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ON THE DAMPING ADJUSTMENT FACTORS FOR EARTHQUAKE RESPONSE SPECTRA

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SUMMARY

Damping adjustment factors for converting 5%-damped earthquake response spectra to other damping levels are evaluated in this paper. The evaluation is based on statistical analysis of spectra of 1047 horizontal components of earthquake ground shaking recorded between 1933 and 1994. The dependency of damping adjustment factors to response period is studied. Results of the evaluation are compared to the damping adjustment factors embodied in the current seismic design code provisions and guidelines which are based on the spectrum amplification factors of Newmark and Hall. Copyright © 2001 John Wiley & Sons, Ltd.

INTRODUCTION

The universal popularity of response spectrum analysis technique in contemporary earthquake engineering is, in no small part, due to the pioneering contributions of Newmark and Hall as summarized in the monograph *Earthquake Spectra and Design* (Newmark and Hall, 1982). Not only did these researchers develop one of the first systematic methods for construction of elastic and inelastic design spectra; they also provided the basis for adjusting 5%-damped spectra to other levels of damping. The spectrum amplification factors of Newmark and Hall are based on 28 accelerograms. These accelerograms represented a fairly complete set of strong motion records at the time of their study. More than two decades have passed since Newmark and Hall introduced their techniques for construction of design spectra and a much larger set of earthquake records is now available. During this same period, energy dissipating devices (dampers) and seismic isolation systems have become more popular, and performance-based design approaches have been developed, such as the capacity spectrum method, that require response spectra at higher damping levels. It is time to critically reevaluate the damping adjustment factors embodied in the contemporary code provisions and based on spectrum amplification factors of Newmark and Hall.

Damping factors contained in current seismic code provisions such as the 1997 Uniform Building Code (UBC; see ICBO, 1997) and the 2000 International Building Code (IBC; see ICC, 1999) have the following basic form:

$$R_x = \frac{R_5}{B} \tag{1}$$

where R_x and R_5 are the spectral ordinates of the x% and 5% damped design spectrum at a given

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period, respectively, and B is the corresponding damping adjustment factor. In the balance of this paper, the term 'damping adjustment factor' refers to the variable B in Equation (1).

This paper statistically evaluates damping adjustment factors based on ratios of response spectra of more than 1000 horizontal components of earthquake ground shaking recorded between 1933 and 1994. These components are selected from magnitude database of earthquake records from North American, Alaskan, and Hawaijan Island events that represent events of engineering significance [magnitude $M \geq 5{\cdot}0$; peak ground acceleration (PGA) $\geq 0{\cdot}05$ (g)]. (see Naeim and Anderson, 1996)

ADJUSTMENT FACTORS USED IN CURRENT PRACTICE

Damping adjustment factors of current seismic code provisions are based on ratios of median spectrum amplification factors of Newmark and Hall (1982, table 2). Newmark and Hall formulae for spectrum amplification distinguish between domains of constant acceleration, constant velocity and constant displacement. The first set of seismic code damping adjustment factors appeared in the 1991 UBC (ICBO, 1991) and applied only to base-isolated buildings. Since these buildings have long periods (e.g. 2–3 s), these factors were based on the spectrum amplification factors of the velocity domain. More recently, the Seismic Evaluation and Retrofit of Concrete Buildings (ATC, 1996) and the National Earthquake Hazard Reduction Program (NEHRP) Guidelines for Seismic Rehabilitation of Buildings (FEMA, 1997) expanded the damping reduction factors to include factors appropriate for both the velocity domain (B_L or B_1) and the acceleration domain (B_S) (where B_L, B_1 and B_S are the long-period, 1-s and short-period damping coefficients; respectively). Acceleration-domain damping reduction factors were required for design of short-period buildings with damper systems and for nonlinear pushover analysis of buildings using the capacity-spectrum method (ATC, 1996).

Table 1 summarizes damping adjustment factors for various damping levels based on the median spectrum amplification factors of Newmark and Hall. Factors are shown separately for the displacement, velocity and acceleration domains. For each domain, the spectrum amplification factor is 1·0 for 5% damping since damping reduction factors are normalized to 5%-damped spectral response.

Trends in the factors of Table 1 indicate that for a given level of damping (above 5%) the effect of damping increases as the period decreases. That is, the damping reduction factors increase as the period shifts from the displacement domain to the velocity domain and from the velocity domain to the acceleration domain. Recognizing that the number of cycles of response generally increases as the response period decreases provides a physical explanation of this trend. For example, during 10 s of strong shaking a 2-s system would have only a few cycles of significant response, whereas a 0·2-s

Table 1. Damping adjustment factors based on median spectrum amplification factors of Newmark and Hall (1982)

Percentage critical damping	Damping adjustment factor		
	Displacement domain	Velocity domain	Acceleration domain
2	0·85	0·81	0·77
5	1·00	1·00	1·00
10	1·16	1·21	1·29
20	1·37	1·53	1·80
30	1·54	1·80	2·36
40	1·68	2·07	3·02
50	1·81	2·34	3·85

Table 2. Damping adjustment factors of the NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA, 1997, Table 2·15)

Percentage of critical damping	Damping coefficient	
	B_1	B_s
≤ 2	0·8	0·8
5	1·0	1·0
10	1·2	1·3
20	1·5	1·8
30	1·7	2·3
40	1·9	2·7
≥ 50	2·0	3·0

Note: B_1, 1-s damping coefficient; B_s, short-period damping coefficient.

system would experience many cycles of significant response. Since damping is generally more effective as the number of cycles increases, the increase in damping reduction factors with decreases in period seems reasonable.

The damping coefficient (B), first used in the 1991 UBC, was based on the 1990 'Blue Book'. *Recommended lateral Force Requirements and Commentary*, of the structural Engineers Association of California (SEAOC, 1990). The 1990 'Blue Book' was, in turn, based on the original source of damping reduction factors, *Tentative Seismic Isolation Design Requirements* (SEAONC, 1986), the first published set of design requirements for base-isolated structures (Kircher, 1986). Since 1994, the NEHRP Provisions (FEMA, 1995) have used the same damping coefficients as those of the UBC, and the 2000 IBC, which is based on the 1997 NEHRP Provisions (FEMA, 1998), will also use the same damping coefficients.

Table 2 summarizes damping reduction factors (damping coefficients) of the NEHRP Guidelines (FEMA, 1997). These damping coefficients distinguish between short-period response reduction (B_S) which applies to the acceleration domain and the 1-s response (B_1), which applies to the velocity domain. The damping coefficient, B_1, which applies to the velocity domain, is identical to the damping coefficient (B) of the UBC and IBC for design of structures with base-isolation systems.

The damping coefficients of the NEHRP Guidelines (and other seismic codes) shown in Table 2 are essentially the same as the damping reduction factors of Newmark and Hall shown in Table 1 for damping levels up to about 20%. At higher levels of damping, the coefficients tend to be somewhat less (and a bit more conservative) than the reduction factors of Newmark and Hall. Code and guideline development groups, dating to the time of original work of the Structural Engineers Association of Northern California (SEAONC) in the mid-1980s purposely chose conservative coefficients for design of buildings with a very highly damped isolation or damper system.

PROGRAM OF INVESTIGATION

Pseudo-acceleration (PSA) response spectra corresponding to 2%, 5%, 10% and 20% of critical damping were calculated for 1046 horizontal components from events shown in Table 3.

Distribution of magnitude, peak ground acceleration, velocity and displacement among the selected accelerograms are summarized in Tables 4 to 7, respectively. Spectral ordinates were calculated at 0·1-s, 0·3-s, 0·5-s, 0·75-s, 1·0-s, 1·5-s, 2·0-s, 3·0-s and 4·0-s periods. Post-1987 spectral ordinates were read from the Volume 3 processed files supplied by the California Division of Mines and Geology

Table 3. Earthquakes (EQs) contributing records to this study

EQ			Epicenter				Cumulative		Cumulative
no.	Year	Earthquake name	latitude	longitude	Magnitude	Count	count	Percentage	percentage
1	1933	Long Beach, CA	33·617	−117·967	6·3	4	4	0·38	0·38
2	1938	NW California	40·300	−124·800	5·5	2	6	0·19	0·57
3	1941	Santa Barbara, CA	34·367	−119·583	5·9	2	8	0·19	0·76
4	1941	Northern California	40·600	−124·600	6·4	2	10	0·19	0·96
5	1949	Western Washington	47·100	−122·700	7·1	4	14	0·38	1·34
6	1952	Kern County, CA	35·000	−119·033	7·4	6	20	0·57	1·91
7	1954	Wheeler Ridge, CA	35·000	−119·017	5·9	2	22	0·19	2·10
8	1954	Northern California	40·820	−124·080	6·5	4	26	0·38	2·49
9	1955	San Jose, CA	37·370	−121·780	5·8	2	28	0·19	2·68
10	1961	Hollister, CA	36·700	−121·300	5·5	4	32	0·38	3·06
11	1965	Puget Sound, WA	47·400	−122·300	6·5	4	36	0·38	3·44
12	1966	Parkfield, CA	35·900	−120·900	6·1	8	44	0·76	4·21
13	1967	Northern California	40·500	−124·600	5·8	2	46	0·19	4·40
14	1968	Borrego Mountain, CA	33·150	−116·133	6·7	2	48	0·19	4·59
15	1971	San Fernando, CA	34·400	−118·395	6·6	130	178	12·43	17·02
16	1972	Managua, Nicaragua	12·400	−86·100	6·2	2	180	0·19	17·21
17	1973	Honolulu, Hawaii	19·930	−155·100	6·0	2	182	0·19	17·40
18	1975	Northern California	40·570	−124·140	5·7	6	188	0·57	17·97
19	1975	Island of Hawaii	19·350	−155·060	5·7	6	194	0·57	18·55
20	1978	Santa Barbara, CA	34·370	−119·717	5·5	4	198	0·38	18·93
21	1979	Southern Alaska	60·640	−141·590	7·3	4	202	0·38	19·31
22	1979	Coyote Lake, CA	37·110	−121·530	5·7	18	220	1·72	21·03
23	1979	Imperial Valley, CA	32·640	−115·309	6·5	32	252	3·06	24·09
24	1980	Livermore, CA	37·827	−121·787	5·9	2	254	0·19	24·28
25	1980	Anza, CA	33·501	−116·510	5·5	8	262	0·76	25·05
26	1980	Mammoth Lakes, CA	37·609	−118·847	6·5	3	265	0·29	25·33
27	1980	Mammoth Lakes, CA	37·506	−118·826	6·3	6	271	0·57	25·91
28	1980	Mammoth Lakes, CA	37·464	−118·823	6·3	2	273	0·19	26·10
29	1980	Mammoth Lakes, CA	37·464	−118·823	6·3	12	285	1·15	27·25
30	1980	Trinidad, CA (offshore)	41·117	−124·253	7·2	2	287	0·19	27·44
31	1981	Westmoreland, CA	33·130	−115·650	5·6	12	299	1·15	28·59
32	1983	Coalinga, CA	36·230	−120·290	6·7	91	390	8·70	37·28
33	1983	Hawaii	19·433	−155·450	6·6	28	418	2·68	39·96
34	1984	Morgan Hill, CA	37·310	−121·680	6·2	57	475	5·45	45·41
35	1985	Nahanni, NWT, Canada	62·020	−124·130	5·7	10	485	0·96	46·37
36	1986	Hollister, CA	36·800	−121·280	5·5	10	495	0·96	47·32
37	1986	Mt. Lewis, CA	37·466	−121·691	5·8	2	497	0·19	47·51
38	1986	North Palm Springs, CA	33·970	−116·610	5·9	53	550	5·07	52·58
39	1986	Chalfant Valley, CA	37·544	−118·443	6·0	2	552	0·19	52·77
40	1987	Whittier, CA	34·062	118·078	6·1	72	624	6·88	59·66
41	1989	Loma Prieta, CA	37·037	121·883	7·1	82	706	7·84	67·50
42	1991	Sierra Madre, CA	34·262	118·002	5·8	10	716	0·96	68·45
43	1992	Petrolia, CA	40·370	124·310	6·9	12	728	1·15	69·60
44	1994	Northridge, CA	34·209	118·541	6·8	318	1046	30·40	100·00

Table 4. Event magnitudes represented by the records

Magnitude range	Record count	Cumulative count	Percentage of population
$5{\cdot}0 < M \leq 5{\cdot}5$	28	28	2·7
$5{\cdot}5 < M \leq 6{\cdot}0$	119	147	11·4
$6{\cdot}0 < M \leq 6{\cdot}5$	179	326	17·1
$6{\cdot}5 < M \leq 7{\cdot}0$	616	942	58·9
$7{\cdot}0 < M \leq 7{\cdot}5$	104	1046	9·9

Table 5. Distribution of peak ground acceleration (PGA) in the database

PGA (cm s^{-1} s^{-1})	Record count	Cumulative count	Percentage of population
$50 < \text{PGA} \leq 200$	778	778	74·4
$200 < \text{PGA} \leq 400$	197	975	18·8
$400 < \text{PGA} \leq 600$	54	1029	5·2
$600 < \text{PGA} \leq 800$	10	1039	0·9
$800 < \text{PGA} \leq 1000$	5	1044	0·5
$1000 < \text{PGA} \leq 1200$	1	1045	0·1
$1200 < \text{PGA} \leq 1400$	0	1045	0·0
$1400 < \text{PGA} \leq 1600$	1	1046	0·1

Table 6. Distribution of peak ground velocities (PGVs) in the database

PGV (cm s^{-1})	Record count	Cumulative count	Percentage of population
$0 < \text{PGV} \leq 20$	795	795	76·0
$20 < \text{PGV} \leq 40$	179	974	17·1
$40 < \text{PGV} \leq 60$	48	1022	4·6
$60 < \text{PGV} \leq 80$	14	1036	1·3
$80 < \text{PGV} \leq 100$	5	1041	0·5
$100 < \text{PGV} \leq 120$	3	1044	0·3
$120 < \text{PGV} \leq 140$	2	1046	0·2

Table 7. Distribution of peak ground displacements (PGDs) in the database

PGD (cm)	Record count	Cumulative count	Percentage of population
$0 < \text{PGD} \leq 10$	880	880	84·1
$10 < \text{PGD} \leq 20$	128	1008	12·2
$20 < \text{PGD} \leq 30$	17	1025	1·6
$30 < \text{PGD} \leq 40$	15	1040	1·5
$40 < \text{PGD} \leq 50$	3	1043	0·3
$50 < \text{PGD} \leq 60$	0	1043	0·0
$60 < \text{PGD} \leq 70$	3	1046	0·3

(CDMG). Pre-1987 spectral ordinates were calculated using the BAP software (Converse *et al.*, 1993) using the time histories processed elsewhere (Naeim and Anderson, 1996).

For each record, the PSA spectral amplitudes at distinct periods for 5%-damped spectrum were divided by the corresponding value for other damping levels to obtain the adjustment factor. These ratios were then tabulated and used in a statistical analysis to evaluate the mean values and standard deviation of adjustment values and their frequency dependence.

EVALUATION OF RESULTS

The damping adjustment factors (*B*) for 2% damping are shown in Figure 1. Each circle identifies the adjustment factor obtained from a single accelerogram for a distinct period of vibration. The line representing the best linear regression is also shown. As may be observed from Figure 1, the scatter in the data is relatively large. The mean values of the adjustment factors are essentially independent of the period of vibration as indicated by the small slope of the regression curve. The mean value of the adjustment factor across the period range of 0·1–4·0 s is 0·81, which is very close to the code suggested value of 0·80 (see Table 2). Results for 10% and 20% damping ratios are shown in Figures 2 and 3, respectively. Here again, the data scatter is relatively large and the trend of the mean values is a very weak function of response period. The mean value of the adjustment factor for 10% damping is 1·23: again very close to the code suggested value of 1·2. The mean value suggested by the data for 20% damping, 1·62, is about 8% larger than the code suggested value of 1·5. A summary of the statistics for the distribution of adjustment factors as suggested by the data is presented in Table 8. A graphical presentation of these statistics is shown in Figure 4.

CONCLUSIONS AND RECOMENDATIONS

Contrary to the damping coefficients of current codes and the spectrum amplification factors of Newmark and Hall (1982), the results of this study do not support assigning significantly different

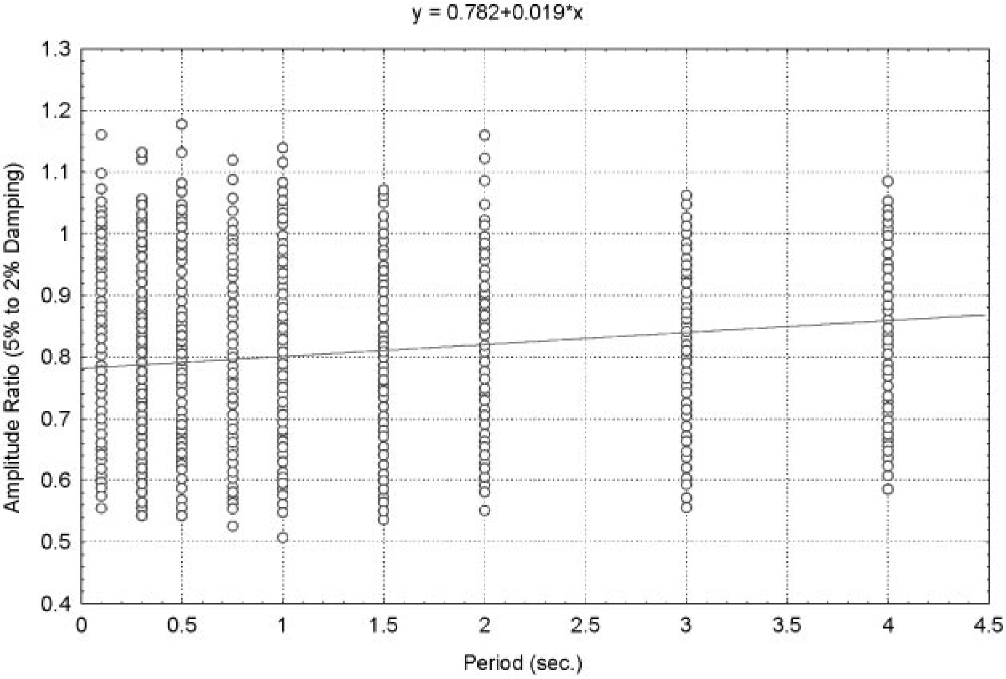

Figure 1. Damping adjustment factors for 2% damping

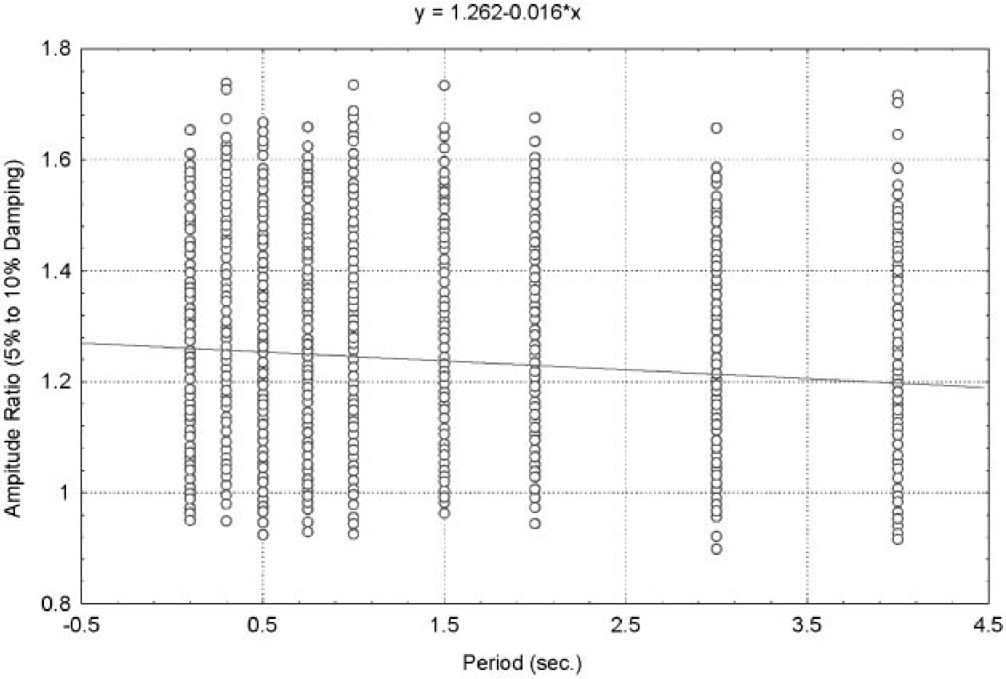

Figure 2. Damping adjustment factors for 10% damping

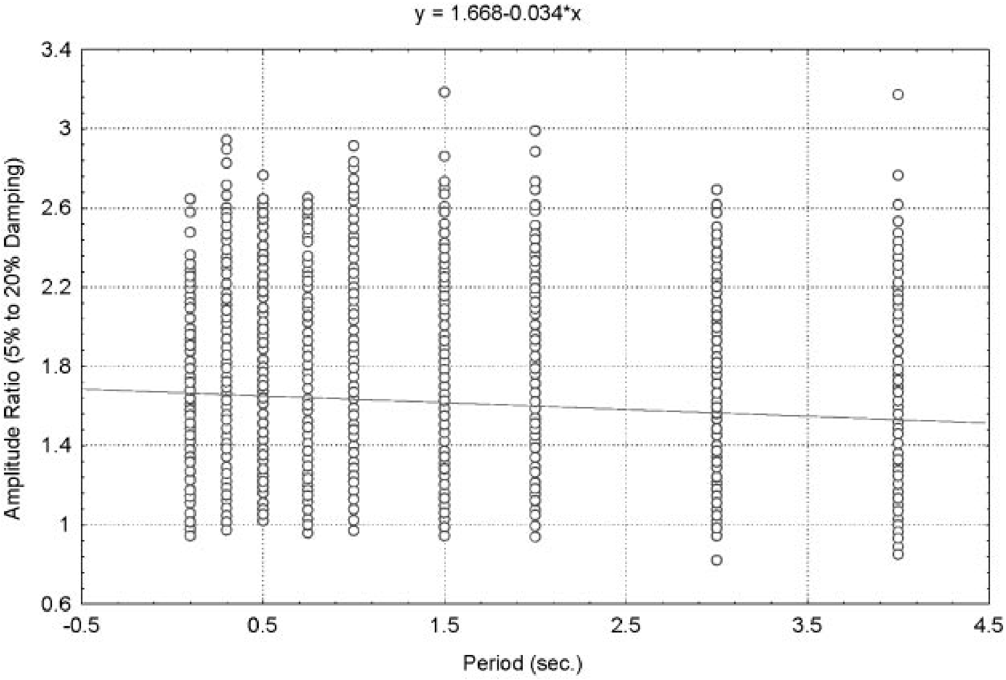

Figure 3. Damping adjustment factors for 20% damping

Table 8. Statistical distribution of damping adjustment factors

Damping (% critical)	Mean value	Standard deviation
2	0·809	0·0987
10	1·239	0·1331
20	1·619	0·3383

damping adjustment factors to acceleration and velocity domains of response spectra. Arguably, the trend of mean values is the same–increase in damping reduction (for damping greater than 5%) with decrease in response period. However, the amount of change in the mean value of damping reduction factor found by this study is negligible considering the large scatter in the underlying data. An explanation for the difference in results of this study and previous work by Newmark and Hall cannot be made. However, the fact that the database of records used in this study was about 20 times larger than that of Newmark and Hall would suggest that results need not be the same.

Damping adjustment factors included in the current seismic design codes and guidelines, such as the 1997 UBC (ICBO, 1997) and NEHRP Guidelines (FEMA, 1997), for design of long-period (velocity domain) structures are accurate at lower levels of damping and slightly conservative at higher levels of damping. It appears that for evaluation of structures with higher (≥20%) damping slightly more liberal values of the damping adjustment factor could be used. However, the results of this study are limited to

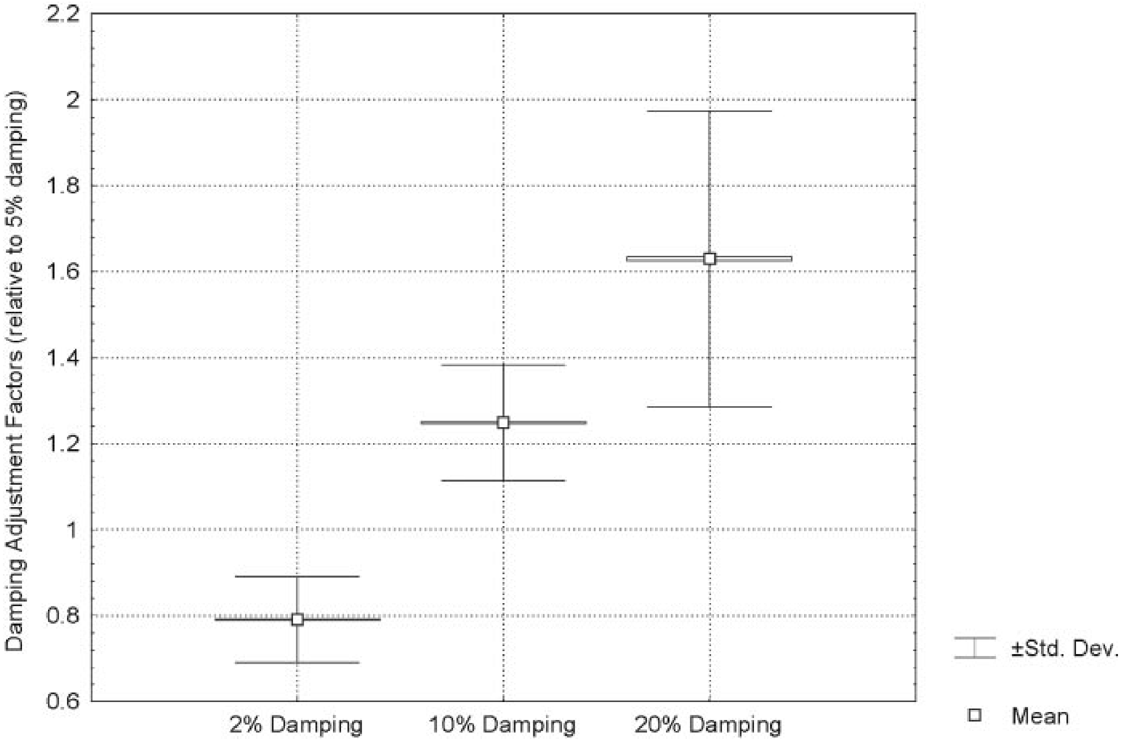

Figure 4. Statistical distribution of damping adjustment factors. Note: Std. Dev., standard deviation

damping up to 20% of critical, and additional studies are needed to extend the statistical evaluations presented in this paper to damping ratios larger than 20%.

The results of this study are dominated by earthquake ground shaking recorded at some distance from fault rupture (not near source). Similarly, both horizontal records were used in the study without consideration of the possible effects of directivity. The results of the study are applicable to the random direction of horizontal ground shaking (not near source) and may not apply to sites near sources. It is expected that evaluation of the damping reduction factor using a database of near-source records only would produce somewhat different results, particularly in the fault normal direction of ground shaking where records often contain a few strong pulses.

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