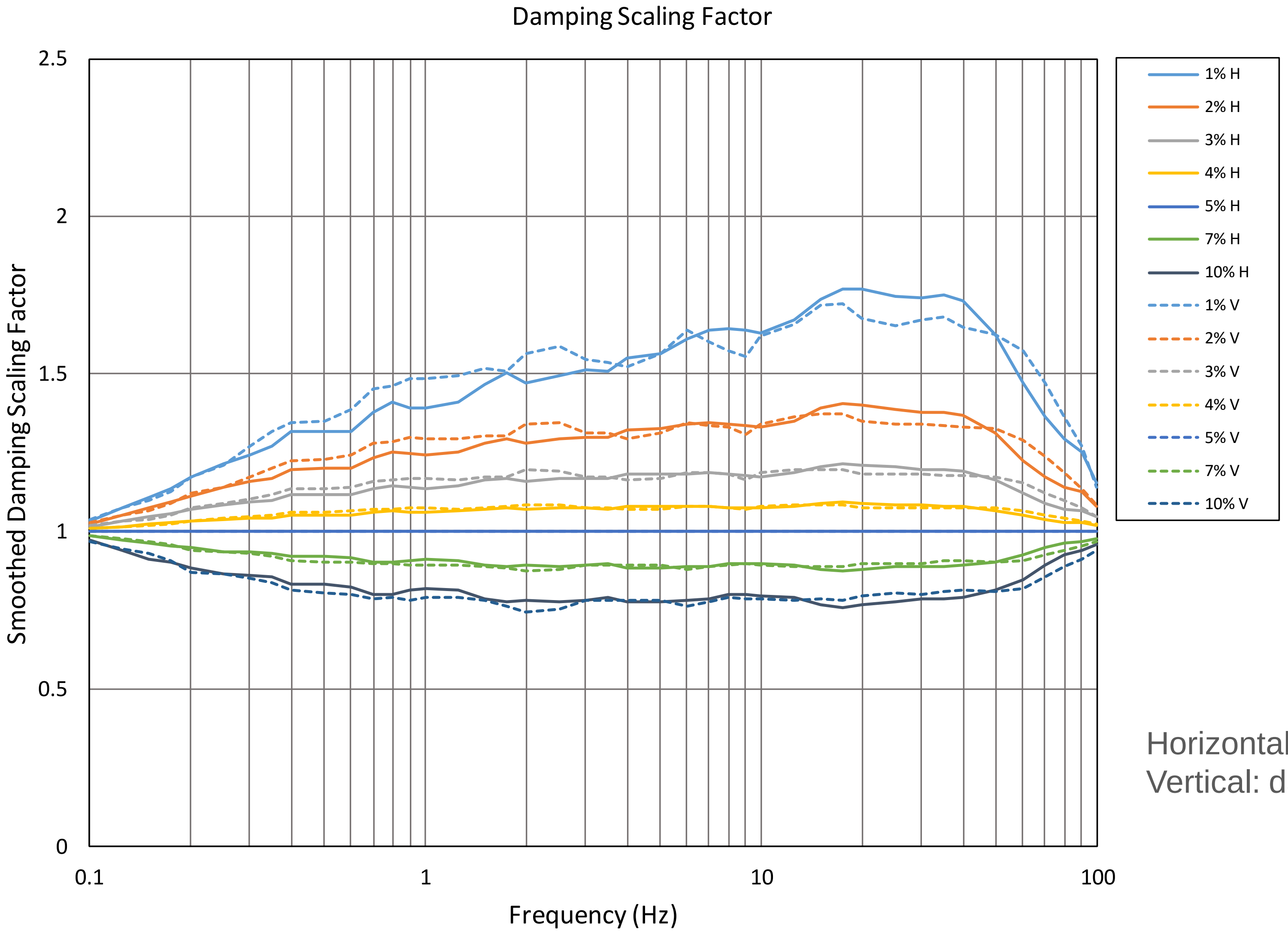


Smoothed DSFs: Min/Max Envelope

Vertical

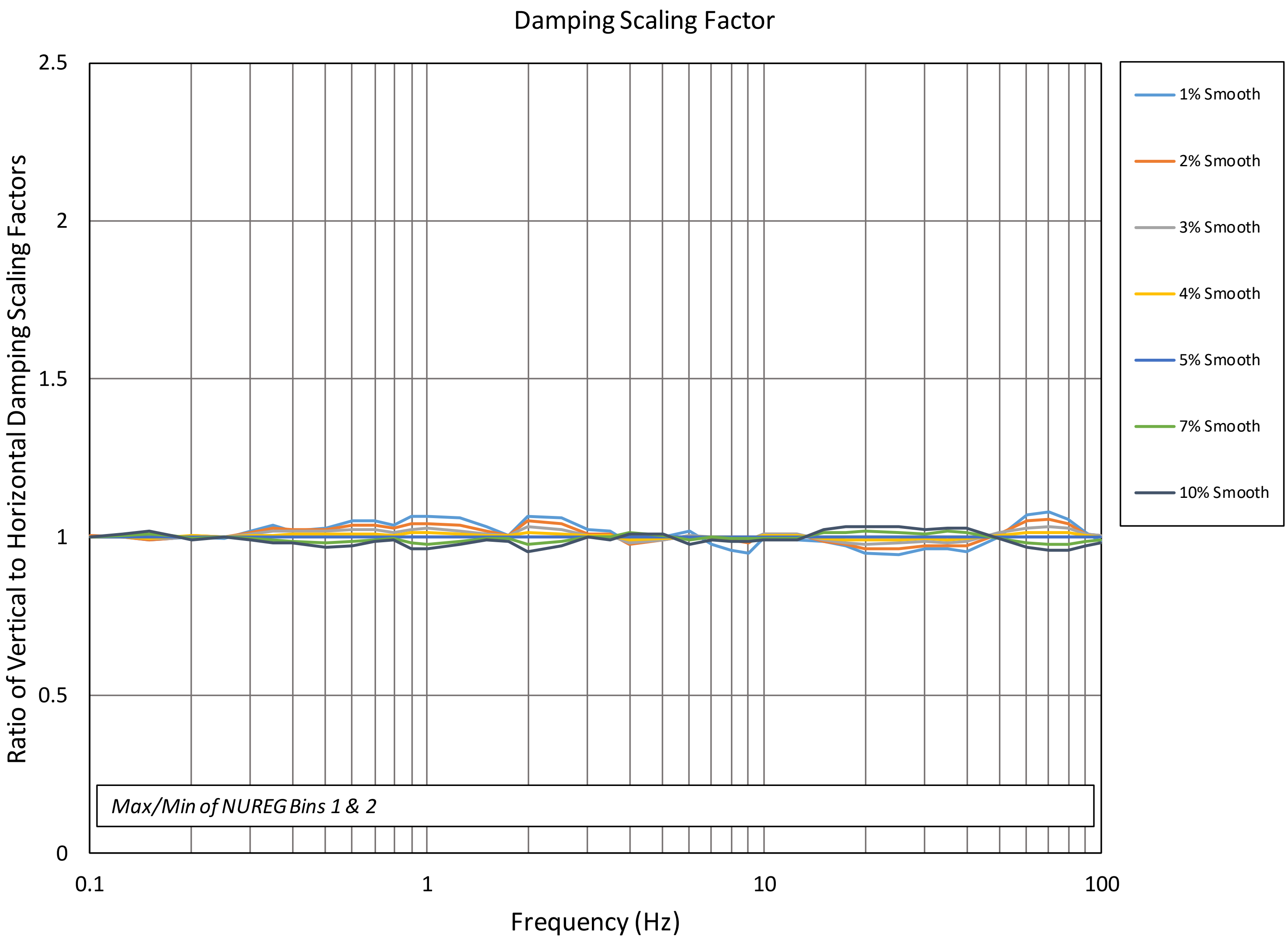


Smoothed DSFs: Min/Max Envelope

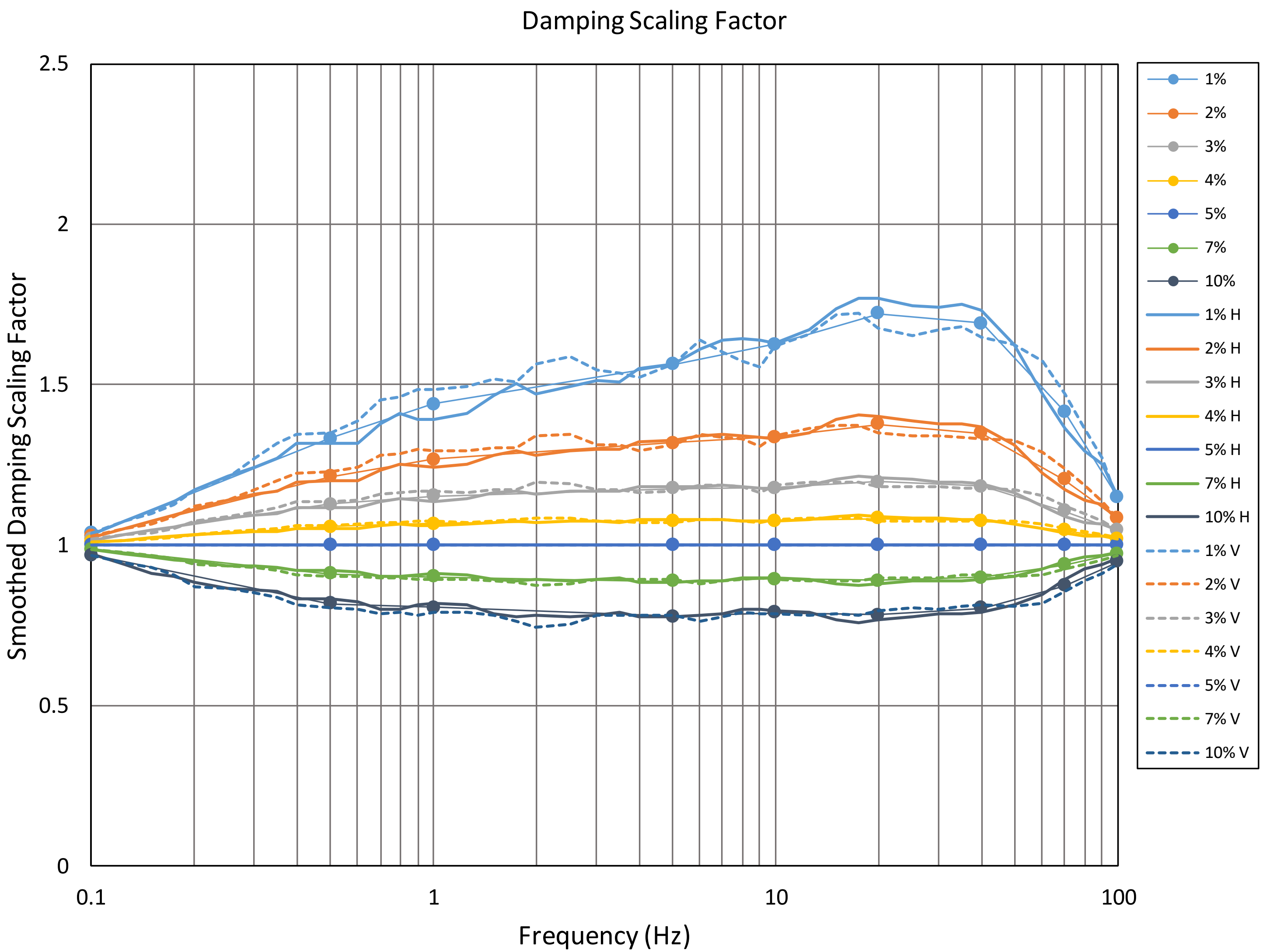


Horizontal: solid
Vertical: dashed

Ratio of Vert. to Hor. Smoothed DSFs

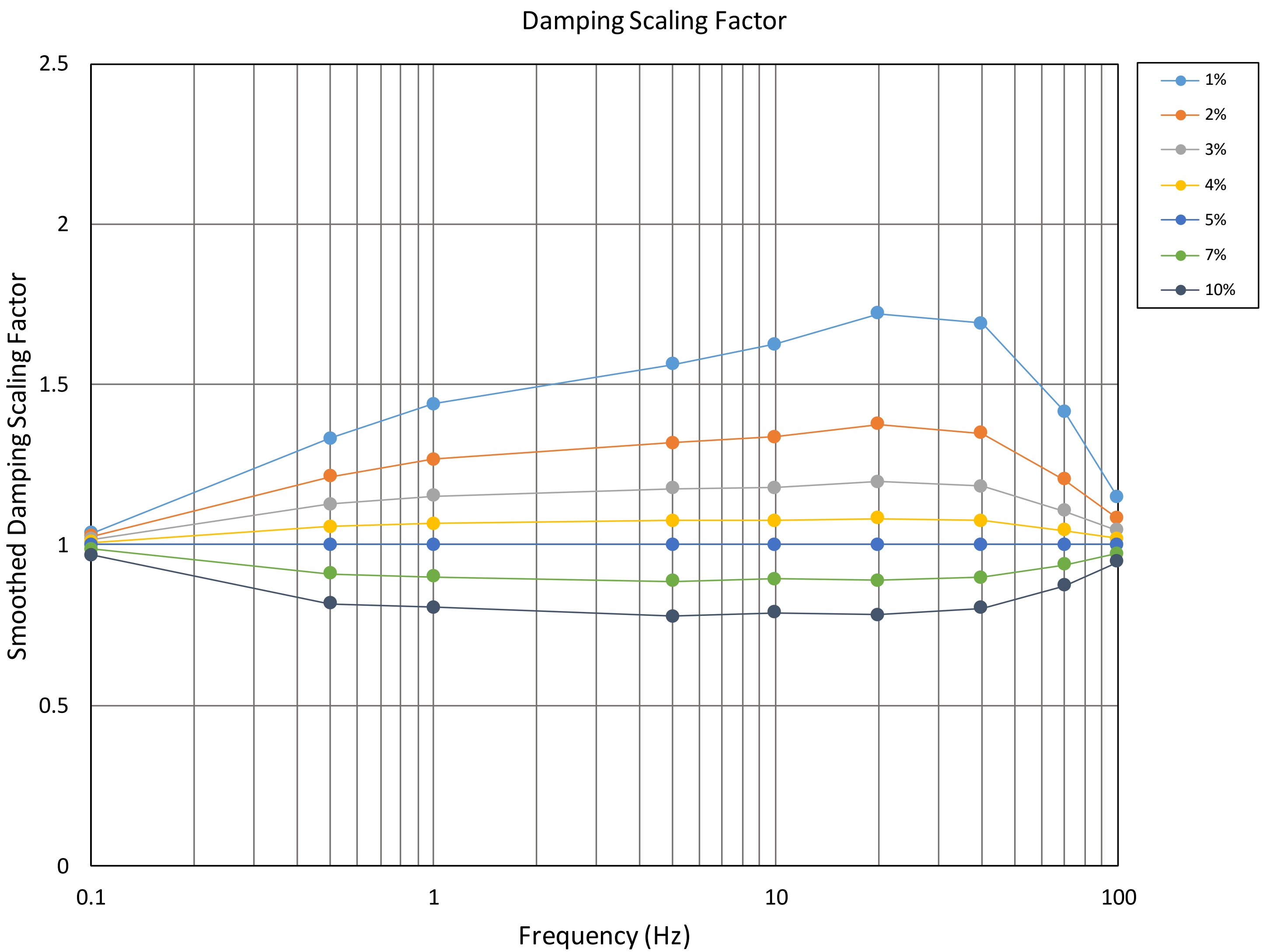


Final DSFs



Damping Scaling Factor
Smoothed Damping Scaling Factor
Frequency (Hz)
2.5
2
1.5
1
0.5
0
0.1
1
10
100
1%
2%
3%
4%
5%
7%
10%
1% H
2% H
3% H
4% H
5% H
7% H
10% H
1% V
2% V
3% V
4% V
5% V
7% V
10% V

Final DSFs


Damping Scaling Factor
Smoothed Damping Scaling Factor
2.5
2
1.5
1
0.5
0
0.1
1
10
100
Frequency (Hz)
1%
2%
3%
4%
5%
7%
10%

Summary

- Rezaeian and others (2012, 2014a, 2014b) provide a robust approach for DSFs as function of magnitude and distance for WUS type motion in active tectonic regions rich in low frequency. The approach is not applicable to CEUS which is rich in high frequency motion.

- DSFs presented for CEUS type motion can be used for scaling of the spectra rich in high frequency motion.