

Response of Elastic and Inelastic Structures with Damping Systems to Near-Field and Soft-Soil Ground Motions

Eleni Pavlou

Graduate Student, Department of Civil, Structural & Environmental Engineering, University at Buffalo

Research Supervisor: Michael C. Constantinou, Professor and Chairman

Summary

The effect of near-field and soft-soil ground motions on structures with viscous-damping systems was examined. Damping modification factors for damping ratios up to 100% of critical were obtained for sets of near-field and soft-soil ground motions and compared to the values presented in 2000 NEHRP Recommended Provisions. A study was carried out for the ductility demand in structures without and with damping systems, where the damped buildings were designed for a smaller base shear than conventional buildings in accordance with the 2000 NEHRP Provisions. Nonlinear response-history and simplified methods of the 2000 NEHRP Provisions were used to analyze single-degree-of-freedom systems and 3-story moment frames with linear and nonlinear viscous damping systems to acquire knowledge on the influence of near-field and soft-soil ground motions on the accuracy of simplified methods of analysis.

Introduction

FEMA's *National Earthquake Hazard Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* of year 2000 (BSSC 2001) and the upcoming Provisions for year 2003 contain the first simplified methods for analysis and design of buildings with damping systems. These procedures are largely based on studies that excluded the effects of near-field and soft-soil seismic excitations (Ramirez et al., 2001, 2002a, 2002b, 2003; Whittaker et al., 2003). This paper concentrates on a systematic assessment of the validity of these methods for these special classes of seismic excitations.

Recently, Ramirez et al. (2001, 2002a, 2002b, 2003) evaluated the accuracy of simplified methods of analysis of buildings with damping systems. Particularly, the simplified analysis methods of 2000 NEHRP Recommended Procedures (BSSC 2001) have been evaluated and shown to produce results of acceptable accuracy. However, the studies did not consider near-field and soft-soil earthquake motions, so the conclusions presented in the Ramirez et al. papers do not necessarily apply to such conditions.

To shed some light on these issues, structures with linear and nonlinear viscous damping systems were employed to examine how the response to near-field and soft-soil ground motions differs from that to far-field motions. This paper presents: (1) a comparison of the values of damping coefficients obtained through analyses with the near-field and soft-soil motions, and the values listed in the 2000

NEHRP Provisions to modify the 5-percent damped response spectrum for the effects of higher damping; (2) a comparison of ductility demands in structures without and with damping systems, where the damped buildings are designed for a smaller base shear than conventional buildings; (3) results of the simplified method of analysis for single-degree-of-freedom structures with linear viscous and nonlinear viscous damping systems along with the results of nonlinear response history analysis; and (4) a comparison of results of dynamic response history analysis and of simplified analysis of 3-story frames with linear and nonlinear viscous damping systems.

A set of ten near-field ground motions assembled by Somerville (1997) and seven soft-soil earthquake histories (Lord 1996) were utilized in the analysis of ductile systems with and without supplemental viscous damping. The single-degree-of-freedom system considered in this study had perfect non-degrading bilinear hysteretic behavior and was characterized by the elastic period with values of $T_e=0.5$ to 2.0 sec, the ductility-based portion of R-factor with values of $R_\mu = 2.0, 3.33,$ and 5.0 and the post-yielding to elastic stiffness ratio with values of $a=0.05, 0.15, 0.25, 0.50,$ and 1.00. In addition, analyses were conducted for 3-story special steel moment resisting frames with linear and nonlinear viscous damping systems. These frames were designed to have base shear strength of $0.75V, V,$ and $0.8V,$ respectively, where V is the base shear for the building frame without a damping system for seismic excitation described by the NEHRP spectrum with parameters $S_{DS} = 1.0, S_{D1} = 0.6,$ and $T_s = 0.6$ seconds. Damping systems were then added to these frames and proportioned in accordance with the 2000 NEHRP Recommended Provisions to satisfy the drift criteria. Detailed description of the above systems is presented in Ramirez et al. (2001).

Modification of Response Spectrum for High Damping

In order to reduce the elastic spectral demands for increases in damping, the damping coefficient is used. Linear response-history analyses were carried out for the two sets of earthquake motions to calculate values for the damping coefficient for damping ratios up to 100% of critical. The value of the damping coefficient B for a particular period is obtained as the ratio of the average 5%-damped spectral acceleration, $S_a(T,0.05),$ to the average spectral acceleration for a different damping ratio $\beta,$ $S_a(T,\beta).$ Figure 1 shows the calculated damping coefficients and the coefficients presented in 2000 NEHRP, for the near-field (fault-normal components) and the soft-soil ground motions for damping ratios up to 50% of critical.

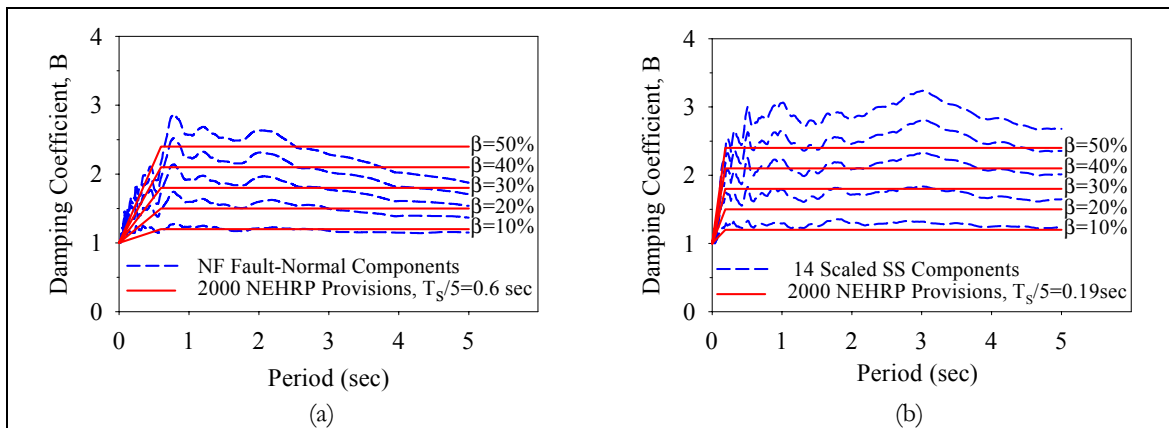


Figure 1. Calculated and NEHRP B coefficient for (a) near-field and (b) soft-soil ground motions

Evaluation of Displacement Ductility Demands in Structures with Viscous Damping Systems

Furthermore, in order to establish values of the displacement ductility demand for the near-field and soft-soil ground motions, nonlinear time history analyses were performed on the ductile single-degree-of-freedom framing systems with and without supplemental linear viscous damping. Figure 2 compares the calculated average displacement ductility ratio for the undamped and the damped systems for the two ground motion sets.

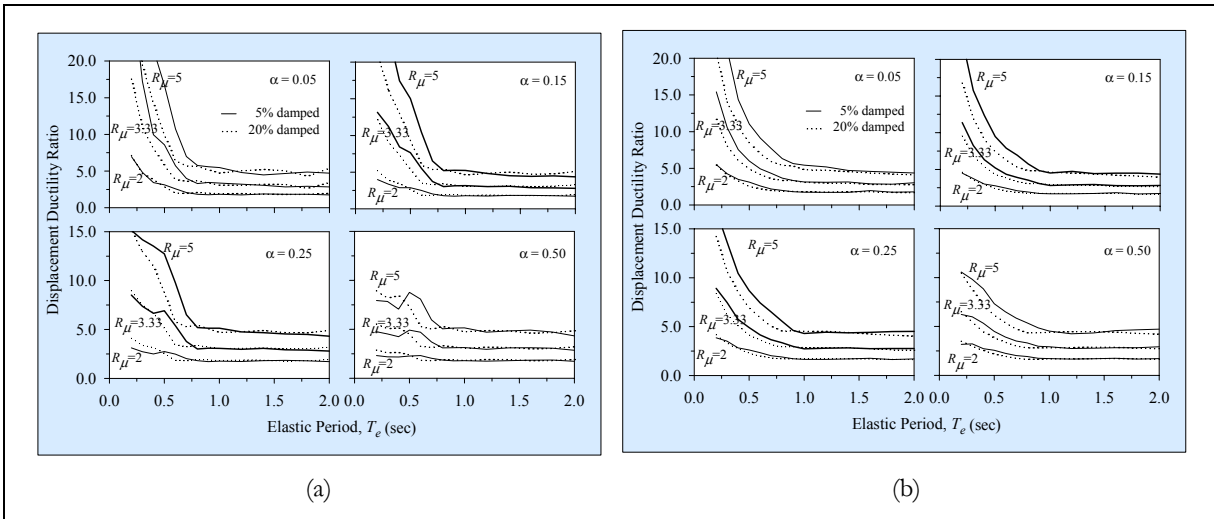


Figure 2. Comparison of average displacement ductility ratio for 5%- and 20%-damped systems for (a) near-field and (b) soft-soil ground motions

Results of Simplified Method of Analysis and Comparison to Results of Nonlinear Response History Analysis

Single-degree-of-freedom Structures

In addition, nonlinear response history analyses for the near-field and soft-soil ground motions were performed to investigate the accuracy of the simplified methods of the 2000 NEHRP Provisions. Figure 3 presents a comparison of the results of nonlinear history analysis and the results of the simplified method of analysis. Graphs of the peak displacement, peak velocity and peak acceleration are presented by plotting the average results of the nonlinear history analyses on the vertical axis against the results of the simplified method of analysis on the horizontal axis for systems with linear viscous damping devices, $\beta_v = 0.15$.

3-story Building Frames

To further examine the influence of near-field and soft-soil ground motions on the accuracy of simplified methods of analysis, multi-degree-of-freedom systems were considered. Nonlinear response-history analysis of the 3-story frames was performed using computer program IDARC2D (Valles 1996). Indicative results of the simplified methods of analysis and nonlinear response-history

analysis are tabulated in Tables 1 and 2 for minimum, maximum, average, and average plus one standard deviation ($\text{avg} + 1\sigma$) responses for the 3-story frame 3S-75 with linear viscous damping system to provide 10% viscous damping ratio. Included in the table are (a) peak interstory drifts, (b) peak interstory velocities, (c) peak damper forces, and (d) maximum story shears (including the viscous component). The results reported in Tables 1 and 2 attest to the accuracy of the equivalent lateral force (ELF) and the modal analysis (RSA) procedures of 2000 NEHRP Recommended Procedures for buildings with damping systems. Both methods provided conservative estimates of drift and predictions for damper forces and member actions in good overall agreement with the average of results of nonlinear response-history analysis.

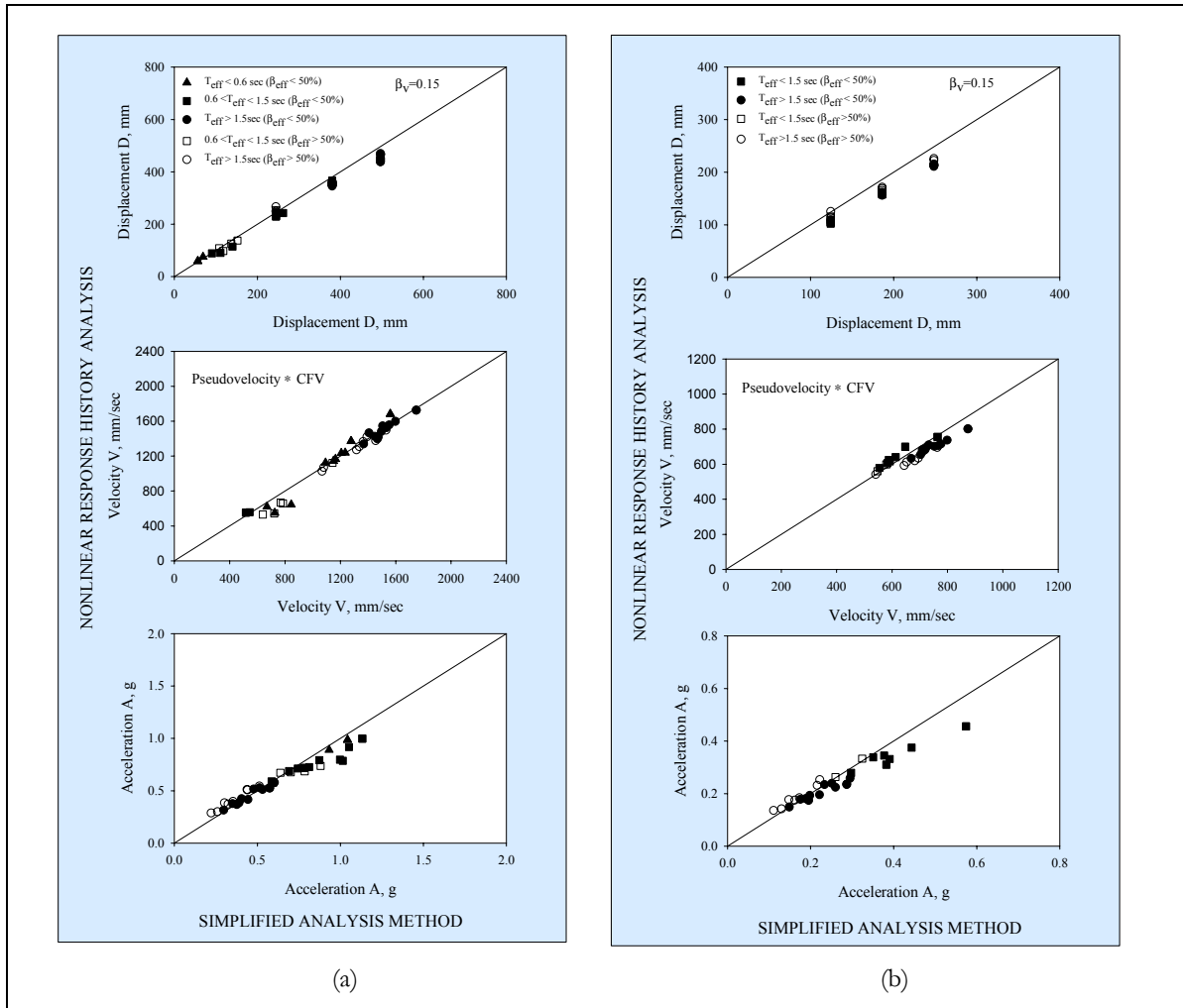


Figure 3. Comparison of response history analysis to simplified method of analysis for systems with linear viscous damping devices, $\beta_v = 0.15$ for (a) near-field and (b) soft-soil ground motions

Table 1. Comparison of results of simplified methods of analysis to results of nonlinear response-history analysis: 3-story frame 3S-75 with linear viscous damping system to provide 10% viscous damping ratio – near-field, fault-normal components

Response Quantity	S T O R Y	Simplified Methods of Analysis NEHRP (2003)				Nonlinear Time History Analysis IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1 σ	Max.
Story Drift (mm)	3	112		113		61	98	131	151
	2	133		127		67	112	150	184
	1	89		80		39	78	112	152
Interstory Velocity (mm/sec)	3	468	460	577	515	287	526	660	694
	2	555	546	435	472	340	484	577	625
	1	499	435	331	324	237	348	426	453
Damper Force (kN)	3	373	367	460	411	229	420	528	554
	2	443	436	347	377	271	386	461	500
	1	398	347	264	258	189	278	341	362
Max. Story Shear (kN)	3	717	709	881	856	513	706	841	936
	2	1161	1165	1157	1165	963	1239	1384	1446
	1	1638	1623	1517	1513	1172	1665	1905	1980

Note: Values in **bold** indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al., (2002a).

Table 2. Comparison of results of simplified methods of analysis to results of nonlinear response-history analysis: 3-story frame 3S-75 with linear viscous damping system to provide 10% viscous damping ratio – soft-soil scaled components

Response Quantity	S T O R Y	Simplified Methods of Analysis NEHRP (2003)				Nonlinear Time History Analysis IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1 σ	Max.
Story Drift (mm)	3	105		108		50	89	110	119
	2	125		121		66	103	128	150
	1	82		76		45	68	92	121
Interstory Velocity (mm/sec)	3	408	415	561	494	186	511	408	415
	2	484	492	410	443	200	484	484	492
	1	419	377	318	307	117	341	419	377
Damper Force (kN)	3	325	331	448	394	149	408	325	331
	2	386	392	327	354	160	386	386	392
	1	334	300	253	245	93	273	334	300
Max. Story Shear (kN)	3	655	653	877	852	341	659	655	653
	2	1134	1142	1162	1169	873	1213	1134	1142
	1	1521	1513	1519	1515	1278	1591	1521	1513

Note: Values in **bold** indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al., (2002a).

Concluding Remarks

The study conducted to investigate the effects of near-field and soft-soil ground motions on the response of yielding structures with viscous damping devices has led to the following conclusions:

- The damping coefficient values in 2000 NEHRP are accurate or conservative for near-field and soft-soil ground motions for periods up to 5 seconds and 3 seconds, respectively.
- The ductility demand in damped structures with lower stiffness and strength is comparable to, or less than, the ductility demand in undamped structures for near-field and soft-soil ground motions.
- The 2000 NEHRP simplified method of analysis for single-degree-of-freedom systems produces results on displacement and acceleration that are generally accurate or conservative for near-field and soft-soil ground motions. Moreover, the use of previously established correction factors for velocity on the basis of analyses with far-field motions produces very good estimates of peak structural velocity in near-field and soft-soil motions.
- The application of the simplified methods of analysis of 2000 NEHRP Recommended Procedures to steel moment frames with linear and nonlinear viscous damping systems provided conservative estimates of drift and predictions for damper forces and member actions in good overall agreement with the average of results of nonlinear response-history analysis.

Acknowledgments

Financial support for this project was provided by the Multidisciplinary Center for Earthquake Engineering Research, Task on Rehabilitation Strategies for Buildings, which is primarily supported by the Earthquake Engineering Research Centers Program of the National Science Foundation, under award number EEC-9701471. The work was performed under the direction of Technical Subcommittee 12, Base Isolation and Energy Dissipation, of the Building Seismic Safety Council, which was tasked with developing analysis and design procedures for inclusion in the 2000 and 2003 editions of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*. The work of Technical Subcommittee 12 was supported by the Federal Emergency Management Agency.

References

Building Seismic Safety Council (BSSC) (2001): *NEHRP recommended provisions for seismic regulations for new buildings and other structures, 2000 Edition*. Report Nos. FEMA 368 and 369. Federal Emergency Management Agency, Washington, DC.

Lord JA (1996): Personal communication with Michael C. Constantinou.

Ramirez OM, Constantinou MC, Gomez JD, Whittaker AS, Chrysostomou CZ (2002): Evaluation of simplified methods of analysis of yielding structures with damping systems. *Earthquake Spectra*; **18**(3): 501-530.

Ramirez OM, Constantinou MC, Gomez JD, Whittaker AS, and Chrysostomou CZ (2002): Elastic and inelastic seismic response of buildings with damping systems. *Earthquake Spectra*; **18**(3): 531-547.

Ramirez OM, Constantinou MC, Kircher CA, Whittaker AS, Johnson MW, Gomez JD, Chrysostomou CZ (2001): *Development and evaluation of simplified procedures for analysis and design of buildings with passive energy dissipation systems, Revision 1*. Report No. MCEER 00-0010,. Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, Buffalo, NY.

Ramirez OM, Constantinou MC, Whittaker AS, Kircher CA, Johnson MW, Chrysostomou CZ (2003): Validation of the 2000 NEHRP provisions equivalent lateral force and modal analysis procedures for buildings with damping systems. *Earthquake Spectra*; to appear.

Somerville P, Smith N, Punyamurthula, S, Sun J (1997): *Development of ground motion time histories for phase 2 of the FEMA/SAC steel project*. Report No. SAC/BD-97-04, Sacramento, CA.

Valles RE, Reinhorn AM, Kunnath SK, Li C, Madan A (1996): *IDARC2D Version 4.0: A computer program for the inelastic damage analysis of buildings*. Report No. NCEER-96-0010. National Center for Earthquake Engineering Research, University at Buffalo, Buffalo, NY. Information on Version 5.0 of IDARC2D can be found at <http://civil.eng.buffalo.edu/idarc2d50/>.

Whittaker AS, Constantinou MC, Ramirez OM, Johnson MW, Chrysostomou CZ (2003): Equivalent lateral force and modal analysis procedures of the 2000 NEHRP provisions for buildings with damping systems. *Earthquake Spectra*; to appear.