Ground Motion Input in Seismic Evaluation Studies

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Impacts of Artificial Time History Input on In-Structure Demand Spectra

R. T. Sewell, S. C. Wu

Risk Engineering, Inc.

Prepared for
U.S. Nuclear Regulatory Commission

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Ground Motion Input in Seismic Evaluation Studies

Impacts of Artificial Time History Input on In-Structure Demand Spectra

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ABSTRACT

This report documents research pertaining to conservatism and variability in seismic risk estimates. Specifically, it examines whether or not artificial motions produce unrealistic evaluation demands, i.e., demands significantly inconsistent with those expected from real earthquake motions.

To study these issues, two types of artificial motions are considered: (a) motions with smooth response spectra, and (b) motions with realistic variations in spectral amplitude across vibration frequency. For both types of artificial motion, time histories are generated to match target spectral shapes. For comparison, empirical motions representative of those that might result from strong earthquakes in the Eastern U.S. are also considered.

The study findings suggest that artificial motions resulting from typical simulation approaches (aimed at matching a given target spectrum) are generally adequate and appropriate in representing the peak-response demands that may be induced in linear structures and equipment responding to real earthquake motions. Also, given similar input Fourier energies at high-frequencies, levels of input Fourier energy at low frequencies observed for artificial motions are substantially similar to those levels noted in real earthquake motions. In addition, the study reveals specific problems resulting from the application of Western U.S. type motions for seismic evaluation of Eastern U.S. nuclear power plants.

CONTENTS

<u>Section</u>	<u>Page</u>
1 INTRODUCTION	1-1
1.1 BACKGROUND: STUDY RELEVANCE	1-1
1.1.1 Relevance of Artificial Motion Input to Seismic Evaluation Studies	1-1
1.1.2 Regulatory Standards for Developing Artificial Motion Input	1-2
1.1.3 Issues on Generating Artificial Motions for the Eastern U.S.	1-2
1.2 APPLICABILITY OF THIS STUDY TO IPEEE	1-6
1.2.1 Applicability to Seismic Margin Assessments	1-6
1.2.2 Applicability to Probabilistic Risk Assessments	1-7
1.3 OVERALL STUDY ORGANIZATION	1-8
1.4 REPORT ORGANIZATION	1-13
1.5 REFERENCES	1-14
2 DESCRIPTION OF STUDY APPROACH AND PARAMETERS	2-1
2.1 OUTLINE OF PARAMETER STUDY	2-1
2.2 DESCRIPTION OF PARAMETER-STUDY VARIABLES	2-4
2.2.1 Target Response Spectra	2-5
2.2.2 Artificial Motions	2-7
2.2.3 Empirical Motions	2-7
2.2.4 Structural Models	2-9
2.2.5 In-Structure Spectra	2-9

2.2.6	Parameters for Anchoring/Scaling Motions	2-10
2.3	USE OF PARAMETER-STUDY RESULTS	2-13
2.4	REFERENCES	2-14
3	BASIS AND CHARACTERISTICS OF ARTIFICIAL MOTIONS	3-1
3.1	SIMULATION OF ARTIFICIAL MOTIONS HAVING SMOOTH SPECTRA	3-2
3.1.1	Methodology: Basis and Procedures for Motion Simulations	3-3
3.1.2	Results: Simulated Motions and Comparisons with Target Spectra	3-4
3.2	SIMULATION OF ARTIFICIAL MOTIONS HAVING JAGGED SPECTRA	3-6
3.2.1	Methodology: Basis and Procedures for Motion Simulations	3-8
3.2.2	Results: Simulated Motions and Comparisons with Target Spectra	3-13
3.3	COMPARISONS BETWEEN SIMULATED MOTIONS AND EMPIRICAL MOTIONS	3-15
3.3.1	Comparisons for Motions Having Smooth Response Spectra	3-15
3.3.2	Comparisons for Motions Having Jagged Response Spectra	3-19
3.4	REFERENCES	3-23
4	RESPONSE RESULTS: EMPIRICAL MOTIONS	4-1
4.1	STRUCTURAL FORCES AND DISPLACEMENTS	4-1
4.1.1	Motion-Specific Results	4-2
4.1.2	EUS versus WUS motions: Implications to Seismic Evaluation and Design Practice	4-3
4.1.3	Response Statistics	4-5
4.2	IN-STRUCTURE RESPONSE SPECTRA	4-7
4.2.1	Motion-Specific Results	4-7

5	RESPONSE RESULTS: ARTIFICIAL MOTIONS WITH SMOOTH SPECTRA	5-1
5.1	STRUCTURAL FORCES AND DISPLACEMENTS	5-1
5.1.1	Motion-Specific Results	5-1
5.1.2	Response Statistics	5-2
5.2	IN-STRUCTURE RESPONSE SPECTRA	5-3
5.2.1	Motion-Specific Results	5-3
5.3	SELECTION OF CASES FOR SUBSEQUENT COMPARISONS	5-4
6	RESPONSE RESULTS: ARTIFICIAL MOTIONS WITH JAGGED SPECTRA	6-1
6.1	STRUCTURAL FORCES AND DISPLACEMENTS	6-1
6.2	IN-STRUCTURE RESPONSE SPECTRA	6-2
6.2.1	Motion-Specific Results for Given Target Spectrum	6-2
6.2.2	Response Statistics for Given Target Spectra	6-3
6.3	SELECTION OF CASES FOR SUBSEQUENT COMPARISONS	6-3
7	MOTION IMPACTS ON IN-STRUCTURE DEMAND SPECTRA	7-1
7.1	COMPARISONS OF EMPIRICAL VERSUS ARTIFICIAL MOTIONS WITH SMOOTH SPECTRA	7-1
7.2	COMPARISONS OF EMPIRICAL VERSUS ARTIFICIAL MOTIONS WITH JAGGED SPECTRA	7-3
7.3	COMPARISONS AMONG ALTERNATIVE SIMULATION APPROACHES	7-4
7.4	COMPARISONS AMONG EASTERN U.S. AND WESTERN U.S. MOTIONS	7-5
8	SUMMARY AND CONCLUSIONS	8-1

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2-1 Target response spectra for use in generating artificial time-history input motions. (a) Unscaled target spectra TEr and TE _s , derived from EPRI UHS results. (b) Unscaled target spectra TLr and TL _s , derived from LLNL UHS results.	2-22
2-2 Target response spectra for use in generating artificial time-history input motions (continued). (c) Unscaled target spectra TL2r and TL2 _s , derived from revised LLNL UHS results. (d) Target spectra TW _r and TW _s , derived from the NUREG/CR-0098 median 5%-damped shape, anchored to 0.3g PGA.	2-23
2-3 (a) Ground acceleration time histories from empirical records: (a) MSag1, (b) MSag2, (c) MSag3 and (d) MSag4.	2-24
2-4 (a) Ground acceleration time histories from empirical records (continued): (e) MNah1, (f) MNah2, (g) MNah3 and (h) MImp1.	2-25
2-5 Response spectra for empirical ground motions. (a) Motion MSag1. (b) Motion MSag2.	2-26
2-6 Response spectra for empirical ground motions (continued). (c) Motion MSag3. (d) Motion MSag4.	2-27
2-7 Response spectra for empirical ground motions (continued). (e) Motion MNah1. (f) Motion MNah2.	2-28
2-8 Response spectra for empirical ground motions (continued). (g) Motion MNah3. (h) Motion MImp1.	2-29
2-9 Power spectral density functions (PSDs) for empirical ground motions. (a) Motion MSag1. (b) Motion MSag2.	2-30
2-10 PSDs for empirical ground motions (continued). (c) Motion MSag3. (d) Motion MSag4.	2-31
2-11 PSDs for empirical ground motions (continued). (e) Motion MNah1. (f) Motion MNah2.	2-32

2-12	PSDs for empirical ground motions (continued). (g) Motion MNAh3. (h) Motion MImp1.	2-33
2-13	Ground response spectra (GRS) for empirical motions scaled to a common value of PGA of 0.3g.	2-34
2-14	GRS for empirical motions scaled to a common value of $\overline{S_a}$ (2.55 Hz to 3.45 Hz) of 0.6g.	2-35
2-15	GRS for empirical motions scaled to a common value of $\overline{S_a}$ (5.95 Hz to 8.05 Hz) of 0.6g.	2-36
2-16	GRS for empirical motions scaled to a common value of $\overline{S_a}$ (8.50 Hz to 11.5 Hz) of 0.6g.	2-37
2-17	GRS for empirical motions scaled to a common value of $\overline{S_a}$, averaged over 2.00 Hz to 10.0 Hz, of 0.6g.	2-38
2-18	Target response spectra scaled to a common value of PGA of 0.3g.	2-39
2-19	Target response spectra scaled to a common value of $\overline{S_a}$ (2.55 Hz to 3.45 Hz) of 0.6g.	2-40
2-20	Target response spectra scaled to a common value of $\overline{S_a}$ (5.95 Hz to 8.05 Hz) of 0.6g.	2-41
2-21	Target response spectra scaled to a common value of $\overline{S_a}$ (8.50 Hz to 11.5 Hz) of 0.6g.	2-42
2-22	Target response spectra scaled to a common value of $\overline{S_a}$, averaged over 2.00 Hz to 10.0 Hz, of 0.6g.	2-43
3-1	Acceleration time histories for artificial motions having smooth re- sponse spectra.	3-24
3-2	Acceleration time histories for artificial motions having smooth re- sponse spectra (continued).	3-25
3-3	Response spectrum for simulated motion versus its target spectrum: (a) Motion MArS1(TEr) and (b) Motion MArS1(TEs).	3-26
3-4	Response spectrum for simulated motion versus its target spectrum (continued): (a) Motion MArS1(TLr) and (b) Motion MArS1(TLs).	3-27
3-5	Response spectrum for simulated motion versus its target spectrum (continued): (a) Motion MArS1(TL2r) and (b) Motion MArS1(TL2s).	3-28
3-6	Response spectrum for simulated motion versus its target spectrum (continued): (a) Motion MArS1(TWr) and (b) Motion MArS1(TWs).	3-29
3-7	Acceleration time histories for artificial motions having jagged re- sponse spectra matching, on average, target TEr.	3-30

3-8	Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TEs.	3-31
3-9	Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TLr.	3-32
3-10	Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TLs.	3-33
3-11	Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TL2r.	3-34
3-12	Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TL2s.	3-35
3-13	Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TWr.	3-36
3-14	Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TWs.	3-37
3-15	(a) Response spectra for multiple simulated motions MArJ1-5(TEr) versus their target spectrum TEr. (b) Average response spectrum for the five motions versus target spectrum.	3-38
3-16	(a) Response spectra for multiple simulated motions MArJ1-5(TEs) versus their target spectrum TEs. (b) Average response spectrum for the five motions versus target spectrum.	3-39
3-17	(a) Response spectra for multiple simulated motions MArJ1-5(TLr) versus their target spectrum TLr. (b) Average response spectrum for the five motions versus target spectrum.	3-40
3-18	(a) Response spectra for multiple simulated motions MArJ1-5(TLs) versus their target spectrum TLs. (b) Average response spectrum for the five motions versus target spectrum.	3-41
3-19	(a) Response spectra for multiple simulated motions MArJ1-5(TL2r) versus their target spectrum TL2r. (b) Average response spectrum for the five motions versus target spectrum.	3-42
3-20	(a) Response spectra for multiple simulated motions MArJ1-5(TL2s) versus their target spectrum TL2s. (b) Average response spectrum for the five motions versus target spectrum.	3-43
3-21	(a) Response spectra for multiple simulated motions MArJ1-5(TWr) versus their target spectrum TWr. (b) Average response spectrum for the five motions versus target spectrum.	3-44

3-22	(a) Response spectra for multiple simulated motions MArJ1-5(TWs) versus their target spectrum TWs. (b) Average response spectrum for the five motions versus target spectrum.	3-45
3-23	Power spectral densities for artificial motions having smooth response spectra: (a) motion MArS1(TEr), (b) motion MArS1(TEs).	3-46
3-24	Power spectral densities for artificial motions having smooth response spectra: (a) motion MArS1(TLr), (b) motion MArS1(TLs).	3-47
3-25	Power spectral densities for artificial motions having smooth response spectra: (a) motion MArS1(TL2r), (b) motion MArS1(TL2s).	3-48
3-26	Power spectral densities for artificial motions having smooth response spectra: (a) motion MArS1(TWr), (b) motion MArS1(TWs).	3-49
3-27	Power spectral densities for artificial motions MArJn(TEr), having jagged spectra matching target TEr: (a) motion MArJ1(TEr), (b) motion MArJ2(TEr).	3-50
3-28	Power spectral densities for artificial motions MArJn(TEr), having jagged spectra matching target TEr (continued): (c) motion MArJ3(TEr), (d) motion MArJ4(TEr).	3-51
3-29	Power spectral densities for artificial motions MArJn(TEr), having jagged spectra matching target TEr (continued): (e) motion MArJ5(TEr).	3-52
3-30	Power spectral densities for artificial motions MArJn(TEs), having jagged spectra matching target TEs: (a) motion MArJ1(TEs), (b) motion MArJ2(TEs).	3-53
3-31	Power spectral densities for artificial motions MArJn(TEs), having jagged spectra matching target TEs (continued): (c) motion MArJ3(TEs), (d) motion MArJ4(TEs).	3-54
3-32	Power spectral densities for artificial motions MArJn(TEs), having jagged spectra matching target TEs (continued): (e) motion MArJ5(TEs).	3-55
3-33	Power spectral densities for artificial motions MArJn(TLr), having jagged spectra matching target TLr: (a) motion MArJ1(TLr), (b) motion MArJ2(TLr).	3-56
3-34	Power spectral densities for artificial motions MArJn(TLr), having jagged spectra matching target TLr (continued): (c) motion MArJ3(TLr), (d) motion MArJ4(TLr).	3-57
3-35	Power spectral densities for artificial motions MArJn(TLr), having jagged spectra matching target TLr (continued): (e) motion MArJ5(TLr).	3-58

3-36 Power spectral densities for artificial motions MArJn(TLs), having jagged spectra matching target TLs: (a) motion MArJ1(TLs), (b) motion MArJ2(TLs).	3-59
3-37 Power spectral densities for artificial motions MArJn(TLs), having jagged spectra matching target TLs (continued): (c) motion MArJ3(TLs), (d) motion MArJ4(TLs).	3-60
3-38 Power spectral densities for artificial motions MArJn(TLs), having jagged spectra matching target TLs (continued): (e) motion MArJ5(TLs).	3-61
3-39 Power spectral densities for artificial motions MArJn(TL2r), having jagged spectra matching target TL2r: (a) motion MArJ1(TL2r), (b) motion MArJ2(TL2r).	3-62
3-40 Power spectral densities for artificial motions MArJn(TL2r), having jagged spectra matching target TL2r (continued): (c) motion MArJ3(TL2r), (d) motion MArJ4(TL2r).	3-63
3-41 Power spectral densities for artificial motions MArJn(TL2r), having jagged spectra matching target TL2r (continued): (e) motion MArJ5(TL2r).	3-64
3-42 Power spectral densities for artificial motions MArJn(TL2s), having jagged spectra matching target TL2s: (a) motion MArJ1(TL2s), (b) motion MArJ2(TL2s).	3-65
3-43 Power spectral densities for artificial motions MArJn(TL2s), having jagged spectra matching target TL2s (continued): (c) motion MArJ3(TL2s), (d) motion MArJ4(TL2s).	3-66
3-44 Power spectral densities for artificial motions MArJn(TL2s), having jagged spectra matching target TL2s (continued): (e) motion MArJ5(TL2s).	3-67
3-45 Power spectral densities for artificial motions MArJn(TW _r), having jagged spectra matching target TW _r : (a) motion MArJ1(TW _r), (b) motion MArJ2(TW _r).	3-68
3-46 Power spectral densities for artificial motions MArJn(TW _r), having jagged spectra matching target TW _r (continued): (c) motion MArJ3(TW _r), (d) motion MArJ4(TW _r).	3-69
3-47 Power spectral densities for artificial motions MArJn(TW _r), having jagged spectra matching target TW _r (continued): (e) motion MArJ5(TW _r).	3-70
3-48 Power spectral densities for artificial motions MArJn(TW _s), having jagged spectra matching target TW _s : (a) motion MArJ1(TW _s), (b) motion MArJ2(TW _s).	3-71

3-49	Power spectral densities for artificial motions MArJn(TWs), having jagged spectra matching target TWs (continued): (c) motion MArJ3(TWs), (d) motion MArJ4(TWs).	3-72
3-50	Power spectral densities for artificial motions MArJn(TWs), having jagged spectra matching target TWs (continued): (e) motion MArJ5(TWs).	3-73
4-1	In-structure response spectra for the 3-Hz structure subjected to empirical input motions with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MSag1 and (b) MSag2.	4-16
4-2	In-structure response spectra for the 3-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (c) MSag3 and (d) MSag4.	4-17
4-3	In-structure response spectra for the 3-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (e) MNah1 and (f) MNah2.	4-18
4-4	In-structure response spectra for the 3-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (g) MNah3 and (h) MImp1.	4-19
4-5	In-structure response spectra for the 7-Hz structure subjected to empirical input motions with ScASA scaling. Responses at the first, third, and top/fourth floors for motions: (a) MSag1 and (b) MSag2.	4-20
4-6	In-structure response spectra for the 7-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and top/fourth floors for motions: (c) MSag3 and (d) MSag4.	4-21
4-7	In-structure response spectra for the 7-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and top/fourth floors for motions: (e) MNah1 and (f) MNah2.	4-22
4-8	In-structure response spectra for the 7-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and top/fourth floors for motions: (g) MNah3 and (h) MImp1.	4-23
4-9	In-structure response spectra for the 10-Hz structure subjected to empirical input motions with ScASA scaling. Responses at the first and second floors for motions: (a) MSag1 and (b) MSag2.	4-24
4-10	In-structure response spectra for the 10-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first and second floors for motions: (c) MSag3 and (d) MSag4.	4-25

4-11	In-structure response spectra for the 10-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first and second floors for motions: (e) MNah1 and (f) MNah2.	4-26
4-12	In-structure response spectra for the 10-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first and second floors for motions: (g) MNah3 and (h) MImpl.	4-27
5-1	In-structure response spectra for the 3-Hz structure subjected to artificial input motions MArS1 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArS1(TEr) and (b) MArS1(TEs).	5-14
5-2	In-structure response spectra for the 3-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (c) MArS1(TLr) and (d) MArS1(TLs).	5-15
5-3	In-structure response spectra for the 3-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (e) MArS1(TL2r) and (f) MArS1(TL2s).	5-16
5-4	In-structure response spectra for the 3-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (g) MArS1(TWr) and (h) MArS1(TWs).	5-17
5-5	In-structure response spectra for the 7-Hz structure subjected to artificial input motions MArS1 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArS1(TEr) and (b) MArS1(TEs).	5-18
5-6	In-structure response spectra for the 7-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (c) MArS1(TLr) and (d) MArS1(TLs).	5-19
5-7	In-structure response spectra for the 7-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (e) MArS1(TL2r) and (f) MArS1(TL2s).	5-20
5-8	In-structure response spectra for the 7-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (g) MArS1(TWr) and (h) MArS1(TWs).	5-21

5-9	In-structure response spectra for the 10-Hz structure subjected to artificial input motions MArS1 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArS1(TEr) and (b) MArS1(TEs).	5-22
5-10	In-structure response spectra for the 10-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (c) MArS1(TLr) and (d) MArS1(TLs).	5-23
5-11	In-structure response spectra for the 10-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (e) MArS1(TL2r) and (f) MArS1(TL2s).	5-24
5-12	In-structure response spectra for the 10-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (g) MArS1(TW _r) and (h) MArS1(TW _s).	5-25
6-1	In-structure response spectra for the 3-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArJ1-5(TEr) and (b) MArJ1-5(TEs).	6-52
6-2	In-structure response spectra for the 3-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).	6-53
6-3	In-structure response spectra for the 3-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MArJ1-5(TL2r) and (f) MArJ1-5(TL2s).	6-54
6-4	In-structure response spectra for the 3-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TW _r) and (h) MArJ1-5(TW _s).	6-55
6-5	In-structure response spectra for the 7-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArJ1-5(TEr) and (b) MArJ1-5(TEs).	6-56

6-6	In-structure response spectra for the 7-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).	6-57
6-7	In-structure response spectra for the 7-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MArJ1-5(TL2r) and (f) MArJ1-5(TL2s).	6-58
6-8	In-structure response spectra for the 7-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TWr) and (h) MArJ1-5(TWs).	6-59
6-9	In-structure response spectra for the 10-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArJ1-5(TEr) and (b) MArJ1-5(TEs).	6-60
6-10	In-structure response spectra for the 10-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).	6-61
6-11	In-structure response spectra for the 10-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MArJ1-5(TL2r) and (f) MArJ1-5(TL2s).	6-62
6-12	In-structure response spectra for the 10-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TWr) and (h) MArJ1-5(TWs).	6-63
6-13	ISS statistics for the 3-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArJ1-5(TEr) and (b) MArJ1-5(TEs).	6-64
6-14	ISS statistics for the 3-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).	6-65
6-15	ISS statistics for the 3-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MArJ1-5(TL2r) and (f) MArJ1-5(TL2s).	6-66

6-16	ISS statistics for the 3-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TWr) and (h) MArJ1-5(TWs).	6-67
6-17	ISS statistics for the 7-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArJ1-5(TEr) and (b) MArJ1-5(TEs).	6-68
6-18	ISS statistics for the 7-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).	6-69
6-19	ISS statistics for the 7-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MArJ1-5(TL2r) and (f) MArJ1-5(TL2s).	6-70
6-20	ISS statistics for the 7-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TWr) and (h) MArJ1-5(TWs).	6-71
6-21	ISS statistics for the 10-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArJ1-5(TEr) and (b) MArJ1-5(TEs).	6-72
6-22	ISS statistics for the 10-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).	6-73
6-23	ISS statistics for the 10-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MArJ1-5(TL2r) and (f) MArJ1-5(TL2s).	6-74
6-24	ISS statistics for the 10-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TWr) and (h) MArJ1-5(TWs).	6-75
7-1	Comparisons of ISS demands in St3 produced for empirical motions with those produced for artificial motions MArS1. (a) Case-1 comparison, (b) Case-2 comparison.	7-6
7-2	Comparisons of ISS demands in St3 produced for empirical motions with those produced for artificial motions MArS1 (continued). (c) Case-3 comparison.	7-7
7-3	Comparisons of ISS demands in St7 produced for empirical motions with those produced for artificial motions MArS1. (a) Case-1 comparison, (b) Case-2 comparison.	7-8

7-4	Comparisons of ISS demands in St7 produced for empirical motions with those produced for artificial motions MArS1 (continued). (c) Case-3 comparison.	7-9
7-5	Comparisons of ISS demands in St10 produced for empirical motions with those produced for artificial motions MArS1. (a) Case-1 comparison, (b) Case-2 comparison.	7-10
7-6	Comparisons of ISS demands in St10 produced for empirical motions with those produced for artificial motions MArS1 (continued). (c) Case-3 comparison.	7-11
7-7	Comparisons of ISS demands in St3 produced for empirical motions with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.	7-12
7-8	Comparisons of ISS demands in St3 produced for empirical motions with those produced for the average of multiple artificial motions MArJ1-5 (continued). (c) Case-3 comparison.	7-13
7-9	Comparisons of ISS demands in St7 produced for empirical motions with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.	7-14
7-10	Comparisons of ISS demands in St7 produced for empirical motions with those produced for the average of multiple artificial motions MArJ1-5 (continued). (c) Case-3 comparison.	7-15
7-11	Comparisons of ISS demands in St10 produced for empirical motions with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.	7-16
7-12	Comparisons of ISS demands in St10 produced for empirical motions with those produced for the average of multiple artificial motions MArJ1-5 (continued). (c) Case-3 comparison.	7-17
7-13	Comparisons of ISS demands in St3 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.	7-18
7-14	Comparisons of ISS demands in St3 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5 (continued). (c) Case-3 comparison.	7-19
7-15	Comparisons of ISS demands in St7 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.	7-20

7-16 Comparisons of ISS demands in St7 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5 (continued). (c) Case-3 comparison.	7-21
7-17 Comparisons of ISS demands in St10 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.	7-22
7-18 Comparisons of ISS demands in St10 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5 (continued). (c) Case-3 comparison.	7-23

LIST OF TABLES

<u>Table</u>	<u>Page</u>
2-1 Description of Empirical Motion Time Histories Used in Study	2-16
2-2 Dynamic Characteristics of 3-Hz, Five-Story (5 DOF) Building Model	2-17
2-3 Dynamic Characteristics of 7-Hz, Four-Story (5 DOF) Building Model	2-18
2-4 Dynamic Characteristics of 10-Hz, Two-Story (2 DOF) Building Model	2-19
2-5 Ground-Motion Amplitude Measures, and Scale Factors to Achieve Anchor Bases, for Empirical Motions	2-20
2-6 Ground-Motion Amplitude Measures, and Scale Factors to Achieve Anchor Bases, for Artificial Motions	2-21
4-1 Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases	4-8
4-2 Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases	4-9
4-3 Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases	4-10
4-4 Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases	4-11
4-5 Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases	4-12
4-6 Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases	4-12
4-7 Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 3-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases	4-13

4-8	Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 7-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases	4-14
4-9	Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 10-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases	4-15
5-1	Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases	5-5
5-2	Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases	5-6
5-3	Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases	5-7
5-4	Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases	5-8
5-5	Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases	5-9
5-6	Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases	5-10
5-7	Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 3-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases	5-11
5-8	Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 7-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases	5-12

5-9	Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 10-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases	5-13
6-1	Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Different Anchor Bases	6-4
6-2	Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEs) Scaled to Four Different Anchor Bases	6-5
6-3	Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Different Anchor Bases	6-6
6-4	Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLs) Scaled to Four Different Anchor Bases	6-7
6-5	Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases	6-8
6-6	Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Different Anchor Bases	6-9
6-7	Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TW _r) Scaled to Four Different Anchor Bases	6-10
6-8	Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWs) Scaled to Four Different Anchor Bases	6-11
6-9	Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Different Anchor Bases	6-12
6-10	Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEs) Scaled to Four Different Anchor Bases	6-13

6-11 Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Different Anchor Bases	6-14
6-12 Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLs) Scaled to Four Different Anchor Bases	6-15
6-13 Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases	6-16
6-14 Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Different Anchor Bases	6-17
6-15 Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TW _r) Scaled to Four Different Anchor Bases	6-18
6-16 Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TW _s) Scaled to Four Different Anchor Bases	6-19
6-17 Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Different Anchor Bases	6-20
6-18 Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TE _s) Scaled to Four Different Anchor Bases	6-21
6-19 Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Different Anchor Bases	6-22
6-20 Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL _s) Scaled to Four Different Anchor Bases	6-23
6-21 Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases	6-24
6-22 Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Different Anchor Bases	6-25

6-23 Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWr) Scaled to Four Different Anchor Bases	6-26
6-24 Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWs) Scaled to Four Different Anchor Bases	6-27
6-25 Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Different Anchor Bases	6-28
6-26 Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEs) Scaled to Four Different Anchor Bases	6-29
6-27 Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Different Anchor Bases	6-30
6-28 Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLs) Scaled to Four Different Anchor Bases	6-31
6-29 Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases	6-32
6-30 Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Different Anchor Bases	6-33
6-31 Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWr) Scaled to Four Different Anchor Bases	6-34
6-32 Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWs) Scaled to Four Different Anchor Bases	6-35
6-33 Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Different Anchor Bases	6-36
6-34 Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEs) Scaled to Four Different Anchor Bases	6-37

6-35	Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Different Anchor Bases	6-38
6-36	Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLs) Scaled to Four Different Anchor Bases	6-39
6-37	Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases	6-40
6-38	Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Different Anchor Bases	6-41
6-39	Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWr) Scaled to Four Different Anchor Bases	6-42
6-40	Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWs) Scaled to Four Different Anchor Bases	6-43
6-41	Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Different Anchor Bases	6-44
6-42	Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEs) Scaled to Four Different Anchor Bases	6-45
6-43	Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Different Anchor Bases	6-46
6-44	Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLs) Scaled to Four Different Anchor Bases	6-47
6-45	Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases	6-48
6-46	Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Different Anchor Bases	6-49

6-47 Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWr) Scaled to Four Different Anchor Bases	6-50
6-48 Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWs) Scaled to Four Different Anchor Bases	6-51

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Section 1

INTRODUCTION

1.1 BACKGROUND: STUDY RELEVANCE

1.1.1 Relevance of Artificial Motion Input to Seismic Evaluation Studies

Seismic margin assessment (SMA) and seismic probabilistic risk assessment (SPRA) require the development of appropriate ground-motion input, in order that seismic evaluation demands may be computed for components (both structures and equipment) in nuclear power plants. Usually, the ground-motion input in seismic evaluation studies is specified by means of a single response spectrum. This response spectrum is used to evaluate forces and displacements in structures, as well as to evaluate in-structure spectra that represent motion input to equipment. Where structural responses and in-structure spectra are already available (such as from original design analyses), and where these existing results are judged to be valid for use in seismic evaluation, structure and equipment evaluation demands may be simply obtained by appropriately scaling the existing results, based on relative demands of the evaluation spectrum to those of the design spectrum. Such an approach usually assumes linear response, but may account for nonlinear behavior in an approximate manner.

In many instances, results of available existing analyses may not be considered valid for seismic evaluation purposes. In some cases, for instance, non-linear soil-structure interaction may have an important influence on computed structure and in-structure demands, an influence that would not likely have been explicitly factored into the design process. In other cases, results of the design analyses may be considered to be too crudely represented for use in developing realistic evaluation demands. Or, the evaluation input may differ too dramatically from the input that was used in developing the existing results. Whatever the reasons, it is often the case that a complete set of new results for structural responses and in-structure spectra must be generated for purposes of seismic evaluation. Such new results are almost always obtained by time-history response analysis, although simpler response-spectra analysis may be appropriately applied in some cases.

In generating new seismic evaluation demands using time-history analysis, it is necessary to develop an input ground-motion time history that is compatible with the ground-motion

evaluation spectrum (just as is often done in developing spectrum-compatible time-history motion input for analysis of design demands). For this purpose, artificial time-histories are most frequently generated.

1.1.2 Regulatory Standards for Developing Artificial Motion Input

Regulatory guidelines on the development of artificial time-history inputs for design purposes are contained in NUREG-0800, the Standard Review Plan (1). These guidelines are based on recommended power spectral density (PSD) requirements which have been developed to be compatible with design-type response spectra. Such PSD requirements have been documented, for instance, in NUREG/CR-3509 (2), Reference (3), and NUREG/CR-5347 (4). Artificial motions generated using these recommended guidelines have greatest validity to motions characteristic of the Western U.S., as design procedures for nuclear power plants have predominantly relied on the empirical database of strong motions recorded in the Western U.S., primarily California. Such design procedures include the criteria found in the AEC Regulatory Guide 1.60 (5) and in NUREG/CR-0098 (6).

1.1.3 Issues on Generating Artificial Motions for the Eastern U.S.

For over the past decade, empirical data and theoretical research pertaining to Eastern U.S. motions has demonstrated that characteristics of motions in the Eastern U.S. differ significantly from those in the Western U.S. Specifically, for motions pertaining to a given earthquake magnitude and distance, relative amplitudes of high-frequency spectral response to low-frequency spectral response are generally significantly greater for Eastern U.S. motions than for Western U.S. motions. Conversely, relative amplitudes of low-frequency spectral response to high-frequency spectral response are generally significantly greater for Western U.S. motions than for Eastern U.S. motions. Consequently, PSD requirements governing the frequency content of artificial time-histories generated to match design or design-type response spectra are not generally applicable for the purpose of generating artificial time histories that match a seismic evaluation spectrum representative of Eastern U.S. motions. This does not mean that artificial time-histories compatible with Eastern U.S. spectra cannot be generated; they can, in fact, be readily obtained. However, formal PSD requirements for generating artificial time histories representative of Eastern U.S. motions do not yet exist. This means that there are no specific regulatory standards to ensure that artificially generated motions will possess PSDs compatible with the PSDs expected for real Eastern U.S. earthquake motions.

Potential Deficiencies in Input Power Spectral Density. A principal objective of this report is to demonstrate whether or not the PSDs (i.e., true frequency contents) of artificial motions, generated to match a fixed response spectrum characteristic of Eastern U.S. motions,

adequately represent the actual PSDs of real Eastern U.S. motions. Specifically, the primary concern is that the input energy at low-to-moderate frequencies (in the range of about 1 Hz to 5 Hz) may be inadequate for artificial, as compared to empirical, Eastern U.S. motions. This is a concern not just for structures of low-to-moderate fundamental frequency, but also for high-frequency equipment contained within such structures. A number of research studies [e.g., (7, 8, 9, 10)] have confirmed that, despite the high-frequency energy prevalent in Eastern U.S. motions, the force (or acceleration) response of high-frequency equipment contained in structures of low-to-moderate frequency can often be dominated by the low-frequency response of the structure. In such a situation, by simply "riding" on top of a structure responding strongly to low-frequency motion, a piece of high-frequency equipment can experience a high absolute acceleration (and hence, a high force), without itself responding significantly at its own natural vibration frequency. If PSDs of artificial time histories are deficient at low frequencies, therefore, seismic evaluation demands computed for structures of low-to-moderate fundamental frequency, or for equipment of any frequency found within such structures, could likewise be seriously deficient.

One plausible manner in which the PSD of an artificial motion could be deficient at low frequencies, and yet result in response spectral amplitudes at low frequency sufficient to match a target Eastern U.S. spectrum, has to do with the response behavior of a single-degree-of-freedom (SDOF) oscillator. Whereas the PSD or Fourier amplitude spectrum (FAS) is a substantially pure measure of a motion's frequency content, the response spectrum (which is derived from responses of SDOF oscillators) is not a clean nor precise measure of frequency content. This is because a SDOF system of given fundamental frequency will always experience some measure of response to any given input, even if the input has no energy for frequencies in the vicinity of the structure's fundamental frequency. The maximum response of the SDOF structure, which is the basis for defining a response spectrum, depends both on the magnitude of transient response and on the magnitude of steady-state response. The transient response decays with time for a damped system, and is governed by vibration at the structure's predominant frequency. The steady-state response is governed by vibration at the input frequency. The magnitude of the combined transient and steady-state response diminishes as the frequency of the input forcing function departs from the frequency of vibration of the structure.

Because of these response characteristics, it is conceivable that response spectrum amplitudes sufficient to match or envelope a target spectrum over low frequencies, can be achieved by an artificial motion having very high PSD amplitudes solely over a range of high frequencies. Alternatively, the target spectrum could be achieved by an artificial motion having gaps in its

PSD over a number of narrow frequency bands. Clearly, if such gaps in the PSD happen to coincide with modal vibration frequencies of a multiple-degree-of-freedom (MDOF) structure, there exists the potential to significantly underestimate response demands, either for the structure itself, or for in-structure spectra at a location where perhaps an important piece of equipment might exist. Without formal PSD requirements specifically designed to be compatible with Eastern U.S. motions, the PSD associated with any artificial time history should be carefully checked to ensure that such deficiencies or gaps do not exist. This study explores to what extent, if any, gaps in PSDs may tend to arise when artificial motions are generated to match Eastern U.S. spectra.

Potential Effects of Closely Matching Smooth Response Spectra. If the PSD of an artificial motion has no energy at low frequencies, the response spectrum of the motion will, as a result, vary smoothly across low frequencies (because there is no excitation at low-frequencies to cause peaks or valleys in the response spectrum there). Another way of viewing this situation is that a response spectrum that is smooth over a given frequency range can (but may not necessarily) be caused by a lack of input energy over that frequency range. This becomes a concern because artificial motion time histories are typically generated to closely match a smooth spectral shape. Hence, there may exist a tendency for motions so generated to possess gaps in their PSDs.

Another potential problem with artificial motions produced to have spectra that closely match a smooth target spectrum has to do with the realism of such motions, and the ability of such motions to represent reasonably well the response demands in structures and equipment that are likely to result from real earthquake motions. In fact, it is now well known [see, for instance, NUREG/CR-3805 (11)] that realistic peak-to-valley variations in motion response spectra have a significant impact on inelastic behavior; artificial motions with smooth spectra, therefore, are not generally adequate in realistically representing variations in inelastic response potential of motion. (This point has been a major motivation for developing highly realistic motion simulations, with representative peak-to-valley variations, in earlier Phase 1 research and in later parts of present Phase 2 research, where evaluating realistic non-linear responses, and responses sensitive to multiple frequencies, has been of prime importance). Here (in Part 1 of Phase 2 research), however, attention is limited to linear response of structures and equipment; for this application, use of artificial motions possessing smooth response spectra may be adequate. Such adequacy is most clearly demonstrated through the comparison of structure and equipment demands resulting from the artificial motions, against similar results for real motions, representative of Eastern U.S. earthquakes, having roughly the same strength. Besides this, however, it is important that

the artificially generated motions themselves have time-history traces and strong-motion durations resembling those of real earthquake records for the Eastern U.S. (Matching a given target spectrum, in itself, does not insure that the time-dependent character of an artificial motion will appear reasonable; many artificial motions generated to match the same target spectrum may, in fact, demonstrate highly spurious time-dependent characteristics, i.e., time histories which are strange in appearance).

This study, therefore, also explores whether or not structure and in-structure demands resulting from artificial motions (generated both to match a given target spectrum and to possess reasonable time-dependent characteristics) are representative of such demands resulting from motions likely to occur in the Eastern U.S.

Potential Effects of the Type of Target Response Spectrum. Another aspect of this study pertains to the potential impacts of the type of target response spectrum selected for use in generating motions and computing evaluation demands. Among three peer-review, published SMA studies (12, 13, 14) conducted for Eastern U.S. nuclear power plants, two have relied upon seismic margin earthquake (SME) inputs most representative of Western U.S. motions, i.e., the NUREG/CR-0098 spectrum. Use of the NUREG/CR-0098 spectrum as SME has been thought to be generally conservative for purposes of seismic evaluation of nuclear power plants located in the Eastern U.S. Particularly for low-to-moderate frequencies (1 Hz to 5 Hz, approximately), the input demands of the NUREG/CR-0098 spectrum [anchored to a given peak ground acceleration (PGA) or to a given value of average spectral acceleration (averaged, say, over the frequency range of 2 Hz to 10 Hz)] will generally be notably greater than those exhibited by a site-specific input demand derived from the shape of the uniform hazard spectrum (UHS) [and anchored to the same basis as used for anchoring the NUREG/CR-0098 shape]. The opposite, however, may generally be the case for input demands at higher frequencies (above 8 Hz, approximately). For low-to-moderate frequency structures, and equipment (whether of high or low frequency) contained in such structures, therefore, use of the NUREG/CR-0098 spectrum should be generally conservative. Yet, for higher frequency structures, it is not clear that structural demands and in-structure spectral demands (i.e., equipment demands) computed for the NUREG/CR-0098 spectrum would not be frequently exceeded by corresponding results for a similarly anchored site-specific spectrum.

This study, therefore, also compares corresponding structure and in-structure evaluation demands produced by use of NUREG/CR-0098 spectra versus use of site-specific Eastern U.S. spectra based on UHS results.

1.2 APPLICABILITY OF THIS STUDY TO IPEEE

This study concerns development of ground-motion input for use in evaluating the seismic performance of nuclear power plants (NPPs). The purpose of evaluating NPP seismic performance is to better understand what might occur in the event of an earthquake that results in exceedance of the design basis (i.e., the design spectrum itself or computed in-structure seismic demands used in design). For any given NPP, the design basis will have a very low annual frequency of being exceeded. Evaluation demands will usually have significantly lower chance still of being exceeded; in all cases, evaluation demands can be categorized as rare, extreme, or severe for the given seismic environment within which the NPP lies. Consequently, this study is applicable to the performance of NPPs under severe earthquakes; i.e., earthquakes either with the potential to challenge a plant's design (and perhaps to induce the plant's severe-accident response mechanisms), or earthquakes having such low probability of occurrence that the risk of severe-accident response can be comfortably bounded to a sufficiently low level (of insignificant concern).

Evaluation of NPPs under severe conditions, having the potential to induce accidents or adverse impacts within a plant, has been the objective in developing both the Individual Plant Examination (IPE) and the Individual Plant Examination of External Events (IPEEE) programs, undertaken in response to the NRC's severe-accident policy (15, 16, 17, 18). The IPEEE program includes the evaluation of NPP severe-accident resistance to earthquake events. The present study, therefore, relates directly to seismic evaluations performed for IPEEEs, and technical reviews of such evaluations. The primary types of studies being implemented for IPEEEs include seismic margin assessments and probabilistic risk assessments.

1.2.1 Applicability to Seismic Margin Assessments

When implementing SMA methods in response to the IPEEE, guidelines outlined in NUREG-1407 (19) state that the NUREG/CR-0098 median rock or soil spectrum (depending on the primary site condition) should be used (except for plants in the reduced-scope category, where the SSE ground response spectra and in-structure spectra are to be used).

In cases where new in-structure spectra are generated for the IPEEE, artificial motion time histories are likely to be generated. These motions should produce spectra that match the NUREG/CR-0098 spectrum anchored to the appropriate value of the RLE (review-level earthquake). In addition, these motions should generally satisfy Standard Review Plan procedures and recommended PSD requirements compatible with design response spectra. Aside from this, it is reasonable to select motion parameters, such as characteristics of the

time-history enveloping function and the motion duration, to represent the expected nature of site-specific motions. Artificial time-histories thus generated should be checked to insure that they are not unreasonable representations of real earthquake ground motions.

The motivation for use of a non-site-specific shape in conducting an SMA is to have a consistent, standard basis by which severe-accident seismic capacity can be compared among various NPPs, regardless of the nature of the input. For Eastern U.S. sites, the consequence of using a standard review spectrum characteristic of Western U.S. motions is, as noted above, that demands in the case of higher frequency structures may potentially be underestimated.

This study is applicable to IPEEE investigation using SMA methods, in that it examines the impacts on structure and in-structure demands of (1) using a Western U.S. spectrum for Eastern U.S. sites, and (2) using a smooth target spectrum to represent the characteristics of real motions which have non-smooth spectra. Artificial motions derived from NUREG/CR-0098 spectra and Eastern U.S. uniform hazard spectra are produced to accomplish this examination.

1.2.2 Applicability to Probabilistic Risk Assessments

When implementing PRA methods in response to the IPEEE, for the purpose of developing seismic response demands, guidelines in NUREG-1407 (19) state that the median site-specific spectral shape of 10,000-year return period, as found in NUREG/CR-5250 (20), should be used (alternatively, other site-specific spectral shapes, derived from a suite of appropriate recorded earthquakes, may be used). For Western U.S. sites, spectral shapes are not provided in NUREG/CR-5250, requiring that the 10,000-year site-specific spectrum must either be determined, or some other consistent basis for establishing a site-specific spectral shape be implemented.

In nearly all cases where a new PRA is being conducted for the IPEEE, structural response and in-structure spectra will need to be generated. Again, this will be most frequently accomplished by generating a spectrum-compatible artificial time history and computing response-evaluation demands from this input. For motions representative of Eastern U.S. sites, as mentioned above, there are no standard guidelines and recommended PSD requirements compatible with expected motion spectra. Clearly, when developing artificial motions to match an Eastern U.S. spectrum, care should be taken to select motion parameters, such as characteristics of the time-history enveloping function and the motion duration, to represent the expected nature of real motions. Resulting artificial time-histories should likewise

be checked to insure that they have the basic appearance of real Eastern U.S. earthquake ground motions. There is no guarantee, in spite of such care that would normally be exercised, however, that the PSD characteristics of the artificial motions will represent those from real earthquakes. As noted above, there is the potential for gaps to exist within the PSD, and these can lead to the under-estimation of seismic evaluation demands.

This study is applicable to IPEEE investigation using PRA methods, in that it examines the potential for input PSDs used in PRA evaluations to have unwanted gaps, and it assesses the impacts of using artificial versus real motions on typical seismic demand measures developed for PRAs.

1.3 OVERALL STUDY ORGANIZATION

This study is an element of Phase-2 research pertaining to conservatism and variability in seismic risk estimates. The original Phase-1 study was undertaken to identify potential sources of error arising from approximations introduced in the way ground-motion input is often developed and used in seismic evaluation studies, and to determine the magnitude of such potential errors. Phase 1 resulted in a project report documenting the impacts of methods of ground-motion characterization on magnitude-dependent assessments of seismic hazard, fragility, and risk results (21).

The present Phase 2 research consists of a two-part investigation undertaken to examine specific additional aspects of the characterization and use of ground-motion input in seismic evaluation studies. Each part of Phase 2 research is documented in a separate volume of the overall report. This first part of Phase 2 (volume 1) addresses the impacts of using artificial versus real (empirical) time-history inputs to assess structure and equipment response demands. The second part examines the effects of using the uniform hazard spectrum (UHS) as input for deriving probabilistic estimates of in-structure demand levels, as compared to more-exact use of realistic time history inputs (of given probability) that depend explicitly on magnitude and distance. In addition, we also need to understand the effect of UHS on obtaining failure probabilities for components and systems (as opposed to in-structure demand levels) and ultimately, develop methods for assessing representative, simplified seismic inputs for evaluation purposes. These topics, however, will depend heavily on the findings of the current research and are not included in the scope of this study.

The approach throughout Phase 2 differs significantly from that in Phase 1, particularly in its more exhaustive treatment of the ground-motion threat, and in its more detailed assessment of component responses to that threat.

The significant topics addressed in Phase 1 were: (1) the relative conservatisms inherent in using Western U.S. type spectral shapes to characterize the seismic threat at Eastern U.S. sites; (2) the impact of magnitude disaggregation on assessments of seismic fragility, hazard, and risk; (3) the implications of nonlinear dynamic response modeling on magnitude-dependent results; (4) the effect of alternate motion parameterizations (PGA, spectral acceleration average over a frequency range of interest, inelastic spectral acceleration at a given frequency) on fragility and risk results; and (5) the impact of strong-motion duration on fragility estimates.

To address these topics, Phase 1 implemented methods for development and use of motion characterization considerably more detailed than those used in normal seismic evaluation practice. Hazard assessment and fragility assessment were conducted on a magnitude-dependent basis. A large number of highly realistic magnitude-dependent motions were simulated. Magnitude-dependent fragility families were obtained using nonlinear time-history analysis for the simulated motions and an extensive set of structural model parameters. The methods employed in fragility assessment were quite similar to those implemented in the state-of-the-art fragility study of the Diablo Canyon turbine building (22). Magnitude-dependent hazard and fragility results were combined to obtain magnitude-dependent risk estimates, revealing the contributions to core-damage frequency from each magnitude range considered. Results of this type of seismic risk assessment were compared with results from methods of seismic risk assessment normally implemented in practice. The sensitivity of seismic fragility curves and computed seismic risk estimates, to a variety of parameters (PGA, average spectral acceleration, and inelastic spectral acceleration) for characterizing ground motion input, was examined.

Despite the detail of Phase 1 investigation, a number of important issues regarding ground-motion input to seismic evaluation studies still remained to be addressed or clarified. These issues were raised in an early project meeting, and were described by the following questions:

- Does the UHS define the most appropriate basis of ground-motion input in a seismic PRA or SMA?
- Can realistic, expected input to equipment mounted in structures be obtained in a practical way? Through use of a single motion time history, either artificial or real? Through use of a small suite of time histories?

- How can the multitude of possible spectral shapes be represented by practical descriptions of input ground motion, particularly to capture the expected impacts on system responses which are sensitive to simultaneous impacts on both low-frequency and high-frequency components? [In a real earthquake motion, input demands at low frequency and high frequency will vary from average demands in a random, yet (weakly) correlated way, with resulting random effects on system response. Because system response (failure or success) is not a simple linear function of motion demands at individual component frequencies, the expected impacts on system response may not be very well represented by component demands derived from a single motion with a smooth response spectrum.]
- Why is the variability in response spectra treated as simple randomness, i.e., by values of σ at given frequencies, without consideration of the correlation of amplitudes across frequency that lead to variations in spectral shape?
- Is there an appropriate (i.e., consistent with the seismic hazard) and practical (i.e., manageably small) set of scenario earthquake motions that may be used to produce realistic input for seismic evaluations? How can such earthquakes be developed or identified? How can it be insured that these earthquakes are physically consistent?

Each of these questions implies that the UHS shape is generally not representative of specific real motions that might be expected in real earthquakes. Consequently, evaluation demands determined using the UHS shape as the basis for input may likewise not be representative of real earthquake demands. For a system that responds primarily to a narrow range of frequencies, the variations in spectral shape found in real earthquake motions would intuitively be less important than for multiple-frequency systems. Yet, in the typical case, NPP systems will respond importantly to multiple frequencies, and hence, maintaining realistic variations in input spectral shape may likely be important.

The critical issue to be resolved in Phase 2 investigation, therefore, is whether one must rely on realistic scenario earthquakes to adequately represent evaluation demands for structures and equipment mounted in structures, or whether a suitable procedure may be found for one to adequately assess evaluation demands using the UHS (or using motions derived simply therefrom).

To resolve this issue, it was decided that a much more complete description of the seismic threat would be needed to ascertain the adequacy of the UHS. Such a description of

the seismic threat would be most accurately conveyed by a large suite of ground motions (with realistic variabilities in spectral shape) obtained from a comprehensive set of scenario earthquakes developed for all magnitude-distance pairs. To complete the description of the seismic threat, associated values of annual probability for each motion would be required. The motions and their respective probabilities could then be used in any way; i.e., to evaluate probabilities of in-structure demands, probabilities of component and system response states (including component and system failures), etc. These results could be readily compared with corresponding results derived from use of the UHS shape alone.

The approach in Phase 2, therefore, relies on an entirely new format for conducting probabilistic risk assessment; one that does not make use of seismic hazard and fragility curves, but rather, is based on fundamental (scenario) events (motions) and their probabilities for all possible cases. Knowing the scenario motion time histories and their probabilities, whatever responses of interest (in-structure demands, component failures, system failures, etc.) can be computed directly, and corresponding risk measures can be directly obtained. The approach is more detailed and precise than conventional methods used for seismic risk assessment, because it introduces no simplifying approximations in characterizing the motion threat, which in turn effects the nature and accuracy of component and system response assessments. Thus, it serves as an accurate analysis for comparison of results with conventional methods that do introduce such approximations in motion characterization and seismic risk methodology.

Because this approach to seismic risk assessment is new, the principal task in Phase 2 work has been to fully develop the methodology, which has involved a rigorous approach for developing scenario motion time histories. This development, however, has been only a means to an end; that of being able to assess the most representative, simplified motion input to seismic evaluation studies. To accomplish this objective systematically in search for meaningful answers to the questions noted above, the following elements of project study in Phase 2 were identified. These elements correspond to the parts noted earlier; the objective and format of each of these studies is described as follows:

- Part 1, Impacts of the Use of Artificial Motion Inputs

Before impacts on system responses, inelastic responses, risk measures, and the like are considered for (M,R)-dependent motions, a more basic concern to be addressed has to do with the appropriateness of using artificial time history inputs in seismic evaluation studies. Specific issues pertaining to this concern have been described

in Section 1.1. Overall, the fundamental aspect of Part 1 study is to determine whether or not artificial motions, generated to match a UHS shape using common procedures and recommendations for motion simulation, produce realistic evaluation demands for NPP structures and equipment; i.e., demands generally representative of those computed for strong empirical earthquake motions. The intent in Part 1 is not to address what specific (M,R) pairs might dominate evaluation-demand risks or failure risks, and hence, to ascertain whether or not artificial motions adequately represent effects of those specific risk-dominant magnitudes and distances. Rather, the intent is to test simply if a single artificial motion input would generally tend to either possess or produce fundamental characteristics that are deficient with respect to corresponding characteristics expected from a real strong ground motion. All analyses undertaken for Part 1 study pertain to linear structure and equipment responses.

- **Part 2. Realistic Evaluation of In-Structure Demand Risks**

The purpose of this study is to develop realistic and accurate descriptions of risk-consistent floor motions (in-structure response spectra) to be used as input to equipment, and to test whether or not the UHS can be used as a basis for developing realistic risk-consistent input to equipment mounted in structures. All analyses for this study pertain to linear structure and equipment responses.

The first aspect of this study is to obtain uniform-hazard in-structure spectra directly by using scenario motion time history inputs (and their probabilities) and evaluating in-structure demands for each scenario time history. Knowing the in-structure demands and their annual rates of occurrence, the probability of exceeding any given level of in-structure demand can be determined; alternatively, the in-structure demand level corresponding to a given annual probability of exceedance can be evaluated. A plot of in-structure demands, as a function of equipment vibration frequency, for a fixed annual probability level, results in a uniform-hazard in-structure spectrum (UH-ISS). An approximation to the UH-ISS can be obtained simply by generating an artificial motion that closely matches the UHS, and calculating the in-structure spectrum (ISS) corresponding to this input. For instance, a 10^{-4} UH-ISS can be approximated as a corresponding ISS computed in response to an artificial motion that is closely compatible with the 10^{-4} UHS.

The second aspect of this study is to examine how shapes of scenario ISS [derived from motions for given magnitude-distance (M,R) pairs] compare with shapes of UH-ISS and shapes of ISS derived from artificial motions generated from the UHS shape.

These two parts will hopefully provide a solid foundation that can be extended for further study in the future of realistic evaluation of NPP component and system and ultimately lead to the development of simplified methods for obtaining and using representative motion inputs.

1.4 REPORT ORGANIZATION

A detailed outline of the study conducted for Part 1 of Phase 2 work is provided in Chapter 2. The study approach and parameters are fully described in that chapter, including the types of target response spectra used, the set of empirical earthquake motions included for comparison, the properties of the structural models, and the locations and other variables employed in developing in-structure demand spectra.

In Chapter 3, the various procedures for simulating artificial ground motions is presented. Artificial motion time histories, their response spectra, and their Fourier amplitude spectra are plotted. These results are compared with corresponding results for the real earthquake motions, and a discussion of the comparisons is provided.

Chapter 4 presents the results of in-structure response spectrum analyses conducted using the empirical earthquake ground motions as inputs. Chapters 5 and 6 present the results of in-structure evaluation-demand computations for artificial motions generated to match specific target response spectra. In Chapter 5, a single time history is used to describe the input associated with each target spectrum; thus, each time history has a smooth response spectrum that closely matches its target. In Chapter 6, for each target spectrum, a suite of artificial motions, with each motion having realistic peak-to-valley variations in spectral shape (representative of those exhibited by real earthquake records), are used. Any such motion does not, by itself, have a response-spectrum shape that closely matches its target spectrum. But a sufficient number of such motions will, on average, match the particular target spectrum of interest. For this study, a set of five simulated motions with realistic variations in response spectral shape are obtained and used for each target spectrum. Chapter 6 thus presents and discusses results of both motion-specific in-structure evaluation demands, and average in-structure demands, obtained for the five artificial motions.

Chapter 7 provides a detailed comparison of evaluation demands among the three sets of in-structure response spectra results presented in Chapters 4 through 6. Various bases for anchoring the input motion spectra, so that comparisons are made on a consistent basis among results, are considered. Hence, in-structure demand results are scaled, and compared, to

consider cases where input motion spectra are anchored (separately) to have identical values of PGA, identical values of spectral acceleration (at fundamental structural frequencies), and identical values of average spectral acceleration (where the frequency range for averaging is 2 Hz to 10 Hz). Results of these various comparisons are discussed.

Finally, Chapter 8 summarizes the comparisons, and provides conclusions pertaining to the impacts, on seismic evaluation studies, of using artificial time history inputs to develop in-structure demand spectra. Implications of these Part-1 study results and conclusions to considerations in Part 2 of the investigation are clarified.

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Section 2

DESCRIPTION OF STUDY APPROACH AND PARAMETERS

To examine the impacts of artificial time history input on in-structure evaluation-demand spectra, an analytical parameter study is undertaken. This approach is appropriate because similar analytical methods, response models, and parameter characterizations are employed in actual seismic evaluation studies. The impacts observed in this study should, therefore, correspond well with expected impacts on results of seismic margin assessments or probabilistic risk assessments undertaken, in practice, for nuclear power plant evaluations.

This chapter provides an outline of the basic study approach, and identifies the set of parameter variations used in producing the numerous results. The intended use of the parameter study results, for making comparisons and drawing relevant conclusions, is also explained.

2.1 OUTLINE OF PARAMETER STUDY

The principal elements of work undertaken for this parameter study can be outlined as follows:

1. Selection of Target Response Spectra.

Target response spectra are those for which artificial motions are generated to match. In many seismic margin studies for the Eastern U.S., input motion spectra characteristic of the Western U.S. have been used. In other SMA studies and in seismic PRA studies of Eastern U.S. nuclear power plants, site-specific input motion spectra characteristic of the Eastern U.S. are used. For Western U.S. NPP sites, site-specific input motion spectra characteristic of the Western U.S. are always used. Consequently, selection of target spectra in this study has involved consideration of both Eastern U.S. and Western U.S. motions. In addition, this selection has considered both rock and soil sites.

2. Generation of Artificial Motions Matching Target Spectra.

Common procedures for generating an artificial motion that matches a target response spectrum rely on fundamental random-vibration analysis. In these procedures, energy

in the PSD is generally increased or decreased, over selected frequency ranges, to alter the amplitudes of the response spectrum. A trial and error process is generally used in modifying the PSD to produce a close match between the resulting response spectrum and the target response spectrum.

Various means are used to obtain an appropriate PSD. A real motion may be used to obtain an initial PSD, which is subsequently altered, producing a modified version of the original time history. The original time history is chosen to match as closely as possible the characteristics of expected motion for the evaluation site. This approach helps insure that the time-history trace of the final motion will appear relatively normal. Alternatively, a PSD can be initially assumed in a fundamental form, and then altered to match the target spectrum. An appropriate analytical time-dependent enveloping function and appropriate motion duration are used to help insure that the time-history trace of the motion does not appear abnormal. Another method is to derive an appropriate site-specific PSD from variations of geophysical parameters and engineering parameters used as inputs to random-vibration models of wave propagation through bedrock and soil. The PSD thus obtained will result in a representative time-history wave-form, by using an appropriate enveloping function and value of motion-duration.

Whatever the specific approach implemented, the usual result is a motion with smooth response spectrum that closely matches (or envelopes) the target response spectrum. The time history of such a motion typically appears to have the characteristics of real earthquake ground motions. The smoothness of its response spectrum, however, suggests that it is artificial; real earthquake motions rarely produce smooth response spectra.

To produce motions with more realistic characteristics, it is useful to remove the constraint that a given artificial motion should closely match the target response spectrum, and simply insure that the average response spectrum from a set of artificial motions closely matches the target. Such an approach can be taken in generating improved artificial motion input to seismic evaluation studies. An artificial motion, thus produced, will generally possess a "jagged" response spectrum; i.e., one with significant peaks and valleys that do not typically align with amplitudes of the target spectrum. When the response spectra for a sufficient number of such artificial motions are averaged, however, the result is a smooth spectrum which does closely match the target. Hence, individual variations in spectral shape are demonstrated by the artificial motions. The variations in spectral shape are not obtained haphazardly,

but rather, are simulated based on empirical results of the correlation among spectral amplitudes across vibration frequency. Consequently, artificial motions with spectral shape variations representative of those exhibited by real earthquake motions can be obtained. The principal drawback to this approach for specifying artificial motion input, however, is that it multiplies the effort required in assessing response demands. This increased effort, nonetheless, may be required to produce adequate and realistic evaluation results.

In this study, methods for producing artificial motion inputs having smooth response spectra are implemented to represent the manner in which motions are typically obtained for seismic evaluation studies. Methods for producing artificial motion input with jagged response spectra are also introduced, in order to present an improved way for developing simplified motion input to seismic evaluation studies, and to compare demands derived from alternative approaches for simulating artificial motion inputs.

3. Selection of Empirical Motions.

Use of empirical motions enables comparisons to be made among evaluation demands derived from the artificial motion inputs and corresponding demands (similarly scaled) produced from representative real earthquake motions. Also, PSDs of the artificial motion inputs can themselves be directly compared with those from real earthquake records. For these purposes, this study involves selecting appropriate empirical records representative of Eastern U.S. motions and Western U.S. motions. The main objective in selection of empirical earthquakes for the purposes of this study is to use a set of strong motions from earthquakes with significant magnitudes.

4. Selection of Structure Model Parameters.

In order to obtain seismic evaluation demands for structures and for equipment mounted in structures, it is necessary to have representative structural models. The purpose in this study is to consider a variety of evaluation demands developed for a number of alternative, likely cases. Multiple parameters variations of structural vibration frequency and structural configuration are selected for this purpose.

5. Selection of Parameters Defining In-Structure Spectra.

Parameters defining in-structure spectra must also be selected for this investigation. The parameters which need to be considered for this purpose include: the locations of in-structure spectra, the set of frequencies used to represent in-structure spectra, and the value of damping for constructing in-structure spectra.

6. Time-History Computations of Seismic Evaluation Demands.

Once all motion inputs, structural model variations, and parameters defining in-structure spectra have been developed, response analyses need to be conducted to determine evaluation demands for structures and equipment. In all cases introduced in this report, structures are considered to behave linearly and vibration responses are evaluated using multiple-degree-of-freedom stick models subjected to base input. Hence, linear dynamic analyses of lumped mass models are conducted to obtain time histories of floor-motion responses for the structural models subjected to the artificial and empirical motion inputs. From results of inter-story forces or displacements, structural evaluation demands, in terms of maximum forces (and maximum displacements), are obtained. From time histories of floor absolute accelerations, equipment evaluation demands are computed as in-structure (floor) response spectra.

7. Comparisons of Seismic Demands.

The final aspect of this study is to plot and compare results of seismic demands obtained for the various cases. In particular, results obtained for corresponding cases of structural model parameters and parameters defining in-structure spectra, are compared for different input motions. Where multiple artificial motions with jagged spectra are used as input for analysis, individual demands for each motion are presented as well as the average of the demands produced by all such motions.

For meaningful comparison, it is important to have a common basis for anchoring or scaling the input motions and the results they produce. Since all evaluation analyses in this report pertain to linear response of structures and equipments, all demands can be scaled linearly corresponding to modifications in scale of the input motions.

Although a fairly large number of parameter variations are considered in this study, the objective is to produce representative results, as opposed to an exhaustive set of results derived from all possible combinations of models and parameters. In this way, comparisons are facilitated and attention is focused on specific cases of substantial interest.

2.2 DESCRIPTION OF PARAMETER-STUDY VARIABLES

Emphasis in selection of parameter-study variables has been on constructing cases that are applicable primarily to the Eastern U.S. or to typical seismic evaluation practice employed for Eastern U.S. plants. This is the case because the impacts of current practice with respect to artificial motions, on response demands computed in seismic evaluation studies, are expected

to be more critical for Eastern U.S. applications. (In other words, the main concern that has served as impetus for this study relates primarily to impacts for Eastern U.S. NPPs. That is, formal requirements for developing artificial motions representative of the Eastern U.S. have not yet been developed, whereas such requirements have been developed for Western U.S. motions.) Cases representative of the Western U.S. are nonetheless considered in this study, but mainly for the purpose of enabling comparisons with Eastern U.S. results. Impacts of significance, in conducting seismic evaluation studies, that are common to both the Eastern and Western U.S. are addressed, however, and cases of importance to Western U.S. seismic evaluation studies are noted as appropriate in this report.

2.2.1 Target Response Spectra

Four sets of target response spectra were chosen for consideration in this study. Each set consists of two response spectra, one spectrum for rock conditions and one spectrum for soil conditions. A total of eight target spectra are, therefore, used as bases for generating artificial time-history motion inputs. Six spectra apply to Eastern U.S. sites and two spectra represent design criteria derived from Western U.S. motions. These target response spectra are identified and described as follows:

Set #1

- [TEr] The 10,000-yr median uniform hazard spectrum for the Millstone nuclear power station, as obtained from EPRI NP-6395-D (1). This spectrum represents results from an EPRI hazard analysis for rock-site conditions.
- [TEs] The 10,000-yr median uniform hazard spectrum for the Pilgrim nuclear power plant, as obtained from EPRI NP-6395-D. This spectrum represents results from an EPRI hazard analysis for soil-site conditions.

Set #2

- [TLr] The 10,000-yr median uniform hazard spectrum for the Millstone nuclear power station, as obtained from NUREG/CR-5250(2). This spectrum represents results from an LLNL hazard analysis for rock-site conditions.
- [TLs] The 10,000-yr median uniform hazard spectrum for the Pilgrim nuclear power plant, as obtained from NUREG/CR-5250. This spectrum represents results from an LLNL hazard analysis for soil-site conditions.

Set #3

- [TL2r] The 10,000-yr median uniform hazard spectrum for the Millstone nuclear power station, as obtained from NUREG-1488(3). This case corresponds to TLr, but is based on revised LLNL hazard estimates.
- [TL2s] The 10,000-yr median uniform hazard spectrum for the Pilgrim nuclear power plant, as obtained from NUREG-1488. This case corresponds to TLs, but is based on revised LLNL hazard estimates.

Set #4

- [TWr] The median, 5%-damped rock spectrum, as obtained from seismic criteria presented in NUREG/CR-0098(4). This spectrum characterizes Western U.S. motions and represents typical criteria used in seismic design and in SMA evaluation of Eastern U.S. plants and Western U.S. plants founded on rock.
- [TWs] The median, 5%-damped soil spectrum, as obtained from seismic criteria presented in NUREG/CR-0098(4). This spectrum characterizes Western U.S. motions and represents typical criteria used in seismic design and in SMA evaluation of Eastern U.S. plants and Western U.S. plants founded on soil.

For sets 1, 2 and 3, the 10,000-yr median UHS was chosen, as this input reflects IPEEE recommendations for PRA investigation of NPP severe-accident response (5). All eight target spectra have different amplitude levels, as indicated in the plots of the target spectra shown in Figures 2-1 and 2-2. In generating artificial motions, the important objective is to match the shape of the target spectrum. Once the shape is matched, the proper amplitude of spectral ordinates can be achieved simply by scaling the motion time history appropriately, which correspondingly scales the motion response spectrum. (It is important, of course, to select representative motion characteristics, e.g., a proper value of motion duration, for the purpose at hand). The basis for scaling motions to a prescribed level, to establish consistency when comparing evaluation demands produced from various motions, is described in Section 2.2.6.

The target spectra shown in Figures 2-1 and 2-2 differ, to varying degrees, in terms of shape. Not all target spectral shapes differ meaningfully, and it is not of importance to develop and compare evaluation-demand results produced for similar cases. Consequently, not all of the eight cases of target spectra described above are needed in establishing distinct inputs for purposes of developing and comparing results. Those cases which do produce meaningfully different results, attributable to notable differences in target spectral shape, are subsequently identified and serve as the focus for the final comparisons in Chapter 7.

2.2.2 Artificial Motions

For each of the eight target response spectra, two sets of artificial motions are generated. The first set consists of one motion, and the second set consists of five motions. These sets of artificial motions are identified and described as follows:

[MArS1] A single artificial time history with a relatively smooth response spectrum that closely matches the given target spectrum.

[MArJn] Five artificial time histories, each with a jagged response spectrum, representing realistic variations in spectral shape. The average response spectrum over the five motions produces a smooth spectrum which matches the target spectrum. [The approach used in developing these motion simulations is such that a large number of motions (on the order of 50 to 100) is generally needed to produce an (natural, unforced) average response spectrum that closely matches the target spectrum. Closely matching a target spectrum with only five motions (i.e., forcing a fit) introduces analytical constraints which somewhat compromise the realism of the simulated motions. This issue is discussed in some detail in Chapter 3, particularly with respect to the tendency to introduce unrealistic energy gaps in the PSDs of individual artificial motions]. The five motion simulations are identified by codes MArJ1, MArJ2, MArJ3, MArJ4 and MArJ5. Results pertaining to averages derived from these motions are identified by the code MArJAvg.

The procedures used in simulating each set of artificial motions are described in Chapter 3. A total of 48 artificial motions are produced for this study: six simulations for each of the eight target spectra. Subsequently in this report, artificial motions are identified by a combination of codes designating the target spectrum and the simulation basis. For example, motion MArJ2(TLs) is the second artificial motion, having jagged spectrum, generated to match the LLNL target soil-site spectrum.

2.2.3 Empirical Motions

Eight empirical motions are used in this study. Four of these are from the M_{Lg} 6.5 Saguenay, Québec, Canada earthquake of November 25, 1988 (6); three are from the M_S 6.9 Nahanni, Northwest Territories (NWT), Canada earthquake of December 23, 1985 (7, 8, 9); and the remaining one is from the M_S 6.5 Imperial Valley, California earthquake of October 15, 1979. Of the four Sageunay records, one was recorded on soil, and the rest on rock; all three Nahanni records were recorded on rock; and the Imperial Valley, CA record was recorded on soil. These eight records are identified and described as follows:

- [MSag1] The longitudinal component (214°) recorded on bedrock at the Chicoutimi-Nord, Québec station (Site 16); PGA=0.11g.
- [MSag2] The longitudinal component (0°) recorded on bedrock at the St-André-du-Lac-St-Jean, Québec station (Site 17); PGA=0.16g.
- [MSag3] The longitudinal component (0°) recorded on bedrock at the Les Éboulements, Québec station (Site 20); PGA=0.13g.
- [MSag4] The transverse component (85°) recorded on alluvium at the Baie-St-Paul, Québec station (Site 7); PGA=0.17g.
- [MNah1] The 280° component of motion recorded on bedrock at the Iverson station (Site 1); PGA=1.35g.
- [MNah2] The 330° component of motion recorded on bedrock at the Slide Mountain station (Site 2); PGA=0.39g.
- [MNah3] The 360° component of motion recorded on bedrock at the Battlement Creek station (Site 3); PGA=0.19g.
- [MImp1] The 140° component of motion recorded on alluvium at the El Centro Array, No. 5 station; PGA=0.53g.

Table 2-1 provides, for later reference, a summary of the characteristics of each empirical motion used in this study. Figures 2-3 and 2-4 present plots of unscaled ground acceleration versus time for the set of empirical motions; corresponding response spectra plots are provided in Figures 2-5 to 2-8, and PSD plots are shown in Figures 2-9 to 2-12.

In selecting records from the Saguenay and Nahanni earthquakes, the objective was to find the strongest available motion records believed to well represent characteristics of motions that might be caused by significant earthquakes in the Eastern U.S. In terms of Eastern U.S. seismicity, the magnitudes of these two earthquakes are large, and the selected motions, among those available, generally have the greatest potential for causing damage to structures and equipment.

The record from the Imperial Valley, CA earthquake was chosen to represent a typical strong Western U.S. motion. The frequency content of this motion differs significantly from motions representative of the Eastern U.S. The earthquake magnitude and duration associated with this record, however, are not unrepresentative of those that would define likely severe-motion input for the Eastern U.S.

2.2.4 Structural Models

Three structural models are used to examine the effects of each artificial and empirical motion input on response demands. These models are identified and described as follows:

- [St3] A five degree-of-freedom (DOF) model of a hypothetical NPP five-story building having 3-Hz fundamental vibration frequency. The model has uniform mass and stiffness.
- [St7] A five degree-of-freedom model of a real, four-story NPP control building having 7-Hz fundamental vibration frequency. This model was used as the basis for fragility analyses and failure probability calculations in Phase 1 study (10).
- [St10] A two degree-of-freedom model of a hypothetical two-story NPP building having 10-Hz fundamental vibration frequency. The model has uniform mass and stiffness.

Structural damping in all cases is assumed to be 5% (of critical) in the first two modes. [The value of 5% is typical of values recommended for seismic margin evaluations (11)]. Damping ratios for higher modes are computed based on Rayleigh damping. Tables 2-2 to 2-4 present basic dynamic characteristics of the three structural models.

2.2.5 In-Structure Spectra

In-structure spectra (ISS) results are computed for each building structure. For structure St3, ISS results are obtained at floors 1, 3 and 5; for structure St7, ISS demands are evaluated at floors 1, 3 and 4; and for structure St10, ISS results are presented for floors 1 and 2. Subsequently in this report, specific ISS results are identified by a combination of codes designating the particular structure and floor location. For example, the code ISS2(St10) refers to the in-structure spectrum obtained for the second floor in the 10 Hz, 2 DOF building model.

In each ISS analysis, maximum acceleration responses are calculated for a set of 100 equipment fundamental-vibration frequencies. These frequencies vary from 0.1 Hz to 50 Hz, and are equally spaced on logarithmic scale.

The damping used in all ISS analyses is 5%. Again, 5% is a representative value of equipment damping recommended for use in SMA evaluation procedures (11).

2.2.6 Parameters for Anchoring/Scaling Motions

The target spectra specified in Section 2.2.1, in general, have different relative amplitudes (at given frequency). Hence, motions simulated to match these spectra may likewise have notably different amplitudes. In addition, the empirical motions selected for use in this study also have significant differences in amplitudes of ground acceleration. Evaluation demands computed from the various motions cannot be simply compared, because of inconsistencies in the level of input motion. In order to compare, on a consistent basis, demands produced from the various motions, it is necessary to have a common means for scaling or anchoring motions, as described in Section 2.1.

The parameters used for anchoring motions to a common basis in this study include PGA, spectral acceleration averaged over a narrow vicinity ($\pm 15\%$) surrounding the structural vibration frequency, and spectral acceleration averaged over the broad frequency range of 2 Hz to 10 Hz. A total of five bases for scaling motions are thus considered for this study:

[ScPGA] All motions are scaled to a common PGA of 0.3g.

[ScSa3] All motions are scaled to a common value of spectral acceleration, in the vicinity of 3 Hz (average over 2.55 Hz to 3.45 Hz), of 0.6g.

[ScSa7] All motions are scaled to a common value of spectral acceleration, in the vicinity of 7 Hz (average over 5.95 Hz to 8.05 Hz), of 0.6g.

[ScSa10] All motions are scaled to a common value of spectral acceleration, in the vicinity of 10 Hz (average over 8.50 Hz to 11.50 Hz), of 0.6g.

[ScASA] All motions are scaled to a common value of average spectral acceleration — where the average is taken over the frequency range of 2.00 Hz to 10.0 Hz — of 0.6g.

Because all analyses in this study are for linear responses, computed evaluation demands can be simply scaled to reflect, exactly, changes in scale of the input motion. Hence, once ISS responses have been evaluated for a given input motion, these responses may be simply adjusted by an appropriate scale factor reflecting the desired anchor basis for the input motion. The scale factor is simply the desired value of the specific motion parameter divided by the actual value of the parameter computed for the motion. For instance if an input motion is to be scaled to have a desired (common) value of average spectral acceleration equal

to 0.6, whereas the computed value of average spectral acceleration for the original (unscaled) motion is 0.15, a scale factor of $(0.6/0.15)=4.0$ would be introduced. All ISS results (and structural forces and displacements) based on the unscaled motion input would simply be multiplied by the factor of 4.0, in order to obtain the desired demands for subsequent comparisons.

Because the artificial motions produced for this study have been generated to very closely match (to within 5%) their associated target spectra, scaling of evaluation results is based simply on relative spectral amplitudes of the target response spectra, rather than on the relative spectral amplitudes for the artificial motions themselves. Variations within about 5%, in computed evaluation demands for empirical versus artificial motions are, therefore, considered unimportant. For artificial motions MArJn, a single scale factor is applied, in any given case, for all five motions (as opposed to scaling each motion independently). The single scale factor is determined as the desired motion amplitude normalized by the amplitude of the appropriate target spectrum. Hence, individual motions in this case will not be anchored to the same basis, but the average of the motions will be anchored appropriately (which is one logical manner in which such motions would be used in seismic evaluation studies). Consequently, when comparing structure and in-structure demands for this case, the average demands (for the five motions) are presented, together with variations in demands resulting from the five individual cases.

In this study, artificial motions MArS1, the average of artificial motions MArJn, and all empirical motions are initially scaled to achieve a desired initial, reference anchor basis, in terms of a PGA value of 0.3g. Incremental scale factors are then applied to these reference cases to achieve other desired anchor levels, such as spectral acceleration in the vicinity of a structure's predominant-response frequency and average spectral acceleration over 2 to 10 Hz. For subsequent reference, Table 2-5 presents the reference scale factors which adjust the original empirical motions to the common PGA of 0.3g, as well as the incremental scale factors adjusting these inputs to achieve the other motion-anchoring bases of interest. Corresponding scale factors which are to be applied to the artificial motions, for achieving the various anchor bases, are presented in Table 2-6. These two sets of scale factors are used to adjust demands appropriately, enabling consistent comparisons of demands produced for the various cases of empirical and artificial inputs.

Comparisons of Motion Spectral Shapes. To give an idea of the impact, on comparative response demands evaluated for artificial time-history inputs, Figures 2-13 to 2-17 show the various target response spectra scaled according to each of the five different anchoring bases.

Examination of these figures reveals that, when scaled to a consistent anchor basis (regardless of the particular scale parameter), all Eastern U.S. target spectra have very similar shapes, and display relatively minor variations amongst one another. Spectra TL2r and TL2s have nearly identical shapes, and targets TLr and TLs have very similar shapes. Targets TEr and TEs differ somewhat in shape, yet not greatly. In addition, the shape of TL2r or TL2s is very similar to an average of the shapes TEr and TEs. The shapes of TLr and TLs are slightly broader below 10 Hz than the other four Eastern U.S. target spectra, and above 10 Hz they are noticeably flatter than (i.e., not as amplified as) the other spectra. Consequently, among the six Eastern U.S. target spectra, two groups can be identified as having subtle differences in spectral shape: (1) the spectra TEr, TEs, TL2r, TL2s, and (2) the spectra TLr and TLs.

Among the two Western U.S. target spectra, TWr and TWs, a difference in shapes is seen only below about 2.2 Hz; above this frequency, the spectra are identical. Because this study examines motion impacts on evaluation demands for structures and equipment having vibration frequencies no lower than 3 Hz, the difference in shapes of TWr and TWs has no practical significance on the results of this study. In other words, these two spectra are essentially identical for the purposes of this study. Target spectra TWr and TWs, therefore, together define a third spectral-shape group among the entire set of eight target spectra.

Clearly, the most significant variation in spectral shapes among the the three groups of target spectra is, as expected, between the Eastern U.S. spectra and the Western U.S. spectra. Response demands are not expected to vary significantly among those produced for artificial motions matching any of the Eastern U.S. spectra. Response demands are expected to vary among those produced for artificial motions matching Eastern U.S. spectra versus Western U.S. spectra. These response variations are expected simply due to variations in input demands, among Eastern U.S. type spectra and Western U.S. type spectra, in the vicinities of structural modal vibration frequencies. Such variations in response are readily predictable from structural dynamics; fundamental differences in characteristics of Eastern U.S. and Western U.S. motion spectra translate to determinable fundamental differences in dynamic response characteristics of important NPP components. Such fundamental differences in the nature of response to Eastern U.S. and Western U.S. motions are demonstrated in the results of this study. These results serve to clarify that, in order to well anticipate the nature of response of a NPP to a potential severe seismic accident, the most representative (site-specific) motion input must be used in any seismic evaluation study. Use of a Western U.S. spectrum as input to seismic evaluation for an Eastern U.S. plant encourages fundamental misunderstanding of how the plant can be expected to respond to potential severe earthquakes.

Aside from these points, the major concern of relevance to the objectives of this study is how evaluation demands computed for artificial motions compare with those computed for empirical records. Are the demands computed from artificial motions spuriously low, in some instances, compared to those computed for similarly scaled empirical motions? For (artificial versus empirical) Western U.S. motions, one can confidently answer "no" to this question, provided appropriate (and well-known) PSD requirements and simulation procedures are followed. For Eastern U.S. motions, in the absence of detailed comparative investigation, formal PSD requirements, and agreed simulation procedures, the answer to this question is uncertain.

Real earthquake ground-motion spectra, scaled to each of the five alternate anchor bases described above, are presented in Figures 2-18 to 2-22. These plots demonstrate variations in spectral shape representative of real Eastern U.S. motions. Even when similarly scaled, significant variations in spectral amplitudes exist among the motions. These input variations will result in predictable variations in evaluation demands, both with respect to the other empirical motions and with respect to artificial motions. The spectral shapes of the empirical motions, on average, however, roughly match the shapes of corresponding target spectra. Consequently, the average demands produced by artificial motions and empirical motions (for corresponding cases) should be substantially similar. If, however, the average demands computed for the artificial motions are notably lower than those produced from empirical motions, a deficiency in the artificial motions is suggested, which must be identified and corrected.

2.3 USE OF PARAMETER-STUDY RESULTS

Results of this parameter study include structure and equipment responses computed for a variety of real and artificial motions. These results are used to represent and compare demands that would be produced in actual seismic evaluation studies. Tables of structural demands, plots of in-structure response spectra, and plots of input PSD, are all produced. Comparisons are made for three distinct groups of motions: the empirical records, the simulated motions having smooth response spectra matching the target spectra, and the simulated motions with jagged spectra that, on average, match the target spectra. Within-group comparisons and between-group comparisons are made among the results.

Within-group comparisons for the empirical motions show average demands, and motion-to-motion variability in demands, for specific comparison categories (Eastern U.S. rock motions, Eastern U.S. soil motions, and Western U.S. motion, each scaled to a given anchor basis). These comparisons demonstrate typical variations in seismic demands due to real variations

in input spectral shapes, and variations in average seismic demands among each category. Within-group comparisons for the artificial motions with smooth spectra show variations in seismic demands resulting from each target spectrum. These comparisons reveal similarities in demands (among the distinct spectral-shape groups of target spectra) that allow the number of inter-group comparisons to be reduced, by selecting only those artificial motion cases where meaningful differences are observed in results. (That is, only those target spectra resulting in notably different demands are important to consider). Within-group comparisons for the artificial motions having jagged spectra are made on a similar basis as comparisons for artificial motions having smooth spectra. Hence, results of average evaluation demands show variations in seismic demands produced for the various target spectra. And, similarity in demands among the target spectra is used as a basis to effectively narrow the scope of subsequent inter-group comparisons. Because, however, five motions are considered for each set of artificial motions with jagged spectra, motion-to-motion variations in demands can be seen (and later compared with such variations in demands seen for real motions). The general purpose of all within-group comparisons is to organize the evaluation-demand results in a meaningful way for effective between-group comparisons of results.

Comparisons of evaluation-demand results between motion groups (i.e., empirical, artificial smooth, artificial jagged) are most significant to this study. The purpose of these comparisons is to determine whether or not artificially generated time histories produce seismic evaluation demands representative of those produced by real earthquake ground motions. Such a determination is made by examining how closely the demands from artificial motions match those from real motions, for similar cases (i.e., same motion-anchor basis, same structure and in-structure location, same site condition, etc.). In addition, comparisons of results from the multiple artificial motions having jagged spectra with corresponding results from the multiple empirical motions, enables the determination of whether or not realistic variations in response demands can be represented simply by use of an appropriate set of artificial motions. Any significant advantages of using multiple artificial motions with jagged spectra, over using a single artificial motion with smooth spectrum, are also revealed by comparing demands for these cases relative to demands from the real motions.

Before presenting computed evaluation demands and their comparisons, the following chapter describes the bases and results of methods for simulating the various artificial time histories used in this study.

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Table 2-1
Description of Empirical Motion Time Histories Used in Study

Earthquake Name	Date	Mag	Station Description	Comp	Epicentral Dist. (km)	Soil Type	PGA (g)	T'_D (sec)
Saguenay, Québec CANADA	11-25-88	M_{Lg} 6.5	Chicoutimi-Nord, Québec (Site 16)	214°	43.05	Rock	0.11	7.70
			St-André-du-Lac-St-Jean Québec (Site 17)	0°	64.09	Rock	0.16	6.00
			Les Éboulements, Québec (Site 20)	0°	90.43	Rock	0.13	4.81
			Baie-St-Paul, Québec (Site 07)	85°	91.10	Soil	0.17	6.50
Nahanni, NWT, CANADA	12-23-85	M_S 6.9	Iverson station (Site 01)	280°	7.71	Rock	1.35	7.22
			Slide Mountain station (Site 02)	330°	6.25	Rock	0.39	4.90
			Battlement Creek station (Site 03)	360°	25.01	Rock	0.19	7.32
Imperial Valley, California	10-15-79	M_S 6.5	El Centro Array, No. 5 station	140°	4.0*	Soil	0.53	3.53

* Fault distance.

Table 2-2

Dynamic Characteristics of 3-Hz, Five-Story (5 DOF) Building Model

Property	Mass, Element, or Mode Number				
	1	2	3	4	5
Mass ($\text{k-s}^2/\text{in}$)	20.00	20.00	20.00	20.00	20.00
Stiffness (k/in)	90000	90000	90000	90000	90000
Frequency (Hz)	3.04	8.87	14.0	18.0	20.5
Damping (%)	5.00	5.00	6.68	8.17	9.15
Displacement of:	Normalized Mode Shapes				
Mass #1	+.170	-.456	-.597	+.549	+.326
Mass #2	+.326	-.597	-.170	-.456	-.549
Mass #3	+.456	-.326	+.549	-.170	+.597
Mass #4	+.549	+.170	+.326	+.597	-.456
Mass #5	+.597	+.549	-.456	-.326	+.170

Table 2-3

Dynamic Characteristics of 7-Hz, Four-Story (5 DOF) Building Model

Property	Mass, Element, or Mode Number				
	1	2	3	4	5
Mass ($\text{k-s}^2/\text{in}$)	12.90	12.63	4.05	12.58	8.81
Stiffness (k/in)	209300	220800	283900	253900	195100
Frequency (Hz)	7.01	19.3	31.2	36.2	63.1
Damping (%)	5.00	5.00	6.76	7.60	12.4
Displacement of:	Normalized Mode Shapes				
Mass #1	+.062	-.156	-.161	-.152	+.012
Mass #2	+.114	-.171	+.047	+.164	-.088
Mass #3	+.144	-.707	+.128	+.032	+.451
Mass #4	+.174	+.576	+.140	-.143	-.077
Mass #5	+.191	+.170	-.192	+.106	+.126

Table 2-4
Dynamic Characteristics of 10-Hz, Two-
Story (2 DOF) Building Model

Property	Mass, Element, or Mode Number	
	1	2
Mass ($\text{k-s}^2/\text{in}$)	10.00	10.00
Stiffness (k/in)	103380	103380
Frequency (Hz)	10.0	26.2
Damping (%)	5.00	5.00
Displacement of:	Normalized Mode Shapes	
Mass #1	+ .526	+ .851
Mass #2	+ .851	- .526

Table 2-5

Ground-Motion Amplitude Measures, and Scale Factors to Achieve Anchor Bases, for Empirical Motions

Parameter or Scale Factor	Ground-Motion Amplitude Measures and Scale Factors for Empirical Ground Motion:							
	MSag1	MSag2	MSag3	MSag4	MNah1	MNah2	MNah3	MImp1
PGA	0.107	0.156	0.126	0.174	1.345	0.390	0.194	0.527
ScPGA (to 0.3g)	2.816	1.924	2.390	1.724	0.223	0.769	1.547	0.569
$\overline{S}_a$ (2.55 to 3.45 Hz)	0.039	0.062	0.224	0.394	1.308	0.401	0.102	1.047
ScSa3 (to 0.6g)	15.33	9.671	2.679	1.523	0.459	1.496	5.882	0.573
(ScSa3/ScPGA)	5.444	5.027	1.121	0.883	2.057	1.945	3.803	1.008
$\overline{S}_a$ (5.95 to 8.05 Hz)	0.183	0.112	0.280	0.386	1.785	0.566	0.328	1.110
ScSa7 (to 0.6g)	3.283	5.356	2.141	1.554	0.336	1.061	1.831	0.541
(ScSa7/ScPGA)	1.166	2.784	0.896	0.902	1.507	1.379	1.184	0.950
$\overline{S}_a$ (8.50 to 11.5 Hz)	0.217	0.176	0.265	0.340	2.534	0.600	0.329	1.146
ScSa10 (to 0.6g)	2.770	3.401	2.261	1.766	0.237	0.999	1.824	0.524
(ScSa10/ScPGA)	0.984	1.768	0.946	1.024	1.062	1.299	1.179	0.920
$\overline{S}_a$ (2 to 10 Hz)	0.115	0.094	0.222	0.393	1.680	0.496	0.189	1.089
ScASA (to 0.6g)	5.209	6.372	2.707	1.526	0.357	1.210	3.180	0.551
(ScASA/ScPGA)	1.850	3.312	1.132	0.885	1.601	1.572	2.056	0.969

Table 2-6

Ground-Motion Amplitude Measures, and Scale Factors to Achieve Anchor Bases, for Artificial Motions

Parameter or Scale Factor	Ground-Motion Amplitude Measures and Scale Factors for Artificial Ground Motion(s) Matching Target:							
	TEr	TEs	TLr	TLs	TL2r	TL2s	TWr	TWs
PGA	0.152	0.277	0.201	0.331	0.131	0.222	0.300	0.300
ScPGA (to 0.3g)	1.974	1.083	1.496	0.905	2.294	1.351	1.000	1.000
$\overline{S}_a$ (2.55 to 3.45 Hz)	0.094	0.227	0.177	0.351	0.099	0.188	0.636	0.636
ScSa3 (to 0.6g)	6.385	2.644	3.392	1.709	6.037	3.195	0.943	0.943
(ScSa3/ScPGA)	3.235	2.442	2.267	1.888	2.632	2.365	0.943	0.943
$\overline{S}_a$ (5.95 to 8.05 Hz)	0.182	0.428	0.291	0.537	0.179	0.314	0.636	0.636
ScSa7 (to 0.6g)	3.306	1.401	2.065	1.117	3.354	1.913	0.943	0.943
(ScSa7/ScPGA)	1.675	1.294	1.380	1.234	1.462	1.416	0.943	0.943
$\overline{S}_a$ (8.50 to 11.5 Hz)	0.226	0.461	0.327	0.580	0.211	0.355	0.565	0.565
ScSa10 (to 0.6g)	2.658	1.302	1.833	1.035	2.849	1.689	1.063	1.063
(ScSa10/ScPGA)	1.347	1.202	1.225	1.144	1.242	1.250	1.063	1.063
$\overline{S}_a$ (2 to 10 Hz)	0.136	0.324	0.232	0.438	0.138	0.247	0.631	0.632
ScASA (to 0.6g)	4.400	1.850	2.592	1.370	4.361	2.428	0.951	0.949
(ScASA/ScPGA)	2.229	1.709	1.732	1.513	1.901	1.797	0.951	0.949

Target Response Spectra TEr and TEs
EPRI 10,000-yr, Median UHS (Millstone and Pilgrim Sites)

Target Response Spectra TLr and TLs
LLNL 10,000-yr, Median UHS (Millstone and Pilgrim Sites)

Figure 2-1. Target response spectra for use in generating artificial time-history input motions. (a) Unscaled target spectra TEr and TEs, derived from EPRI UHS results. (b) Unscaled target spectra TLr and TLs, derived from LLNL UHS results. All plots of target spectra are for 5% damping.

Target Response Spectra TL2r and TL2s
 Revised LLNL 10,000-yr, Median UHS (Millstone and Pilgrim Sites)

Target Response Spectra TWr and TWs
 NUREG/CR-0098, Median 5%-Damped Spectra (Rock and Soil)

Figure 2-2. Target response spectra for use in generating artificial time-history input motions (continued). (c) Unscaled target spectra TL2r and TL2s, derived from revised LLNL UHS results. (d) Target spectra TWr and TWs, derived from the NUREG/CR-0098 median 5%-damped shape, anchored to 0.3g PGA. All plots of target spectra are for 5% damping.

Figure 2-3. (a) Ground acceleration time histories from empirical records: (a) MSag1, (b) MSag2, (c) MSag3 and (d) MSag4. (Note: the scales of time and acceleration axes are different from case to case).

Figure 2-4. (a) Ground acceleration time histories from empirical records (continued): (e) MNah1, (f) MNah2, (g) MNah3 and (h) MImp1. (Note: the scales of time and acceleration axes are different from case to case).

Ground Response Spectra

Frequency (Hertz)

Figure 2-5. Response spectra for empirical ground motions. (a) Motion MSag1: the 214° component of the Chicoutimi-Nord, Québec (Site 16) recording of the 11/25/88 Saguenay earthquake. (b) Motion MSag2: the 0° component of the St-André-du-Lac-St-Jean, Québec (Site 17) recording of the 11/25/88 Saguenay earthquake.

Figure 2-6. Response spectra for empirical ground motions (continued). (c) Motion MSag3: the 0° component of the Les Éboulements, Québec (Site 20) recording of the 11/25/88 Saguenay earthquake. (d) Motion MSag4: the 85° component of the Baie-St-Paul, Québec (Site 07) recording of the 11/25/88 Saguenay earthquake.

Ground Response Spectra

Ground Response Spectra

Figure 2-7. Response spectra for empirical ground motions (continued). (e) Motion MNah1: the 280° component of the Iverson station (Site 01) recording of the 12/23/85 Nahanni, NWT, earthquake. (f) Motion MNah2: the 330° component of the Slide Mountain station (Site 02) recording of the 12/23/85 Nahanni, NWT, earthquake.

Figure 2-8. Response spectra for empirical ground motions (continued). (g) Motion MNah3: the 360° component of the Battlement Creek station (Site 03) recording of the 12/23/85 Nahanni, NWT, earthquake. (h) Motion MImp1: the 140° component of the El Centro Array, No. 5 station recording of the 10/15/79 Imperial Valley, CA, earthquake.

Figure 2-9. Power spectral density functions (PSDs) for empirical ground motions. (a) Motion MSag1: the 214° component of the Chicoutimi-Nord, Québec (Site 16) recording of the 11/25/88 Saguenay earthquake. (b) Motion MSag2: the 0° component of the St-André-du-Lac-St-Jean, Québec (Site 17) recording of the 11/25/88 Saguenay earthquake.

Figure 2-10. PSDs for empirical ground motions (continued). (c) Motion MSag3: the 0° component of the Les Éboulements, Québec (Site 20) recording of the 11/25/88 Saguenay earthquake. (d) Motion MSag4: the 85° component of the Baie-St-Paul, Québec (Site 07) recording of the 11/25/88 Saguenay earthquake.

Figure 2-11. PSDs for empirical ground motions (continued). (e) Motion MNah1: the 280° component of the Iverson station (Site 01) recording of the 12/23/85 Nahanni, NWT, earthquake. (f) Motion MNah2: the 330° component of the Slide Mountain station (Site 02) recording of the 12/23/85 Nahanni, NWT, earthquake.

Figure 2-12. PSDs for empirical ground motions (continued). (g) Motion MNah3: the 360° component of the Battlement Creek station (Site 03) recording of the 12/23/85 Nahanni, NWT, earthquake. (h) Motion MImp1: the 140° component of the El Centro Array, No. 5 station recording of the 10/15/79 Imperial Valley, CA, earthquake.

Figure 2-13. Ground response spectra (GRS) for empirical motions scaled to a common value of PGA of 0.3g. (a) Saguenay rock motions, (b) Saguenay soil motion, (c) Nahanni rock motions, and (d) Western U.S. soil motion.

Figure 2-14. GRS for empirical motions scaled to a common value of $\bar{S}_a$ (2.55 Hz to 3.45 Hz) of 0.6g. (a) Saguenay rock motions, (b) Saguenay soil motion, (c) Nahanni rock motions, and (d) Western U.S. soil motion.

Figure 2-15. GRS for empirical motions scaled to a common value of $\bar{S}_a$ (5.95 Hz to 8.05 Hz) of 0.6g. (a) Saguenay rock motions, (b) Saguenay soil motion, (c) Nahanni rock motions, and (d) Western U.S. soil motion.

Figure 2-16. GRS for empirical motions scaled to a common value of $\bar{S}_a$ (8.50 Hz to 11.5 Hz) of 0.6g. (a) Saguenay rock motions, (b) Saguenay soil motion, (c) Nahanni rock motions, and (d) Western U.S. soil motion.

Figure 2-17. GRS for empirical motions scaled to a common value of $\bar{S}_a$, averaged over 2.00 Hz to 10.0 Hz, of 0.6g. (a) Saguenay rock motions, (b) Saguenay soil motion, (c) Nahanni rock motions, and (d) Western U.S. soil motion.

Figure 2-18. Target response spectra scaled to a common value of PGA of 0.3g. (a) Target spectra TEr and TE_s, (b) Target spectra TLr and TL_s, (c) Target spectra TL2r and TL2_s, and (d) Target spectra TW_r and TW_s.

Figure 2-19. Target response spectra scaled to a common value of $\bar{S}_a$ (2.55 Hz to 3.45 Hz) of 0.6g. (a) Target spectra TEr and TEs, (b) Target spectra TLr and TLs, (c) Target spectra TL2r and TL2s, and (d) Target spectra TWr and TWs.

Figure 2-20. Target response spectra scaled to a common value of $\bar{S}_a$ (5.95 Hz to 8.05 Hz) of 0.6g. (a) Target spectra TEr and TEs, (b) Target spectra TLr and TLs, (c) Target spectra TL2r and TL2s, and (d) Target spectra TWr and TWs.

Figure 2-21. Target response spectra scaled to a common value of $\bar{S}_a$ (8.50 Hz to 11.5 Hz) of 0.6g. (a) Target spectra TEr and TE_s, (b) Target spectra TLr and TL_s, (c) Target spectra TL2r and TL2_s, and (d) Target spectra TW_r and TW_s.

Figure 2-22. Target response spectra scaled to a common value of $\bar{S}_a$, averaged over 2.00 Hz to 10.0 Hz, of 0.6g. (a) Target spectra TEr and TE_s, (b) Target spectra TLr and TL_s, (c) Target spectra TL2r and TL2_s, and (d) Target spectra TW_r and TW_s.

Section 3

BASIS AND CHARACTERISTICS OF ARTIFICIAL MOTIONS

This chapter provides descriptions of methodologies for simulating artificial time histories of ground acceleration to be used as inputs to seismic response-evaluation analyses. As discussed in Chapter 2, two different approaches for simulating artificial time histories are considered: (1) a methodology producing a single motion whose response spectrum smoothly matches a given target spectrum, and (2) a methodology producing multiple motions, each having a jagged response spectrum, but whose collective average response spectrum closely matches a given target spectrum. The first approach is based on conventional random vibrations techniques that are not necessarily designed to relate directly to physical models of ground motion. The second approach is based on a random-vibrations methodology that makes use of geophysical parameters in a meaningful way. In the second approach, not only are motions generated to match, on average, a given target spectrum, but realistic variabilities in motion duration, spectral amplitudes, and correlation in spectral amplitudes across vibration frequencies are all reasonably well captured by multiple motions. Each simulation approach is implemented to obtain motion time histories matching each of the eight target spectra described in Chapter 2.

For each simulated motion, its acceleration time history, response spectrum, and power spectrum are all obtained and plotted. To demonstrate the validity and accuracy of the simulation approaches, artificial-motion response spectra are compared with the corresponding target spectra they were generated to match. For the motions with jagged spectra, response spectra for individual motions are presented, together with the average response spectrum.

To demonstrate to what extent the artificial motions represent characteristics of real earthquake motions, comparisons are made between the artificial records and empirical records. Response spectra are compared (for corresponding cases) to demonstrate how well average spectral shapes and motion-to-motion variations in spectral shapes for the artificial motions represent those observed for real earthquake motions. Power spectral densities are compared to assess whether or not the artificial motions possess noticeable gaps in input energy content over significant frequency bands, which might have implications on the magnitudes of computed response demands.

3.1 SIMULATION OF ARTIFICIAL MOTIONS HAVING SMOOTH SPECTRA

Input to response models for purposes of seismic evaluation (and seismic design also) has typically been a single motion time history, either real or simulated, which matches or envelopes a specified evaluation (or design) response spectrum. The purpose, in this study, of simulating a single artificial time history having a smooth response spectrum that closely matches a given target spectrum is, therefore, to follow the state-of-practice typically employed in seismic evaluation studies. A variety of simulation approaches may be implemented, but generally these are all based on fundamental random vibration techniques. In these approaches, the primary effort is to obtain a PSD, through trial and error, that leads to a response spectrum that matches the specified target. Energy is simply either added or subtracted, over appropriate frequency bands, to produce the desired response spectrum. An initial PSD may be evaluated from a reference real or artificial time history, or a fundamental initial form of the PSD may be assumed. Whatever the case, a PSD is obtained that produces the desired match. A representative motion duration and time-history enveloping function are introduced to insure a realistic temporal nature.

In some cases, to avoid the trial-and error process of determining an appropriate PSD, the database of empirical records is searched to find a motion having a response-spectral shape as similar as possible to that of the desired target response spectrum. The real motion is then scaled appropriately such that the target response spectrum is matched as closely as desired (or, in some cases, simply enveloped) by the scaled empirical spectrum. In general, however, such an approach would not be suitable for developing motions for use in this study. First, the database of empirical records for the Eastern U.S. is comparatively slim. And second, to eliminate conservatism in seismic evaluation practice, analysts may likely be inclined to favor use of simulation approaches that result in a smooth response spectrum that just matches the target spectrum, without any localized peaks in the spectrum that may lead to increases in computed responses.

One objective of this study is to test whether or not problems may arise due to the basis for input specification in seismic evaluation studies. Hence, the intent in this case is not to implement the most sophisticated or conservative methods for seismic input specification. On the other hand, the purpose is neither to consider cases where deficiencies may be intentionally introduced in the input specification; e.g., deficiencies that may not be specifically precluded from regulations and assessment guidelines, but that may be unlikely to be introduced without purposeful technical effort. Rather, simple methods that could be implemented by a prudent engineer or analyst (having a credible level of experience) are considered.

For similar reasons to those just discussed, the approach implemented in this study does not involve use of initial real PSDs in ascertaining a final desired PSD. Hence, the artificial time history may be a reasonably simplistic motion that may not best represent the temporal nature (e.g., non-stationarity) of expected real earthquake motions. On the other hand, simulations are neither made that produce time histories that appear abnormal, having clearly spurious strong-motion durations or temporal character.

Consequently, the simulated inputs considered for this case of analysis (involving a single artificial time history generated to match a target spectrum) are credible inputs for purposes of seismic evaluation (i.e., ones not likely to be readily rejected by either analysts, reviewers, or regulators), but are not necessarily based on the most sophisticated available methods.

The basis and procedures followed in developing such artificial time-history inputs are described as follows.

3.1.1 Methodology: Basis and Procedures for Motion Simulations

The objective here is to generate a single motion that will smoothly match a desired target spectrum, exhibit a representative value of duration, and match an appropriate level of peak ground acceleration (PGA). It has also been important that the artificial motion has reasonable time domain appearance for reasonable representation of real earthquakes.

Since the response spectrum is closely related to the power spectrum through the duration in a large range of frequencies [see, e.g., (1) and (2)], one usually can adjust the required power spectrum until the motion that was generated, based on the (power) spectrum, matches the desired response spectrum. One concern with this approach, however, is that excessive altering of the power spectrum individually at various frequencies usually invites loss of causality, which in turn will affect the time history appearance of the motion. Causal filters could be applied to solve this problem (G. Toro, personal communication, 1993); this study, however, introduces a simpler approach to avoid it.

This approach for generating a single motion to match a target spectrum basically follows the same procedures as those used in generating multiple motions that, on average, match the target spectrum. [see the Phase-1 report (3), and Section 3.2.1, for details of generating multiple motions that match the desired spectrum.] However, to match the desired response spectrum with only one motion, the initial target *response spectrum* needs to be calibrated so that the motion generated based on the initial response spectrum matches the real, desired, target response spectrum. This is to be distinguished from calibrating the required *power*

spectrum for fitting; the latter approach may introduce poor time domain appearance if it is not applied with caution.

A number of points need to be noted here. Since we are using only one motion to fit closely a target spectrum, it might require many iterations in the calibrating process. It is also possible that one may never reach a reasonably fit if the target spectrum is not well constrained. (For example, the target spectrum may have high amplitudes at high frequencies, but a low PGA.) Moreover, one may need to add additional amplitudes at low or high frequencies to ensure more realistic time domain appearance of the motion if the target spectrum is defined over only a small frequency range. For faster convergence, one could fix the generated random phasing of the motion in the calibration process.

Considering these points, for each of the eight target spectra, a single artificial motion having a matching smooth response spectrum has been generated. The resulting motions define inputs representative of those that might be developed for seismic evaluation studies.

3.1.2 Results: Simulated Motions and Comparisons with Target Spectra

Acceleration time histories for the artificial motions produced to have smooth spectra which match the eight different target spectra are shown in Figures 3-1 and 3-2. Distinctly different frequency contents are observed in the time history plots for the Eastern U.S. motions [MArS1(TEr), MArS1(TEs), MArS1(TLr), MArS1(TLs), MArS1(TL2r), and MArS1(TL2s)] versus the Western U.S. motions [MArS1(TWr) and MArS1(TWs)]. Clearly, the nature of response demands for structures and equipment can be expected to be significantly different for these two groups of motions. High-frequency motion is clearly predominant in the Eastern U.S. motions, whereas the predominant character of the Western U.S. motions is of considerably lower frequency. With the exception of MArS1(TLr), all Eastern U.S. motions have similar durations; the notably longer duration of MArS1(TLr) is simply an expected product of randomness in duration introduced naturally in the simulation process. The durations of artificial Western U.S. motions MArS1(TWr) and MArS1(TWs) are also similar to one another, yet they typically prove to be significantly longer than durations for the Eastern U.S. motions.

Figure 3-3 to 3-6 show plots of the response spectra for each artificial motion, as compared to the associated target response spectrum from which each motion was generated. The objective in matching the target spectrum has been to match, within 5%, linear ordinates of the spectrum at no fewer than 50 frequencies uniformly spaced on a logarithmic scale. Consequently, as noted in Figures 3-3 to 3-6, observed matches between the simulated and

target spectra are all very close. The fit in each case is closer than what would generally be produced in practice. Such extreme closeness in fit in no way voids the applicability of the motions. Rather, the close fit helps reduce any inconsistencies in comparisons of response demands. Another noteworthy point is that the artificial motions have response spectra that vary slightly about the target spectra, whereas artificial motions generated for an actual seismic evaluation study would generally be simulated to either closely envelope the target spectrum or meet specified criteria related to allowable deviations from the target. Hence, the simulated motions may have ordinates of response spectra slightly lower than those that might be implemented in practice. This situation does not limit the applicability of the artificial motions produced for this study, because the shape of the spectrum is the item of significance (i.e., the spectra are scaled anyway to produce consistent comparisons with empirical motions). Whether or not the motion closely envelopes the target, closely oscillates about the target, or meets specified criteria related to matching the target, the shape of the simulated response spectrum will be quite similar.

Although the artificial motions have response spectra which match their associated targets well over the frequency range of interest (and beyond) for this study, it is worth noting the consistent trend for the Eastern U.S. motions to exceed (a reasonable extrapolation of) the target spectrum over very high frequencies (above 35 Hz). The exceedance of the target spectrum at high frequencies for Eastern U.S. motions is observed in all plots of Figures 3-3 to 3-5. It was discovered in the simulation process that it was not possible to very closely match the target spectrum, match the target PGA, and match the supposed extrapolation of the target response spectrum above 25 Hz (such extrapolation being derived from expected characteristics of real Eastern U.S. earthquake motions). There are a number of possible reasons for this being the case. First, the peak in an acceleration time history (i.e., the PGA) is related to the degree to which peaks exist in the response spectrum. For instance, in one case the PGA may be associated primarily with a 1-Hz spike of motion, whereas in another case the PGA may be driven by a 10-Hz spike of motion. Consequently, a peak in the response spectrum at either 1-Hz or 10-Hz (or any other frequency) can lead to a high PGA, whereas spectral ordinates at other frequencies could be comparatively low. In other words, peaks in a response spectrum can tend to be associated with the level of peaks in the input time history. Conversely, a response spectrum that is flat and smooth can tend to be associated with a comparatively low PGA. As a result, the constraint of having to smoothly match a target response spectrum may tend to correspondingly constrain the PGA to a comparatively low magnitude. Real motions generally exhibit large peak-to-valley variations (i.e., they have bumps or peaks) in response spectra, and hence, they may tend to have high PGAs compared to artificial motions matching smooth spectra. To simultaneously match

a desired PGA and a smooth response spectrum, therefore, leads to problems in motion simulation. The energy needed to drive up the PGA to a desired level must come from somewhere. For simulated Eastern U.S. motions, this energy comes from above 25 Hz, when the spectrum at lower frequencies is constrained to be smooth. A second reason why it is not generally possible to simultaneously match the PGA, a smooth spectrum, and a realistic extrapolation of the target spectrum for the Eastern U.S. cases, is that the target spectrum is defined as a UHS curve, which does not represent the expected spectral shape of any real earthquake motion. It cannot be generally expected that a very realistic earthquake motion, having both a realistic shape above 25 Hz and a realistic PGA, can be obtained by matching an unrealistic spectral shape, such as defined by a uniform hazard spectrum. (There is no guarantee, for instance, that the amplification ratios, over PGA, as seen in UHS results would be representative of any real earthquake motion). A third point is that the extrapolation used for Eastern U.S. target spectra, for frequencies above 25 Hz (as seen in Figures 3-3 to 3-5), is only an approximation; it is not completely consistent with expected characteristics of real Eastern U.S. earthquake motions. Finally, there are fundamental limits in the ability of the simulation model to match desired motion characteristics; a simulation model cannot reasonably be expected to simultaneously and perfectly match a target response spectrum, a target PGA, a target duration, etc.

In matching the Western U.S. target spectra, no significant problems were encountered in simultaneously matching the entire spectrum and the appropriate PGA. Despite the unusually high levels of high-frequency energy introduced for the Eastern U.S. artificial motions, the motions are judged to be well applicable to the objectives of this study because they meet all the requirements appropriate for developing input to actual seismic evaluation studies. (1) They each match their target spectrum over the frequency range of interest. (2) They each match the PGA value of their target spectrum. (3) They each have reasonable time-history characteristics and strong-motion duration. In addition, because the motions meet these evaluation requirements, and yet, they are not completely realistic in all respects, they serve well as basis in satisfying the study objective of assessing the impacts of artificial motions (and artificial characteristics of motion) on seismic evaluation demands.

The eight artificial motions simulated here, therefore, are appropriate for use in producing seismic evaluation demands for comparisons between real and artificial motions.

3.2 SIMULATION OF ARTIFICIAL MOTIONS HAVING JAGGED SPECTRA

Associated with the specific problems just discussed, it is clear that the preceding approach for simulating artificial motions for use in seismic evaluation studies has technical drawbacks

from the standpoints of realism and accuracy. For instance, real earthquake motions do not produce smooth response spectra. Rather, they possess jagged spectra; i.e., spectra that exhibit substantial variability both in amplitudes of motion at given frequencies and in relative motion amplitudes across frequencies (i.e., in spectral shape).

A more-representative basis for input specification is to select a small set of earthquake time histories that reasonably capture realistic variations in spectral shape and amplitudes at given frequencies. Developing such inputs, evaluating their implications on computed response demands, and considering their applicability to practical seismic evaluation studies is an additional aspect of this investigation. Consequently, methodology for generating a meaningful *set* of artificial motions that match, on average, a given target spectrum is also introduced and considered in this study.

Ideally, the most meaningful set of motions would be derived from specific consideration of earthquakes for appropriate magnitudes and distances that dominate key measures of seismic hazard or failure probability. Potential implications of variations in expected motions on nonlinear responses and system responses could then be evaluated. Such issues are more completely addressed in subsequent parts of Phase 2 investigation, where a significant objective is to develop a practical basis for determining risk-dominant scenario earthquakes. (See the project overview discussion in Section 1.3). The present investigation, however, does not consider impacts on nonlinear response and system responses, nor consider evaluation of risk-dominant magnitude/distance-dependent motions.

Still, the method that we now discuss for generating a set of representative artificial motions for use in seismic evaluation studies is based on realistic geophysical models of ground motion. Although the set of motions is not derived from risk-dominant scenario earthquakes, the motions do capture characteristics of credible, real earthquake motions. Realistic variabilities in motion duration, motion frequency content, spectral shape, and spectral amplitudes are all reasonably modeled. In addition, the earthquake magnitudes and distances implicit in the set of motions is, to a large degree, physically consistent with the specified evaluation spectrum. Being a uniform hazard spectrum, a target spectrum for the Eastern U.S. is developed as a combination of spectra derived predominantly from risk/hazard-dominant magnitudes and distances (i.e., from risk-dominant scenario earthquakes). It is likely (although not strictly guaranteed) that multiple motions generated to match the UHS, using the present simulation approach, will have characteristics of scenario earthquakes significant to risk. For instance, if magnitudes greater than 6.0, occurring at distances in the range of 20 to 50 km, dominate contribution to the UHS (and thus have greatest impact on its spectral

shape), it is unlikely that motions representative of magnitude 5.0 earthquakes at 5 km, nor of magnitude 7.0 earthquakes at 100 km, nor of other largely irrelevant scenarios, will be consistently represented by the simulated motions. Rather, the tendency will be that the simulated motions will be substantially characteristic of the motions that were originally of greatest significance to the UHS. To this extent, the present procedure for generating artificial motions has validity to scenario earthquakes expected to be important to risk.

Although more refined approaches are explored in subsequent parts of Phase-2 study, the present approach can serve as a substantial improvement in ground-motion specification for seismic evaluation studies. The approach does have the practical drawback that it increases the effort required in seismic evaluation practice. Whether or not such additional effort is required for accurate evaluation will be determined in subsequent Phase-2 study, where nonlinear effects and system effects are addressed. (Because this Part-1 study pertains exclusively to individual linear responses of structure and equipment behaving as isolated components, the impacts of variations in spectral shapes on responses of importance will intuitively not be as great as for the real case of nonlinear responses of components and systems). For this study, it is still useful to consider the present simulation approach, particularly to demonstrate the representativeness of the simulated motions, and to anticipate the impacts of use of multiple spectra on seismic evaluation implementation and results. Furthermore, the simulation methodology may prove to be adequate as a simple alternative for approximating the development of scenario earthquake motion inputs that may be required for more-detailed and accurate seismic assessment. Clearly, this simulation approach is not representative of current seismic evaluation practice, but constitutes a more sophisticated method for specifying seismic input.

The basis and procedures followed in developing multiple artificial time-history inputs with jagged response spectra, whose collective average spectrum matches a specified target, are described as follows.

3.2.1 Methodology: Basis and Procedures for Motion Simulations

A ground motion time history, in its original form, usually conveys limited information to engineers. Such information might include the peak ground acceleration (PGA), the duration, and a rough indication of the frequency content of the motion. To further reveal the characteristics of the motion for the assessment of engineering impacts, the response spectrum and the power spectrum (or, equivalently, the Fourier amplitude spectrum) need to be generated. The response spectrum is particularly useful since it directly displays the maximum responses of single-degree-of-freedom (SDOF) structures subject to the motion

at various frequencies and dampings. Conversely, because the response spectrum (including the PGA) and the motion duration convey most of a ground motion's key characteristics, it is natural to use these two as criteria for ground motion generations. In other words, one usually wants to generate motions that, individually or on average, match a desired response spectrum and a duration. In addition, these motions should also have realistic temporal appearances, frequency contents, and (record-to-record) variabilities in spectrum shapes and durations.

In what follows, we shall present the basis and procedures for generating realistic artificial ground motions that will, on average, match a desired spectrum and a duration. The theoretical basis of the procedures is mostly derived from random vibration theory and has been discussed extensively in the Phase-1 report (4).

1. Generating one realization of the target PSV

For convenience, we shall assume that the target spectrum is a Pseudo Spectral Velocity (PSV) spectrum. The target PSV , i.e., PSV_t , only constrains the (geometric) mean of the desired spectrum. To preserve the characteristics of real earthquakes, we also need to consider the record-to-record variability of the spectra. This variability is usually modeled assuming a lognormal distribution:

$$\ln(PSV(f)) = \ln(PSV_t(f)) + \epsilon \quad (3-1)$$

where $PSV(f)$ is the pseudo spectral velocity at frequency f and ϵ is a normal random variable with a mean of zero and a standard variation of σ_ϵ , representing the variability. Typical values of σ_ϵ range from 0.37 to 0.65 for frequencies above 1 Hz (5).

Conventionally the variability ϵ is only considered in the marginal sense in developing attenuation functions, i.e., $\epsilon = \epsilon(f)$. Its correlation structure (across vibration frequencies), though remaining unclear, has strong influence on the spectral shape. A perfectly correlated model will lead to a fixed spectral shape; a totally uncorrelated model, on the other hand, may imply large conditional variabilities of the spectral shape at close frequencies. Both models are not entirely consistent with the characteristics of real earthquakes.

Recently, Inoue (6) investigated the correlation issue and studied the correlation of ϵ as a function of frequency. He found that the correlation structure of ϵ is best explained by the following model:

$$\rho_{\epsilon_{f_1}, \epsilon_{f_2}} = \begin{cases} 1 - \frac{1}{3} |\ln(f_1/f_2)|, & |\ln(f_1/f_2)| \leq 3 \\ 0, & \text{otherwise} \end{cases}$$

That is, the correlation coefficient of ϵ at frequencies f_1 and f_2 , $\rho_{\epsilon_{f_1}, \epsilon_{f_2}}$, decreases linearly from 1 to 0 as the difference of the logarithms of the two frequencies increase from 0 to 3. We believe this is a more realistic model than both the perfectly correlated model and the perfectly independent model; we, therefore, adopt this model in this study to realistically model variations in spectral shape. In addition, a representative value of $\sigma_\epsilon(f)$ equal to 0.6 is assumed in the present simulation approach to produce motions with substantially realistic variabilities in absolute magnitude.

With the target PSV and the variation model as discussed above, the procedures for generating one realization of PSV are as follows.

- Generate one realization of ϵ . Since the marginal statistics of ϵ are assumed invariant with respect to the frequency (a mean of zero and a constant standard deviation of 0.6), and the correlation model of ϵ depends only on the *difference* of the (logarithms of) frequencies, we may treat $\epsilon(f)$ as a stationary random process. The autocorrelation function of ϵ can be written as

$$COV(\epsilon(\theta_1), \epsilon(\theta_2)) = \begin{cases} \sigma_\epsilon^2(1 - \frac{1}{\tau_0} |\theta_1 - \theta_2|), & |\theta_1 - \theta_2| \leq \tau_0 \\ 0, & \text{otherwise} \end{cases}$$

where $\theta = \ln(f)$ and $\tau_0 = 3$. The power spectral density function of ϵ can be derived from the autocorrelation function as

$$\begin{aligned} S_\epsilon(\lambda) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{(-i\lambda\tau)} COV[\epsilon(\theta)\epsilon(\theta + \tau)] d\tau \\ &= \frac{\sigma_\epsilon^2}{\tau_0 \lambda^2 \pi} (1 - \cos \lambda \tau_0) \end{aligned}$$

To generate a realization of $\epsilon(f)$, we first sample within its Fourier domain:

$$\epsilon(\lambda_j) = \sqrt{S_\epsilon(\lambda_j) \Delta \lambda} e^{i\phi_j}, \quad j = 1, n/2 + 1$$

where $\lambda_j = (j - 1)\Delta\lambda$ and ϕ_j is a random variable, uniformly distributed between 0 and 2π , representing random phasing. Transformation of ϵ from its Fourier domain back to the original frequency domain yields a realization of $\epsilon(f)$.

- Generate one realization of the target PSV. The desired PSV of this realization is obtained by multiplying the target PSV and this realization of ϵ , i.e.,

$$PSV(f) = PSV_t(f) \exp(\epsilon(f))$$

2. Generating a motion duration

The duration of a motion is modeled as the sum of the duration induced by the source, T_s , and the duration induced by the propagation, T_p . Typically T_s is assumed to be lognormally distributed with a mean of $1/f_0$ and a coefficient of variation of 0.1 where f_0 is the corner frequency of the earthquake. T_p (with units of seconds) is a function of the distance, usually assumed exponentially distributed with a mean of $0.05R$ (where R is the distance in km). In this study, with only the information of a target spectrum and a desired (average) duration, we shall assume that the mean T_p and the mean T_s are equal and are equal to one-half of the desired duration. We use 6 seconds as the desired duration for the Eastern US spectra and 8 seconds for the Western US spectra.

3. Determining the required power spectrum based on Steps 1 and 2

Based on random vibration theory [e.g., (1)], we may express this particular PSV ($= PSV_i \epsilon$) as

$$PSV(f) \approx u_{rms}(f) N_f(f, T) P_f(f, T) \quad (3-2)$$

The three parts of the right-hand side of the equation above are explained as follows.

$u_{rms}(f)$ is the stationary root-mean-square displacement response of a SDOF structure, with frequency f , subject to the ground acceleration with a spectral density function $S_a(\omega)$. Based on Reference (1), $u_{rms}(f)$ can be written as

$$u_{rms}^2(\omega_n) \approx \frac{S_a(\omega_n)}{\omega_n} \left(\frac{\pi}{2\xi} - 2 \right) + \frac{2}{\omega_n^2} \int_0^{\omega_n} S_a(\omega) d\omega \quad (3-3)$$

where $\omega_n = n\Delta\omega$. The first term in the above equation represents the dynamic response; this term is dominant at frequencies where the ground motion contains significant energy. The second term represents static response which is dominant at high frequencies. This term can be further approximated by changing the integration to a summation, as:

$$\frac{2}{\omega_n^2} \int_0^{\omega_n} S_a(\omega) d\omega \approx \frac{2}{\omega_n^2} \sum_{j=1}^n S_a(\omega_j) \Delta\omega_j \quad (3-4)$$

Hence, $S_a(\omega_n)$ can be solved from Equation 3-3 or 3-4, in terms of u_{rms} and $S_a(\omega_i)$, $i = 1, \dots, n-1$, as

$$S_a(\omega_n) = \frac{\omega_n}{\frac{\pi}{2\xi} - 2 + \frac{2\Delta\omega}{\omega_n}} \max \left\{ 0, u_{rms}(\omega_n)^2 - \frac{2\Delta\omega}{\omega_n^2} \sum_{j=1}^{n-1} S_a(\omega_j) \Delta\omega \right\} \quad (3-5)$$

Note that the spectral density function at all frequencies is ensured to be no smaller than zero in Equation 3-5 for the possible errors induced in various approximations.

$N_f(f, T)$ is a non-stationarity correction factor for the above RMS to correct the effect of finite duration of the ground motion. This factor can be expressed approximately as

$$N_f(f, T) \approx \sqrt{1 - \exp(-2\xi(2\pi f)T)}$$

where ξ is the damping ratio (1).

$P_f(f, T)$ is the peak factor (i.e., the peak value divided by RMS). We use an expression for the peak factor which corrects the effect of bandwidth [modified from DerKiureghian (2)]:

$$P_f \approx \sqrt{2 \ln(N_e)} + \frac{0.577}{\sqrt{2 \ln(N_e)}}$$

where N_e is the equivalent number of cycles.

$$N_e = \max\{2fT(1.63\delta^{0.45} - 0.38), 1.33\}$$

and δ is Vanmarcke's bandwidth parameter ($\delta \approx \sqrt{4\xi/\pi}$; for a damping ratio of 5%, $\delta \approx 0.25$ and $(1.63\delta^{0.45} - 0.38) \approx 0.5$.)

Re-examining Equation 3-2 reveals that, given the PSV and the duration T , the only remaining unknown is the power spectra density function of the ground motion, $S_a(\omega)$, which can be solved sequentially.

4. Generating a motion based on the required power spectrum obtained from Step 3.

We use the procedure proposed by Safak and Boore (7) to generate a ground motion, as follows.

- Generate a discrete-time, Gaussian white noise with unit power (i.e., with a variance of $2\pi/\Delta T$ where ΔT is the time step) in the time domain.
- Multiply the white noise signal by the time enveloping function:

$$A(t) = 4 \left(e^{-1.13t/T} - e^{-2.26t/T} \right)$$

whose form was proposed by Shinozuka (8), where T is the duration corresponding to the 5% – 75% accumulative energy. Note that the time window between 5% – 75% of $\int A^2(t)dt$ is equal to T and the maximum of $A(t)$ is equal to 1. Also note that the signal's frequency content is not changed by this windowing.

- Transform the enveloped white noise to the frequency domain.
- Multiply the quantity obtained above by $\sqrt{S_a(\omega)}$. This step introduces the desired amplitude and frequency content in the motion.
- Transform the motion back to the time domain.

5. Calibration

Because various approximations are introduced in the generation of ground motions, as mentioned previously, the (geometric) mean of the spectra of the generated motions may not match exactly the desired spectrum. Calibration factors could be used to modify the desired target spectrum for a better fit. This approach also can be used to fine-tune the fit when only a very small set of motions (even one motion only, as discussed earlier) are generated to fit very closely a desired spectrum.

It should be noted that these procedures may not always produce realistic motions if the desired target spectrum is poorly constrained. For example, if the desired spectrum has a narrow frequency range, the simulated motions may have unusual frequency content outside of the target frequency range. One could fix this problem by adding additional spectral amplitudes at low and high frequencies to ensure more realistic motions. On the other hand, if the target spectrum is overly constrained with an unusual shape, there may not exist corresponding motions that could match the desired spectrum. This is especially a concern if only a very small set of motions are to be generated to fit a target spectrum.

3.2.2 Results: Simulated Motions and Comparisons with Target Spectra

Eight sets of simulated acceleration time-histories, produced according to the foregoing procedures, are plotted in Figures 3-7 to 3-14. These sets correspond to the eight target spectra; five motions are presented for each set. For each set, the five artificial motions are seen to exhibit variabilities in motion duration, amplitude, and frequency content, of the types expected for real earthquake motions. All time histories appear reasonable in time-dependent characteristics, including the nature of non-stationarity.

In Figures 3-15 to 3-22 plots are shown, for each of the eight artificial motion sets, of individual simulated response spectra, and average of the simulated spectra, as compared to the associated target response spectra. Plots showing the spectra of individual motions

demonstrate that a variety of spectral shapes and amplitudes are generated for each set. Tremendous variation is seen among the individual response spectra for any given set of motions. The variation might well represent characteristics of motion resulting from earthquakes of varying magnitude and distance. And yet, the average spectrum derived from any set of artificial motions matches very closely with the appropriate target.

These results demonstrate that the artificial motions produced here, having jagged response spectra, are appropriate as inputs for evaluations and comparisons of seismic response demands. Still, some cautionary aspects need to be raised with respect to the use of these artificial motions; these aspects are discussed in Section 3.3.2.

For linear response, average demands resulting from use of any set of multiple artificial motions may not differ greatly from demands produced from the single artificial motions which (smoothly) match the same target spectrum. This is an assumption implicit in seismic evaluation studies. At first thought, it might be concluded that the average demand, from among any of the eight five-motion sets, should differ little if at all from a corresponding demand produced from the single smooth artificial motion matching the same target spectrum. Such a conclusion would not be just a consequence of linear superposition, but would also require that the assumption be made that the spectral shapes of the five motions were all the same. However, the spectral shapes of the multiple input motions are not the same, and simple linear scaling of high-frequency demands relative to low-frequency demands cannot be applied for the different input shapes. Consider, for instance, two motions having the same spectral shape, but the first motion has twice the amplitude of the second. Clearly, linear scaling applies, and the first motion will simply result in demands everywhere (i.e., for all ISS frequencies) twice as great as those for the second motion. Now, however, consider that the first motion has twice the amplitude at a given structure's predominant frequency of vibration, but the same amplitude (as the second motion) at the structure's second modal vibration frequency. What is the resulting demand produced for the second motion at an ISS frequency equal to the second modal vibration frequency of the structure? It clearly is not the same as the first motion, and it clearly is not twice that of the first motion. Thus, simple linear scaling does not apply in instances where input spectral shapes are different; a more-complicated relationship governs the evaluation of ISS response demands (as a function of ISS vibration frequency). Consequently, an average evaluation demand produced from use of the five artificial motions (whose average spectrum matches a specified target) should not be expected to equal the corresponding demand produced from use of the single artificial motion (having the same response spectrum). Discrepancy in demands produced among the two cases is evaluated and discussed further in Chapter 7.

In addition to such effects for linear-response demands on a single component, impacts in the case of nonlinear response and/or demands on systems comprised of multiple components, can be expected to be more significant. These effects will be examined in later parts of the study.

For the present study, the multiple artificial motions produced here serve to demonstrate the impacts and validity of an alternate approach for developing artificial motion input to seismic evaluation studies.

3.3 COMPARISONS BETWEEN SIMULATED MOTIONS AND EMPIRICAL MOTIONS

For evaluation purposes, an artificial motion need not generally have the temporal appearance or spectral characteristics of any specific real earthquake ground motion. Artificial motions should have time history traces which are reasonable, and preferably characteristics generally descriptive of the types of motions they are intended to represent. The motions must have spectra which match their designated targets.

Aside from these requirements, additional specific characteristics of the artificial motions are generally not considered critical. However, as discussed in Chapter 1, power spectral densities can help reveal potential deficiencies in artificial motions with respect to their ability to adequately represent response demands. In particular, unrealistic gaps in a PSD are suggestive of a potential for underestimating evaluation demands.

In what follows, comparisons are made among characteristics exhibited in acceleration time histories, response spectra, and PSDs for the empirical and artificial motions. Emphasis is given to comparisons of PSDs to evaluate the potential for deficiencies (a potential that may be unseen in time-histories and response spectra) to arise in computation of evaluation demands.

3.3.1 Comparisons for Motions Having Smooth Response Spectra

Time-History Comparisons. Time histories for the set of empirical motions considered in this study were presented in Figures 2-3 and 2-4. In comparing those plots with the artificial motions of Figures 3-1 and 3-2, it is observed that artificial Eastern U.S. motions have general appearance most similar to empirical motions MSag1, MSag2 and MNah3. The high-frequency motion content found in MSag3 is reasonably represented in the artificial motions, although the non-stationarity is considerably different. The durations of strong

ground motion for the artificial motions are, in most cases, somewhat lower than for these empirical records.

None of the artificial Eastern U.S. motions appears similar to empirical motions MSag4, MNah1 and MNah2. Part of the reason for this is that MSag4 was recorded on soil, which clearly led to the significantly lower frequency content of the recorded motion (versus, for instance, the other Saguenay motions). In addition, motions MNah1 and MNah2 were very high-amplitude recordings. The applicability of these Nahanni motions for the Eastern U.S. in general (and versus the Saguenay motions) could be legitimately questioned.

For Western U.S. motions, the frequency content observed in the time history traces of artificial motions MArS1(TWr) and MArS1(TWs) resemble reasonably well that seen for empirical motion MImpl1. The pattern of non-stationarity for MImpl1 is considerably different, however, than for the simulated motions. In addition, the strong-motion durations for the artificial Western U.S. motions are considerably longer than the duration of MImpl1.

For both Eastern U.S. and Western U.S. artificial motions, therefore, it can be said that they are reasonable representations of time-history traces that could be recorded in real earthquakes. There is no readily apparent compelling basis to exclude them from use in seismic evaluation studies.

Response Spectra Comparisons. Response spectra for artificial motions MArS1 are nearly identical to their respective target spectra. Whether or not the shapes of the artificial-motion spectra well represent the shapes of empirical-motion spectra can be ascertained by comparisons of appropriate plots found in Figure 2-13, with related plots found in Figure 2-18. Figure 2-13 shows the target spectra which describe spectral shapes of the artificial motions, whereas Figure 2-18 shows spectral shapes for empirical motions (in both cases, spectra are anchored according to scaling ScPGA).

In developing comparisons from these plots, it can be said that artificial motions derived for TEr, TEs, TL2r and TL2s have spectral shapes most similar to empirical motions MSag1, MSag2 and MNah3. The spectral shape of MSag4 is not adequately represented by any spectral shape among the six Eastern U.S. artificial motions. The same can be said for the spectra of empirical motions MNah1 and MNah2, which are considerably broader than the artificial motion spectra. In fact, the spectra for these two empirical motions are about as broad as that for the Western U.S. empirical motion MImpl1. The spectral shape for MImpl1 is itself reasonably represented by the spectra for artificial motions matching targets TWr

and TWs. The spectral shape of empirical motion MSag3 is reasonably similar to target spectra TLs and TLR.

These comparisons of spectral shapes further suggest that the artificial motions represent characteristics that may likely be (collectively) exhibited by real earthquake motions. No single real earthquake motion has a spectral shape extremely close to the target spectral shapes. Yet, this is not expected since the target spectra are related to the spectral shape of a composite of motions (as opposed to any single real earthquake motion). There is no readily apparent compelling basis to conclude that the artificial motion spectra are not reasonable for purposes of application in seismic evaluation studies.

Similarities in observations noted above related to comparisons of time-history and spectral characteristics of artificial versus empirical motions suggests that subsequent comparisons of evaluation demands in this study are best made by focusing attention on empirical motions MSag1, MSag2, MSag3 and MNah3 for the Eastern U.S. case. Also, comparisons focused on empirical motion MImp1 for the Western U.S. case are substantially valid to this study. It seems apparent, in contrast, that comparisons involving empirical motions MSag4, MNah1 and MNah2 are not particularly valid for the purposes of this study. This is because there are no study variations we have selected where artificial motions reasonably represent these cases. This is not to say that such cases may not be found. But finding such cases is not important to this study. The point of this study is not that some real motions can be found that have characteristics inconsistent with a specified target spectrum. (Such motions can always be found irregardless of the specific objective). Rather, the important point is that we can readily find real, credible earthquake records that provide a reasonably supportable basis for using the selected artificial motion cases in seismic evaluation studies.

In this study, it is clear that the most valid and consistent cases for subsequent comparisons of response demands, for empirical versus real motions, include the following: (1) empirical motions MSag1, MSag2 and MNah3 versus artificial motions derived from TEr or TL2r, (2) empirical motion MSag3 versus artificial motions derived from TLR, and (3) empirical motion MImp1 versus artificial motions derived from TWs. These cases are chosen based on similar site conditions (soil/rock) and on similarity in motion characteristics (response spectra and nature of the time-history). These cases will be emphasized in the comparisons of Chapter 7, but the other cases will not be excluded from subsequent considerations.

Power Spectral Density Comparisons. PSD plots for artificial motions having smooth response spectra are shown in Figures 3-23 to 3-26. These plots can be readily compared with

PSD plots for empirical records found in Figures 2-9 to 2-12. Such comparison reveals clearly that artificial motions MArS1 have credible PSDs. No notable gaps exist in the PSDs of the artificial motions over the frequency range of interest (although isolated and extremely localized dipping spikes of no practical significance can be seen in some PSDs of artificial motions). In many cases (particularly versus PSDs for the Saguenay motions), the artificial-motion PSDs are significantly broader than PSDs for empirical motions. Major reduction in input energy for the Eastern U.S. artificial motions occurs only below 0.5 Hz.

Only for empirical motions MNah1 and MNah2 do the PSDs appear to be meaningfully more intense, over the frequency range of interest, than the PSDs of the artificial Eastern U.S. motions. Again, these two empirical motions appear more like Western U.S. motions below 10 Hz (but, unlike Western U.S. motions, they still have significant energy above 25 Hz). PSDs for artificial Eastern U.S. motions do appear similar to the PSD for motion MNah3, except at very low frequency, where the Nahanni motion has notable higher PSD amplitudes.

All PSDs for artificial Eastern U.S. motions exhibit significantly greater energy at very high frequencies (above about 35 to 50 Hz) than do the empirical-motion PSDs. This increased energy is a consequence, as mentioned before, of having to simultaneously match a given target spectrum and target PGA. This high-frequency energy is clearly artificial and would not be expected in most real earthquake motions. Nonetheless, this energy is outside the frequency range of importance in evaluating seismic demands, and does not have a significant impact on subsequent response calculations and comparisons.

For Western U.S. artificial motions, it is observed that the PSDs are quite similar to the PSD for empirical motion MImp1. The PSDs of the artificial motions show gaps in frequency content above 25 Hz; but this effect is also seen in the PSD for MImp1, and thus describes a realistic characteristic of PSDs that may frequently be observed for Western U.S. motions. The PSDs of the artificial motions diminish rapidly below 0.2 Hz, whereas the PSD of MImp1 diminishes rapidly at about 0.1 Hz. This difference occurs well beyond the frequency range of interest for seismic evaluation of NPPs, and hence, is of no consequence to the comparisons of this study.

The most important conclusion to be drawn from these PSD comparisons is that procedures for generating artificial motions matching a smooth target spectrum most likely do not introduce any deficiencies in the motions that would limit their applicability in seismic evaluation studies. The PSD plots considered here provide no basis for excluding these artificial motions from use in seismic evaluation.

3.3.2 Comparisons for Motions Having Jagged Response Spectra

Time-History Comparisons. Time histories for the eight sets of artificial motions having jagged response spectra are shown in Figures 3-7 to 3-14. These plots show significant variability in time-history traces, for a given target spectrum. Compared to a single artificial time history having smooth response spectra, the five artificial motions (for any given case) together define a much more realistic representation of the ground motion threat for seismic-evaluation purposes. This can be verified by comparing time histories for the multiple artificial motions with time-history plots for the empirical motions (Figures 2-3 and 2-4). For any given target spectrum, the five artificial motions show significant variability in duration; variability found in real earthquake motions, but not captured through use of a single artificial time history.

The multiple artificial motions also demonstrate variations in frequency content and in non-stationarity. Among the multiple artificial motions, MArJ2(TLr) has a time history which resembles the basic characteristics found in empirical motion MNah2. In the set of artificial motions having smooth response spectra, this empirical motion was not represented.

Still, among the Eastern U.S. cases of multiple artificial motions with jagged spectra, empirical motions MSag4 and MNah1 are not well represented, neither in frequency content nor non-stationarity, by any given motion. Among artificial motions simulated for the Western U.S., some can be found which reasonably resemble the nature of motion MSag4; for instance, motions MArJ2(TWr) and MArJ1(TWs). And some can be found that resemble motion MNah2. (But, because these artificial motions are derived from Western U.S. spectra, they would not be generated in the case of seismic evaluation for Eastern U.S. sites). Whereas the frequency content of MNah1 is represented among the artificial Western U.S. motions, its pattern of non-stationarity would likely not be adequately represented by any motion produced from the motion simulation methodology. The conclusion is that there exist some real earthquake motions whose characteristics are not likely to be adequately represented in artificially generated motions. Characteristics for the majority of real motions, however, are likely to be reasonably represented. [Here, we are not referring to exact or similar matches with given empirical time histories, but rather, to resemblance in frequency content, duration, and/or non-stationarity over significant (strong-motion) segments of time histories].

In any case, it can be said that a set of artificial motions better represents (or, is more likely to better represent) the characteristics (and variety of characteristics) found in empirical motions, as compared to a single artificial motion. (Only empirical motions MSag3

and MNah1 would not be reasonably modeled by any among the sets of multiple artificial motions). Hence, multiple artificial motions having jagged spectra that, on average, match a given target, serve to better describe motion input for seismic evaluation studies.

Response Spectra Comparisons. Response spectra for the sets of multiple artificial motions were presented in Figures 3-15 to 3-22. Individual unscaled ground response spectra for the empirical motions were presented in Figures 2-5 to 2-8. Comparisons among these two sets of response spectra further support the observations made above; i.e., that the multiple artificial motions capture relatively well the variability seen in real earthquake motions (even without having to give specific attention to magnitude and distance effects). The most significant point here is that real motion spectra have substantial variations in shapes; they have considerable peaks/bumps and valleys/dips that are random, yet correlated. These effects are captured by the multiple artificial motions, which clearly demonstrate significant variations in shape and realistic peak-to-valley correlations.

Power Spectral Density Comparisons. PSD plots for the eight sets of multiple artificial motions are presented in Figures 3-27 to 3-50. These plots can be compared with PSD results for empirical motions, found in Figures 2-9 to 2-12. The artificial-motion PSD plots show notable variability in shape, as expected (especially as compared to the shape of PSDs for the artificial motions with smooth spectra). The observed variability in PSD shapes for the artificial motions is generally reasonable in comparisons to variabilities observed for real motions. Two notable differences are worthy of some discussion, however.

First, most of the artificial motions still display much greater energy at very high frequencies than do empirical motions. This was seen also for the artificial motions with smooth response spectrum. Possible explanations for this were presented in in Section 3.1.2. One such possible explanation was that a simulated motion may need to have peaks and valleys in its response spectrum in order to have both a reasonable spectrum and reasonably high value of PGA. This explanation can now be largely excluded, however, because the response spectra of the multiple artificial motions do, to a considerable degree, possess peaks and valleys; and yet, we still observe the spurious very high-frequency energy in the PSDs. More likely explanations for this spurious energy, therefore, relate to problems encountered with inconsistencies between the UHS shape and the spectral shape (and typical amplification factors) of real motions, or to limitations of the motion simulation model. Again, however, because the spurious energy is outside the frequency range of interest for this study, it does not introduce any significant concerns with respect to seismic evaluation results.

The other difference observed in PSDs for multiple artificial motions versus empirical motions is more directly related to the motivation for this study. It concerns the potential for gaps to be encountered in PSDs of artificial motions (and the effects any such gaps may have on seismic evaluation demands). The empirical ground motions show no PSD gaps over very broad frequency ranges. For all of the Eastern U.S. empirical motions considered in Chapter 2, there is significant energy above 0.7 Hz, up to 80 Hz; for the Western U.S. empirical motion, there is significant energy below 20 Hz. In most cases, these observations also apply to the artificial motions having smooth response spectra, as well. But there are a few notable exceptions where spurious gaps are observed in the PSDs of artificial motions for isolated cases.

Consider, for instance, the PSD for artificial motion MArJ2(TLr) [see Figure 3-33]. This PSD clearly has two unusual gaps: one in the vicinity of 11 to 12 Hz, and one between about 19 Hz and 42 Hz. No other artificial motion with jagged response spectrum, simulated for an Eastern U.S. target spectrum, displays a notable PSD gap. Of the multiple artificial motions with jagged spectra simulated to match a Western U.S. target spectrum, several instances of PSD gaps are observed. PSD gaps above 20 Hz for real Western U.S. motions are not unexpected. A few of the artificial Western U.S. motions, however, have gaps below this level. These include artificial motions MArJ1(TWr), MArJ4(TWs) and MArJ5(TWs) [see Figures 3-45, 3-49 and 3-50]. The lowest gapped-out frequency among these motions is about 9 Hz.

A number of points need to be made about these observed gaps for PSDs of artificial motions. First, these gaps can readily be avoided in the motion simulation process. We could have eliminated any such motions simply by trying different random simulation seeds or by modifying parameters effecting the variabilities displayed by the artificial motions. We intentionally included these motions to illustrate that opportunities do occur for PSD gaps to be introduced in simulated motions. The hypothesis that PSD gaps might exist in motions used for seismic evaluation purposes is a valid concern.

Second, the gaps observed here do not occur at low frequencies (which was the possibility considered in Section 1). All the target spectra considered in this study have sufficient amplitudes over low frequency to: (a) produce artificial PSDs that consistently do not exhibit low-frequency gaps, and (b) produce PSDs similar in energy content at low frequencies to that observed in real motions. The issue that low-frequency gaps might get consistently introduced in artificial motions is apparently not a general concern. Clearly, though, the possibility cannot be ruled out that a target spectrum/UHS could exist for which the low-frequency limit of energy content produced in artificial PSDs may be high enough (say, above

1 to 2 Hz) to cause problems in calculating adequately representative seismic evaluation demands. But there appears to be no analytical tendency for low-frequency-deficient motions to be simulated from Eastern U.S. evaluation target spectra.

Third, the gaps observed here, in the PSDs of a very few multiple artificial motions, are not a particular concern for seismic evaluation purposes. This is because all five motions would be used for evaluation, as opposed to just the one or two motions that possessed PSD gaps. Furthermore, due to the fact that the average response spectrum for the multiple motions must satisfy a given target, a spurious PSD gap found in one motion would most likely be countered by high PSD values for other motion(s). In other words, the set of motions will, collectively, possess PSD energy spanning the gap(s) observed in any individual motion.

Fourth and finally, the gaps obtained in the present simulations do not imply a deficiency in the simulation methodology. It may appear that, because these gaps are clearly spurious, the motion-simulation procedure is deficient or unrealistic. This is not the case. The gaps are a direct consequence of two constraints imposed on the simulation process: (1) the use of only five motions to match a given target spectrum, and (2) the objective of very smoothly matching a given target spectrum. These two conditions strongly increase the likelihood that PSD gaps will be observed in individual artificial motions. To explain, if a significant peak in the response spectrum for one motion is simulated, it means that other motions must have a spectral valley, at the same frequency, in order to maintain the average spectrum. When only five motions are used for simulations, it is much more likely that the spectral amplitude for a single, individual motion will be significantly reduced. It should be kept in mind that the simulation approach implemented in this study was designed to produce realistic motions (with realistic PSDs) that closely match a given target when on the order of 50 to 100 motions are simulated. For seismic evaluation purposes, 5 motions has been judged to define a maximum practical limit. Hence, for this study, use of additional motions is not appropriate. Nonetheless, 5 very realistic motions (without PSD gaps) could be simulated for use in this study or for use in any seismic evaluation effort. However, in producing the most realistic motions, the average spectrum from the 5 motions will probably not match the target spectrum with extreme precision. For this study, it was judged that having a close match with the target spectrum was important to maintain the greatest consistency in comparisons among seismic evaluation demands computed for various cases. Consequently, because we both use a small set of motions and very closely match the target spectrum, a few motions we have simulated possess PSD gaps. This is a fortunate occurrence for this study, because it creates the opportunity to better understand the circumstances under which PSD gaps can arise, the nature of these gaps, and the effects of these gaps on seismic evaluation

demands. For actual seismic evaluation practice based on use of multiple artificial motion input, however, it is important that the constraint of very closely matching a target spectrum be removed. Once 5 motions are simulated, their average spectrum can be suitably scaled to fit the target spectrum according to desired criteria.

3.4 REFERENCES

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Figure 3-1. Acceleration time histories for artificial motions having smooth response spectra.

Figure 3-2. Acceleration time histories for artificial motions having smooth response spectra (continued).

Target Versus Simulated Response Spectra Target TEr and Artificial Motion MArS1(TEr)

Target Versus Simulated Response Spectra Target TEs and Artificial Motion MArS1(TEs)

Figure 3-3. Response spectrum for simulated motion versus its target spectrum: (a) Motion MArS1(TEr) and (b) Motion MArS1(TEs).

Target Versus Simulated Response Spectra **Target TLr and Artificial Motions MArS1(TLr)**

Target Versus Simulated Response Spectra **Target TLs and Artificial Motion MArS1(TLs)**

Figure 3-4. Response spectrum for simulated motion versus its target spectrum (continued): (a) Motion MArS1(TLr) and (b) Motion MArS1(TLs).

Target Versus Simulated Response Spectra **Target TL2r and Artificial Motion MArS1(TL2r)**

Target Versus Simulated Response Spectra **Target TL2s and Artificial Motion MArS1(TL2s)**

Figure 3-5. Response spectrum for simulated motion versus its target spectrum (continued): (a) Motion MArS1(TL2r) and (b) Motion MArS1(TL2s).

Target Versus Simulated Response Spectra **Target TW_r and Artificial Motion MArS1(TW_r)**

Target Versus Simulated Response Spectra **Target TW_s and Artificial Motion MArS1(TW_s)**

Figure 3-6. Response spectrum for simulated motion versus its target spectrum (continued): (a) Motion MArS1(TW_r) and (b) Motion MArS1(TW_s).

Figure 3-7. Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TEr.

Figure 3-8. Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TEs.

Figure 3-9. Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TLr.

Figure 3-10. Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TLs.

Figure 3-11. Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TL2r.

Figure 3-12. Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TL2s.

Figure 3-13. Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TWr.

Figure 3-14. Acceleration time histories for artificial motions having jagged response spectra matching, on average, target TWs.

Target Versus Simulated Response Spectra **Target TEr and 5 Simulated Motions MArJ1-5(TEr)**

Target Versus Average of Simulated Response Spectra **Target TEr and Average of MArJ1-5(TEr)**

Figure 3-15. (a) Response spectra for multiple simulated motions MArJ1-5(TEr) versus their target spectrum TEr. (b) Average response spectrum for the five motions versus target spectrum.

Target Versus Simulated Response Spectra **Target TEs and 5 Simulated Motions MArJ1-5(TEs)**

Target Versus Average of Simulated Response Spectra **Target TEs and Average of MArJ1-5(TEs)**

Figure 3-16. (a) Response spectra for multiple simulated motions MArJ1-5(TEs) versus their target spectrum TEs. (b) Average response spectrum for the five motions versus target spectrum.

Target Versus Simulated Response Spectra Target TLr and 5 Simulated Motions MArJ1-5(TLr)

Target Versus Average of Simulated Response Spectra Target TLr and Average of MArJ1-5(TLr)

Figure 3-17. (a) Response spectra for multiple simulated motions MArJ1-5(TLr) versus their target spectrum TLr. (b) Average response spectrum for the five motions versus target spectrum.

Target Versus Simulated Response Spectra **Target TLs and 5 Simulated Motions MArJ1-5(TLs)**

Target Versus Average of Simulated Response Spectra **Target TLs and Average of MArJ1-5(TLs)**

Figure 3-18. (a) Response spectra for multiple simulated motions MArJ1-5(TLs) versus their target spectrum TLs. (b) Average response spectrum for the five motions versus target spectrum.

Target Versus Simulated Response Spectra **Target TL2r and 5 Simulated Motions MArJ1-5(TL2r)**

Target Versus Average of Simulated Response Spectra **Target TL2r and Average of MArJ1-5(TL2r)**

Figure 3-19. (a) Response spectra for multiple simulated motions MArJ1-5(TL2r) versus their target spectrum TL2r. (b) Average response spectrum for the five motions versus target spectrum.

Target Versus Simulated Response Spectra **Target TL2s and 5 Simulated Motions MARJ1-5(TL2s)**

Target Versus Average of Simulated Response Spectra **Target TL2s and Average of Motions MARJ1-5(TL2s)**

Figure 3-20. (a) Response spectra for multiple simulated motions MARJ1-5(TL2s) versus their target spectrum TL2s. (b) Average response spectrum for the five motions versus target spectrum.

Target Versus Simulated Response Spectra Target TWr and 5 Simulated Motions MArJ1-5(TWr)

Target Versus Average of Simulated Response Spectra Target TWr and Average of Motions MArJ1-5(TWr)

Figure 3-21. (a) Response spectra for multiple simulated motions MArJ1-5(TWr) versus their target spectrum TWr. (b) Average response spectrum for the five motions versus target spectrum.

Target Versus Simulated Response Spectra **Target TWs and 5 Simulated Motions MArJ1-5(TWs)**

Target Versus Average of Simulated Response Spectra **Target TWs and Average of Motions MArJ1-5(TWs)**

Figure 3-22. (a) Response spectra for multiple simulated motions MArJ1-5(TWs) versus their target spectrum TWs. (b) Average response spectrum for the five motions versus target spectrum.

Figure 3-23. Power spectral densities for artificial motions having smooth response spectra: (a) motion MARSI(TEr), (b) motion MARSI(TEs).

Figure 3-24. Power spectral densities for artificial motions having smooth response spectra: (a) motion MArS1(TLr), (b) motion MArS1(TLs).

Figure 3-25. Power spectral densities for artificial motions having smooth response spectra: (a) motion MArS1(TL2r), (b) motion MArS1(TL2s).

Figure 3-26. Power spectral densities for artificial motions having smooth response spectra: (a) motion MArS1(TWr), (b) motion MArS1(TWs).

Figure 3-27. Power spectral densities for artificial motions MArJn(TEr), having jagged spectra matching target TEr: (a) motion MArJ1(TEr), (b) motion MArJ2(TEr).

Figure 3-28. Power spectral densities for artificial motions MArJn(TEr), having jagged spectra matching target TEr (continued): (c) motion MArJ3(TEr), (d) motion MArJ4(TEr).

Figure 3-29. Power spectral densities for artificial motions MArJn(TEr), having jagged spectra matching target TEr (continued): (e) motion MArJ5(TEr).

Figure 3-30. Power spectral densities for artificial motions MArJn(TEs), having jagged spectra matching target TEs: (a) motion MArJ1(TEs), (b) motion MArJ2(TEs).

Figure 3-31. Power spectral densities for artificial motions MArJn(TEs), having jagged spectra matching target TEs (continued): (c) motion MArJ3(TEs), (d) motion MArJ4(TEs).

Figure 3-32. Power spectral densities for artificial motions MArJn(TEs), having jagged spectra matching target TEs (continued): (e) motion MArJ5(TEs).

Figure 3-33. Power spectral densities for artificial motions MArJn(TLr), having jagged spectra matching target TLr: (a) motion MArJ1(TLr), (b) motion MArJ2(TLr).

Figure 3-34. Power spectral densities for artificial motions MArJn(TLr), having jagged spectra matching target TLr (continued): (c) motion MArJ3(TLr), (d) motion MArJ4(TLr).

Figure 3-35. Power spectral densities for artificial motions MArJn(TLr), having jagged spectra matching target TLr (continued): (e) motion MArJ5(TLr).

Figure 3-36. Power spectral densities for artificial motions MArJn(TLs), having jagged spectra matching target TLs: (a) motion MArJ1(TLs), (b) motion MArJ2(TLs).

Figure 3-37. Power spectral densities for artificial motions MArJn(TLs), having jagged spectra matching target TLs (continued): (c) motion MArJ3(TLs), (d) motion MArJ4(TLs).

Figure 3-38. Power spectral densities for artificial motions MARJn(TLs), having jagged spectra matching target TLs (continued): (e) motion MARJ5(TLs).

Figure 3-39. Power spectral densities for artificial motions MArJn(TL2r), having jagged spectra matching target TL2r: (a) motion MArJ1(TL2r), (b) motion MArJ2(TL2r).

Figure 3-40. Power spectral densities for artificial motions MArJn(TL2r), having jagged spectra matching target TL2r (continued): (c) motion MArJ3(TL2r), (d) motion MArJ4(TL2r).

Figure 3-41. Power spectral densities for artificial motions MArJn(TL2r), having jagged spectra matching target TL2r (continued): (e) motion MArJ5(TL2r).

Figure 3-42. Power spectral densities for artificial motions MarJn(TL2s), having jagged spectra matching target TL2s: (a) motion MarJ1(TL2s), (b) motion MarJ2(TL2s).

Figure 3-43. Power spectral densities for artificial motions MArJn(TL2s), having jagged spectra matching target TL2s (continued): (c) motion MArJ3(TL2s), (d) motion MArJ4(TL2s).

Figure 3-44. Power spectral densities for artificial motions MArJn(TL2s), having jagged spectra matching target TL2s (continued): (e) motion MArJ5(TL2s).

Figure 3-45. Power spectral densities for artificial motions MArJn(TWr), having jagged spectra matching target TWr: (a) motion MArJ1(TWr), (b) motion MArJ2(TWr).

Figure 3-46. Power spectral densities for artificial motions MArJn(TW_r), having jagged spectra matching target TW_r (continued): (c) motion MArJ3(TW_r), (d) motion MArJ4(TW_r).

Figure 3-47. Power spectral densities for artificial motions MArJn(TWr), having jagged spectra matching target TWr (continued): (e) motion MArJ5(TWr).

Figure 3-48. Power spectral densities for artificial motions MARJn(TWs), having jagged spectra matching target TWs: (a) motion MARJ1(TWs), (b) motion MARJ2(TWs).

Figure 3-49. Power spectral densities for artificial motions MArJn(TWs), having jagged spectra matching target TWs (continued): (c) motion MArJ3(TWs), (d) motion MArJ4(TWs).

Figure 3-50. Power spectral densities for artificial motions MArJn(TWs), having jagged spectra matching target TWs (continued): (e) motion MArJ5(TWs).

Section 4

RESPONSE RESULTS: EMPIRICAL MOTIONS

This chapter presents results of evaluation-demand calculations performed using the eight empirical motions (described in Chapter 2) as inputs. The following results are obtained: (a) maximum structural inter-story forces (and displacements), (b) maximum floor zero-period accelerations (ZPAs), and (c) in-structure response spectra (ISS).

Results are compared among the eight motions to demonstrate typical variations in responses attributable to variabilities in spectral shapes of real earthquake motions. The results are used in Chapter 7 to compare with evaluation demands obtained for the various artificial input motions.

4.1 STRUCTURAL FORCES AND DISPLACEMENTS

Linear-elastic response analyses were conducted for each of the three structural models described in Chapter 2, using each of the eight empirical motions as inputs. In a SMA or PRA, the inter-story structural forces and displacements (or drift ratios) determined from these analyses would serve as response demands for evaluating the seismic capacities of the structures themselves. Relative motion-to-motion comparisons of linear structural forces and displacements indicate which motion spectra have greater potential to induce a structure to yield (assuming a common basis for scaling/anchoring the motion spectra). Linear structural demands are a significant element used conventionally in estimating seismic fragility curves for NPP components; hence, they are applicable to seismic margin evaluation and seismic PRA study..

When the empirical motions are scaled to the same anchor basis, variations in evaluated forces and displacements reflect impacts of motion-to-motion variabilities in spectral shape. The spectrum anchor basis resulting in the lowest motion-to-motion variations in elastically computed structural demands will also generally be the most meaningful and consistent means for comparing in-structure spectra results. It is to be generally expected that spectral acceleration averaged over the near vicinity of a structure's predominant frequency will define the most consistent anchor basis for linear response demands. [In a seismic evaluation study, several different structures (having different values of fundamental period) must generally be

considered, and yet, a single motion-anchor basis must be used. Anchoring input motion to a single, localized value of spectral acceleration, therefore, is not applicable, on a global basis, for seismic evaluation. The impact of different anchor bases, on seismic demand comparisons, is discussed further in Chapter 7].

4.1.1 Motion-Specific Results

Tables 4-1, 4-3, 4-5 and Tables 4-2, 4-4, 4-6 indicate (respectively) maximum inter-story forces and zero-period floor accelerations, induced in each structural model for each empirical input motion. (Maximum inter-story displacements can be computed simply by dividing the maximum inter-story forces by the appropriate respective values of inter-story stiffness that were presented in Tables 2-2 to 2-4). Responses are shown for four cases of input scaling: (1) the original (unscaled) ground motions; (2) the motion inputs scaled to have a common PGA of 0.3g; (3) the motion inputs scaled to have a common spectral acceleration, in the near vicinity of the structure's predominant frequency, of 0.6g; and the motion inputs scaled to have a common average spectral acceleration (over a broad frequency range) of 0.6g. Response analyses were conducted only for one set of reference motion inputs. Values in Tables 4-1 to 4-6 for the various anchor bases were obtained by multiplying reference results by the appropriate motion-specific scale factors from Table 2-5. Hence, responses for the original motion inputs are obtained by dividing the results for the reference-PGA analysis by the appropriate, motion-specific ScPGA scale factors found in the second row of Table 2-5. Results for other scale factors (ScSa3, ScSa7, ScSa10, and ScASA) are obtained by simply multiplying the appropriate scaling ratios in Table 2-5 with the corresponding reference-PGA results.

For a given structure, given location within that structure, and given motion, values of maximum forces or ZPAs for different motion-scaling bases (as presented in Tables 4-1 to 4-6) are, therefore, simply related through the appropriate scale factors. In other words, the nature of structural response is not affected by the scaling basis; it depends only on the structure and the motion.

Values in Tables 4-1 to 4-6 for structural forces and ZPAs reveal a fundamental difference for Eastern U.S. (EUS) type versus Western U.S. (WUS) type motions. The difference is in the nature of structural demands, and of the magnitudes of floor motions in relation to the magnitudes of structural forces. This fundamental difference in behavior, and its implications, are discussed below in some detail.

4.1.2 EUS versus WUS motions: Implications to Seismic Evaluation and Design Practice

Maximum inertial forces acting at each structural mass (floor) are obtained by multiplying the floor zero-period accelerations (ZPAs), as found in Tables 4-2, 4-4 and 4-6, by the appropriate magnitudes of lumped floor masses (see Tables 2-2, 2-3 and 2-4). By comparing maximum inertial forces so obtained for the top structural floor mass, against corresponding values of computed maximum inter-story forces for the uppermost structural element, close agreement is always seen. The small difference in values is due to the minor levels of damping forces acting on the mass.

At any given instant, the inter-story shear force acting at any level in the structure is closely approximated as the sum of inertial forces acting on masses above that level. In this approximation, it is important to account for the direction of inertial forces, so that the counter-acting effect of motions in opposing directions (at different story levels) is properly accounted for. Because the masses in a structure do not generally achieve their maximum accelerations at the same instant in time, and because the masses may be moving in opposing directions at any given instant, maximum inter-story forces in all but the top element of a structure will generally not equal the sum of maximum inertial forces acting on masses above the element of interest. The base shear, for instance, cannot generally be obtained as the sum of maximum inertial forces acting on all lumped masses. Only when the structure vibrates predominantly in its fundamental mode, do masses respond in substantial unison (reaching peak inertial forces at about the same time and in the same direction) and thus do maximum inter-element shear nearly equal the sum of inertial forces (or story shears) coming from above.

Viewing it another way, when the sum of maximum inertial forces is significantly different from the base shear, then structural vibration has a substantial component of higher-mode response. Such a situation can, of course, be predicted simply by examining the amplitude of the input response spectrum at the structure's fundamental frequency relative to response-spectral amplitudes at higher-mode frequencies, and by appropriately accounting for modal participation factors.

Because Eastern U.S. motions have strong high-frequency content compared to motions occurring in the Western U.S. for similar magnitudes and distances, higher-mode response is an issue of concern to this study, as well as to seismic evaluation studies for Eastern U.S. nuclear power plants in general. Most importantly, the use of a spectral shape representative of Western U.S. motions cannot be simply assumed to be universally conservative; for

evaluating Eastern U.S. NPPs, such practice can lead one to substantially under-estimate linear demands that may be placed on equipment mounted in typical NPP structures.

For typical NPP structures responding to real Eastern U.S. motions, structural shears themselves may be comparatively low (with respect to similarly scaled Western U.S. motions), and yet the floor motions may be quite strong in comparison. Compare ratios of structural forces versus ratios of ZPAs, for instance, taken from motions MImp1 and MSag1 for the 7-Hz structure and ScSa7 scaling. Whereas the maximum base shear for MImp1 is about 10% higher than for MSag1, the ZPAs are higher for MSag1 at floors 1 and 2 (higher by as much as 33%).

This situation occurs for the reasons described above; the floor motions oppose one another, tending on the one hand to reduce the total base shear and inter-story shears at lower levels in the structure, whereas on the other hand the absolute magnitudes of the floor motions are in reality stronger than what might be anticipated (for fundamental-mode-only response).

For Eastern U.S. NPPs responding to real motions representative of the Eastern U.S., the preceding situation is more the rule rather than the exception; i.e., maximum base shear is not a very good indicator of maximum in-structure (floor) motions for Eastern U.S. NPPs. For Western U.S. NPPs responding to real Western U.S. motions, floor motions that oppose one another is, in contrast, more the exception than the rule; hence, maximum base shear does serve as a good indicator of the strength of floor motions for Western U.S. NPPs (and Western U.S. building structures in general). It can be said, therefore, that seismic response of Eastern U.S. NPPs is fundamentally different from seismic response of Western U.S. NPPs (due to fundamental differences in the character of ground motion). Consequently, analytical simplifications, design simplifications, basic understanding, rules-of-thumb, intuition, etc., derived based on investigation for Western U.S. motions cannot, without explicit verification, be applied to Eastern U.S. NPPs.

Furthermore, analytical and design simplifications are often based on parametric studies that employ simple models of structures. For the reasons discussed above, it is clear that parametric studies conducted to determine seismic design and evaluation procedures for Eastern U.S. structures cannot rely on single-degree-of-freedom (SDOF) models to simultaneously represent the character of base and inter-story shears and intensity of floor motions. An SDOF model is inherently incapable of capturing the significant effects of opposing floor motions that may be generally expected for seismic response in the Eastern U.S.

There are two clearly significant implications of the above facts. First, seismic design or evaluation studies for structures located in the Eastern U.S. must (until simpler applicable methods are developed or verified) rely on fundamental structural dynamics, as opposed to simpler analytical derivatives. Simplified seismic design and evaluation methods must be developed or verified specifically for engineering practice applicable to the Eastern U.S. Second, seismic design and evaluation studies for structures in the Eastern U.S. must be based on input motions representative of those expected for the Eastern U.S.

For NPP evaluation practice, the first implication is not a significant issue, as fundamental dynamic analysis is standard practice. Yet, the second implication clarifies that such fundamental analysis is not being put to good use if representative motion input is not used. Regardless of the level of sophistication in dynamic analysis employed in the evaluation study, it will simply miss capturing the expected impacts of higher-mode responses if high-frequency energy is missing in the input. Making exclusive use of input representative of the Western U.S. for evaluation of an Eastern U.S. NPP presumes that such high-frequency effects are unimportant and may be ignored. More importantly, conducting evaluation studies of Eastern U.S. NPPs using Western U.S. motions as input can lead to significant misunderstanding of the fundamental nature of seismic severe-accident response of NPPs.

4.1.3 Response Statistics

Tables 4-7 to 4-9 present values of response statistics obtained for the eight empirical motions. Averages and coefficients of variation (COV) are presented for maximum inter-story forces and displacements, and for ZPAs. These results are presented primarily to indicate the consistency produced in response demands for the various scaling approaches. Scaling bases that produce the lowest COVs in response demands, among the eight motions, can be generally said to result in the most consistent response comparisons.

As seen in Tables 4-7 to 4-9, for maximum inter-story force or displacement, the lowest COVs are nearly always achieved for the case of motion scaling based on spectral acceleration averaged over the near vicinity of the structure's predominant frequency (i.e., scalings ScSa3, ScSa7, and ScSa10).

The situation is somewhat more complicated for ZPA. For locations near the top of a building, the maximum floor acceleration is influenced primarily by the response of the building; at locations nearer to the ground, the ZPA may be more influenced by the PGA of the input ground motion. Consequently, for locations close to ground level, scaling based on PGA may tend to result in the lowest COV values for ZPA. This is demonstrated in Tables 4-7 and

4-8, for the 5-DOF structural models, where ScPGA scaling produced lower ZPA COVs at lower floor locations, compared to ScSa3 or ScSa7 scaling.

If the structure responds significantly at higher modes of vibration, then scaling based on spectral acceleration in the vicinity of the predominant-mode frequency is not likely to achieve the lowest COV of ZPA. Consequently, for the 3-Hz structure which can be expected to have significant higher-mode response to most EUS-type motions, the lowest COV of ZPA is not expected to occur for ScSa3 scaling. Table 4-7 confirms this expectation; ScASA scaling is seen to result in the lowest COVs in ZPA for the 3-Hz structure. On the other hand, the 7-Hz and 10-Hz structures are not expected to respond as significantly at higher modes; hence, for these structures, low COV values are observed for ScSa7 or ScSa10 scaling, respectively. For the first two floors of the 7-Hz building, ScPGA scaling results in the lowest COV of ZPA; whereas at higher floors, ScSa7 scaling produces the lowest COVs. For the 10-Hz structure, the lowest COVs of ZPA are always observed for ScSa10 scaling.

Scaling according to ScSa3, ScSa7, or ScSa10 is intended to apply only to the specific structure of interest. Such scaling generally results in the most consistent demands, but just for the particular individual structure of interest. It is not expected that any single one of these scaling bases will prove to be a consistent approach for comparing response demands in all NPP structures of interest. ScSa3 scaling would not, in general, be a good basis for anchoring motions to produce consistent demands in a 10-Hz structure, for instance; and vice-versa with respect to ScSa10 scaling being applied to a 3-Hz structure. The reason is that, even though scaled to a common value at 3 Hz, variations in spectral shape can lead to substantial variations in the response spectral ordinate at 10 Hz. For the same reasons, ScPGA scaling can also not be expected to well apply in producing consistent demands in a variety of structures of interest.

In contrast, ScASA scaling provides a reasonable compromise for obtaining consistent demands in a variety of structures of interest. That this is the case can be seen by comparing COV values for the various scaling approaches, among the sets of results shown in Figure 4-7 to 4-9. The scaling approach which results, over all structures, in the lowest COVs for both forces/displacements and ZPAs is clearly ScASA scaling. The practical application of this is that, in seismic evaluation studies where a spectral shape and an anchor basis are specified for defining input, ScASA scaling would be the most adequate general approach for anchoring the spectrum. For the present study, the most consistent individual comparisons would be achieved by applying ScSa scaling for the appropriate frequency. However, because a motion target spectrum would not be scaled differently for different structures in a seismic evaluation study, ScASA is most applicable to this study.

4.2 IN-STRUCTURE RESPONSE SPECTRA

In-structure spectra define input demands to equipment mounted in structures. ISS results may be computed accounting for nonlinear response of the structure. In many cases for seismic evaluation, however, ISS which have been obtained for linear structural response are used. ISS demands are compared against equipment fragilities to assess component failure rates; hence, they are applicable to seismic evaluation studies.

4.2.1 Motion-Specific Results

ISS results for the eight empirical motions are presented in Figures 4-1 to 4-12. The results are for ScASA scaling. Figures 4-1 to 4-4 show results for the 3-Hz structure, Figures 4-5 to 4-8 show results for the 7-Hz structure, and Figures 4-9 to 4-12 show results for the 10-Hz structure,

Examination of these plots reveal that the shapes of ISS curves vary considerably from motion to motion (for a given structure and floor location). This variation in ISS shapes results directly from variation in shapes of the input ground response spectra, particularly variations in relative amplitudes of the input at modal vibration frequencies of the structure. ISS results at lower locations in the structure consistently show greater contribution to floor motion coming from the second mode of vibration, as compared to ISS results for locations higher-up in the structure. In other words, as we go up the structure, the fundamental mode generally has a more dominant effect on the floor motion.

For the 3-Hz structure, ISS demands appear most similar for motions MSag3 and MSag4, and for motions MSag1 and MNah3. For the 7-Hz structure, ISS demands are most similar for motions MSag1, MSag2 and MNah3. And for the 10-Hz structure, ISS demands look most similar for motions MSag1, MSag2 and MNah3, and for motions MSag3 and MSag4. These comparisons are roughly what one would expect based on an examination of the input spectral shapes.

The ISS results presented in Figures 4-1 to 4-12 represent real demands that might be imposed on equipment mounted in structures. Results for MSag1, MSag2, MSag3 and MNah3 describe demands representative of Eastern U.S. motions that are consistent with the Eastern U.S. evaluation target spectra selected for use in this study. Results for MImp1 describe demands representative of Western U.S. motions consistent with the Western U.S. target spectra selected for use. These ISS demands will serve as the basis for comparative discussions in Chapter 7.

Table 4-1

Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Empirical Ground Motion:							
		MSag1	MSag2	MSag3	MSag4	MNah1	MNah2	MNah3	MImp1
No Scaling	1	1522.	2335.	7510.	14471.	50931.	13368.	4095.	37991.
	2	1355.	2156.	7420.	13119.	47399.	11626.	3724.	34005.
	3	1619.	2069.	6696.	10733.	39990.	10415.	3050.	27552.
	4	1348.	1567.	5186.	7635.	29187.	8189.	2293.	19292.
	5	824.	862.	2877.	4047.	15431.	4502.	1463.	10089.
ScPGA	1	4287.	4493.	17950.	24948.	11358.	10280.	6335.	21617.
	2	3816.	4147.	17734.	22617.	10570.	8940.	5761.	19349.
	3	4558.	3981.	16005.	18503.	8918.	8009.	4718.	15677.
	4	3797.	3014.	12394.	13163.	6509.	6297.	3548.	10977.
	5	2319.	1659.	6877.	6977.	3441.	3462.	2264.	5741.
ScSa3	1	23338.	22584.	20120.	22039.	23378.	19999.	24087.	21769.
	2	20776.	20847.	19878.	19980.	21756.	17392.	21903.	19485.
	3	24815.	20012.	17940.	16346.	18355.	15581.	17940.	15787.
	4	20670.	15152.	13892.	11628.	13397.	12251.	13489.	11054.
	5	12626.	8340.	7708.	6163.	7083.	6735.	8607.	5781.
ScASA	1	7930.	14880.	20331.	22083.	18183.	16176.	13022.	20933.
	2	7060.	13736.	20086.	20019.	16921.	14067.	11841.	18737.
	3	8432.	13185.	18127.	16378.	14276.	12602.	9699.	15181.
	4	7023.	9984.	14037.	11651.	10420.	9909.	7293.	10630.
	5	4290.	5495.	7789.	6175.	5509.	5447.	4653.	5559.

Table 4-2

Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Empirical Ground Motion:							
		MSag1	MSag2	MSag3	MSag4	MNah1	MNah2	MNah3	MImp1
No Scaling	1	.1163	.0928	.1794	.2078	.9657	.3675	.1811	.7695
	2	.0947	.0809	.2312	.3331	1.3462	.3974	.1848	.9833
	3	.1019	.0876	.2293	.4212	1.5230	.3956	.1531	1.0833
	4	.0985	.1067	.3009	.4761	1.7874	.4790	.1452	1.2296
	5	.1052	.1117	.3759	.5243	1.9709	.5850	.1944	1.3427
ScPGA	1	.3275	.1785	.4288	.3582	.2153	.2826	.2802	.4378
	2	.2667	.1556	.5526	.5743	.3002	.3056	.2859	.5595
	3	.2870	.1686	.5481	.7261	.3396	.3042	.2369	.6164
	4	.2773	.2052	.7192	.8208	.3986	.3684	.2246	.6996
	5	.2962	.2149	.8984	.9039	.4395	.4499	.3007	.7640
ScSa3	1	1.7827	.8970	.4807	.3165	.4432	.5498	1.0653	.4409
	2	1.4521	.7820	.6194	.5073	.6179	.5944	1.0870	.5634
	3	1.5625	.8474	.6143	.6414	.6991	.5918	.9008	.6207
	4	1.5098	1.0315	.8062	.7251	.8204	.7166	.8540	.7045
	5	1.6123	1.0803	1.0070	.7986	.9047	.8751	1.1432	.7694
ScASA	1	.6057	.5910	.4857	.3171	.3447	.4447	.5759	.4240
	2	.4934	.5153	.6259	.5083	.4806	.4808	.5876	.5418
	3	.5309	.5583	.6208	.6427	.5437	.4787	.4870	.5969
	4	.5130	.6796	.8146	.7266	.6381	.5796	.4617	.6775
	5	.5478	.7118	1.0175	.8001	.7036	.7078	.6180	.7399

Table 4-3

Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Empirical Ground Motion:							
		MSag1	MSag2	MSag3	MSag4	MNah1	MNah2	MNah3	MImp1
No Scaling	1	2844.	2082.	5129.	7121.	27403.	11644.	5360.	18973.
	2	2375.	1783.	4474.	6149.	21964.	9479.	5025.	16677.
	3	1847.	1593.	3556.	4642.	17091.	6618.	4172.	12730.
	4	1672.	1459.	3149.	4035.	15499.	5788.	3719.	11094.
	5	799.	741.	1429.	1761.	7428.	2629.	1749.	4860.
ScPGA	1	8008.	4006.	12258.	12277.	6111.	8954.	8293.	10796.
	2	6688.	3431.	10693.	10601.	4898.	7289.	7773.	9489.
	3	5201.	3066.	8500.	8002.	3811.	5089.	6454.	7243.
	4	4710.	2807.	7525.	6956.	3456.	4451.	5754.	6312.
	5	2249.	1426.	3415.	3035.	1656.	2022.	2706.	2765.
ScSa7	1	9336.	11151.	10981.	11066.	9208.	12354.	9815.	10264.
	2	7797.	9551.	9579.	9556.	7380.	10057.	9201.	9022.
	3	6064.	8534.	7614.	7213.	5743.	7021.	7639.	6887.
	4	5491.	7815.	6741.	6270.	5208.	6141.	6810.	6002.
	5	2622.	3970.	3059.	2736.	2496.	2790.	3202.	2629.
ScASA	1	14813.	13266.	13884.	10867.	9783.	14089.	17046.	10454.
	2	12371.	11362.	12111.	9384.	7841.	11469.	15979.	9189.
	3	9621.	10153.	9627.	7083.	6101.	8007.	13268.	7014.
	4	8712.	9297.	8523.	6157.	5533.	7004.	11828.	6113.
	5	4160.	4723.	3868.	2687.	2652.	3181.	5562.	2678.

Table 4-4

Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Empirical Ground Motion:							
		MSag1	MSag2	MSag3	MSag4	MNah1	MNah2	MNah3	MImp1
No Scaling	1	.1420	.1361	.1578	.2150	1.3095	.5405	.2198	.6462
	2	.1658	.1663	.2443	.3117	1.5781	.6801	.2903	.8890
	3	.1570	.1367	.2790	.3896	1.5371	.6761	.3074	1.0507
	4	.1845	.1629	.3593	.4699	1.7223	.6816	.4127	1.2904
	5	.2367	.2173	.4253	.5189	2.1810	.7729	.5177	1.4365
ScPGA	1	.3998	.2619	.3772	.3706	.2920	.4157	.3400	.3677
	2	.4668	.3200	.5838	.5374	.3519	.5230	.4491	.5059
	3	.4422	.2629	.6667	.6717	.3428	.5199	.4755	.5978
	4	.5196	.3134	.8586	.8101	.3841	.5242	.6384	.7343
	5	.6665	.4181	1.0164	.8947	.4864	.5944	.8009	.8173
ScSa7	1	.4661	.7291	.3379	.3340	.4400	.5735	.4024	.3496
	2	.5442	.8907	.5230	.4844	.5302	.7216	.5315	.4810
	3	.5155	.7319	.5972	.6055	.5165	.7173	.5628	.5684
	4	.6058	.8724	.7692	.7302	.5787	.7232	.7556	.6981
	5	.7770	1.1638	.9105	.8064	.7328	.8200	.9479	.7771
ScASA	1	.7395	.8674	.4273	.3280	.4675	.6540	.6988	.3561
	2	.8634	1.0596	.6612	.4757	.5634	.8229	.9231	.4898
	3	.8179	.8707	.7551	.5946	.5488	.8181	.9774	.5789
	4	.9612	1.0379	.9725	.7170	.6149	.8248	1.3123	.7110
	5	1.2329	1.3845	1.1512	.7919	.7786	.9352	1.6463	.7915

Table 4-5

Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Empirical Ground Motion:							
		MSag1	MSag2	MSag3	MSag4	MNah1	MNah2	MNah3	MImp1
No Scaling	1	1260.	1149.	1808.	2657.	20572.	4115.	2428.	8826.
	2	825.	699.	1096.	1549.	12588.	2628.	1490.	5049.
ScPGA	1	3549.	2212.	4320.	4580.	4588.	3164.	3757.	5022.
	2	2322.	1346.	2619.	2670.	2807.	2021.	2304.	2873.
ScSa10	1	3491.	3909.	4087.	4692.	4876.	4111.	4429.	4625.
	2	2284.	2379.	2478.	2736.	2983.	2625.	2717.	2646.
ScASA	1	6565.	7324.	4893.	4054.	7344.	4979.	7722.	4863.
	2	4296.	4456.	2967.	2364.	4494.	3180.	4737.	2782.

Table 4-6

Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Empirical Ground Motion:							
		MSag1	MSag2	MSag3	MSag4	MNah1	MNah2	MNah3	MImp1
No Scaling	1	.1423	.1414	.1937	.2915	2.1261	.5094	.2941	.9817
	2	.2165	.1822	.2870	.4017	3.2745	.6897	.3843	1.3120
ScPGA	1	.4008	.2720	.4630	.5025	.4741	.3917	.4549	.5586
	2	.6096	.3505	.6859	.6925	.7302	.5304	.5945	.7465
ScSa10	1	.3943	.4809	.4380	.5147	.5039	.5088	.5364	.5144
	2	.5996	.6195	.6489	.7094	.7761	.6890	.7010	.6875
ScASA	1	.7415	.9010	.5245	.4448	.7590	.6163	.9351	.5409
	2	1.1276	1.1607	.7768	.6130	1.1690	.8345	1.2221	.7229

Table 4-7

Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 3-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases

Scaling Basis	Floor No.	Mean Displ. (in)	Mean Force (kips)	COV of Displ. or Force	Mean ZPA (g)	COV of ZPA
No Scaling	1	.1836	16528.	1.0305	.3600	.8523
	2	.1678	15100.	1.0370	.4564	.9437
	3	.1418	12765.	1.0136	.4994	.9826
	4	.1037	9337.	.9935	.5779	.9909
	5	.0557	5012.	.9658	.6513	.9580
ScPGA	1	.1406	12658.	.5881	.3136	.2782
	2	.1291	11617.	.5912	.3750	.4038
	3	.1116	10046.	.5446	.4034	.4644
	4	.0829	7462.	.5190	.4642	.4939
	5	.0455	4092.	.4889	.5334	.4922
ScSa3	1	.2463	22164.	.0633	.7470	.6130
	2	.2250	20252.	.0667	.7780	.3946
	3	.2039	18347.	.1531	.8098	.3752
	4	.1549	13942.	.2025	.8960	.2814
	5	.0876	7880.	.2561	1.0238	.2480
ScASA	1	.1855	16692.	.2648	.4736	.2193
	2	.1701	15308.	.2766	.5292	.0934
	3	.1498	13485.	.2258	.5574	.1001
	4	.1124	10118.	.2087	.6363	.1689
	5	.0624	5615.	.1756	.7308	.1777

Table 4-8

Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 7-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases

Scaling Basis	Floor No.	Mean Displ. (in)	Mean Force (kips)	COV of Displ. or Force	Mean ZPA (g)	COV of ZPA
No Scaling	1	.0481	10070.	.8261	.4209	.9070
	2	.0385	8491.	.7961	.5407	.8528
	3	.0230	6531.	.7924	.5667	.8187
	4	.0229	5802.	.8002	.6604	.7917
	5	.0137	2674.	.8136	.7883	.8108
ScPGA	1	.0422	8838.	.3077	.3531	.1395
	2	.0345	7608.	.3212	.4672	.1829
	3	.0209	5921.	.3093	.4974	.2772
	4	.0207	5246.	.2982	.5978	.3081
	5	.0123	2409.	.2677	.7118	.2712
ScSa7	1	.0503	10522.	.0948	.4541	.2826
	2	.0408	9018.	.0974	.5883	.2283
	3	.0250	7089.	.1179	.6019	.1283
	4	.0249	6310.	.1216	.7167	.1213
	5	.0151	2938.	.1523	.8670	.1507
ScASA	1	.0622	13025.	.1781	.5673	.3274
	2	.0508	11213.	.2086	.7324	.2761
	3	.0312	8859.	.2433	.7452	.1952
	4	.0311	7896.	.2496	.8940	.2353
	5	.0189	3689.	.2743	1.0890	.2753

Table 4-9

Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 10-Hz Structure Subjected to Empirical Motion Inputs Scaled to Four Different Anchor Bases

Scaling Basis	Floor No.	Mean Displ. (in)	Mean Force (kips)	COV of Displ. or Force	Mean ZPA (g)	COV of ZPA
No Scaling	1	.0518	5352.	1.1594	.5850	1.0903
	2	.0313	3240.	1.1641	.8435	1.1631
ScPGA	1	.0377	3899.	.2204	.4397	.1833
	2	.0229	2370.	.1987	.6175	.1976
ScSa10	1	.0414	4277.	.1009	.4864	.0912
	2	.0252	2606.	.0797	.6789	.0768
ScASA	1	.0577	5968.	.2231	.6829	.2466
	2	.0354	3659.	.2378	.9533	.2364

Figure 4-1. In-structure response spectra for the 3-Hz structure subjected to empirical input motions with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MSag1 and (b) MSag2.

Frequency (Hz)

Frequency (Hz)

Figure 4-2. In-structure response spectra for the 3-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (c) MSag3 and (d) MSag4.

Figure 4-3. In-structure response spectra for the 3-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (e) MNah1 and (f) MNah2.

Figure 4-4. In-structure response spectra for the 3-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (g) MNah3 and (h) MImpl.

Figure 4-5. In-structure response spectra for the 7-Hz structure subjected to empirical input motions with ScASA scaling. Responses at the first, third, and top/fourth floors for motions: (a) MSag1 and (b) MSag2.

Figure 4-6. In-structure response spectra for the 7-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and top/fourth floors for motions: (c) MSag3 and (d) MSag4.

Frequency (Hz)

Frequency (Hz)

Figure 4-7. In-structure response spectra for the 7-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and top/fourth floors for motions: (e) MNah1 and (f) MNah2.

Figure 4-8. In-structure response spectra for the 7-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first, third, and top/fourth floors for motions: (g) MNah3 and (h) MImpl.

ISS2(S10); Motion: MSag1
(Floor 2, 10-Hz 2-Story Structure)

ISS2(S10); Motion: MSag2
(Floor 2, 10-Hz 2-Story Structure)

ISS1(S10); Motion: MSag1
(Floor 1, 10-Hz 2-Story Structure)

ISS1(S10); Motion: MSag2
(Floor 1, 10-Hz 2-Story Structure)

Figure 4-9. In-structure response spectra for the 10-Hz structure subjected to empirical input motions with ScASA scaling. Responses at the first and second floors for motions: (a) MSag1 and (b) MSag2.

Figure 4-10. In-structure response spectra for the 10-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first and second floors for motions: (c) MSag3 and (d) MSag4.

Figure 4-11. In-structure response spectra for the 10-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first and second floors for motions: (e) MNah1 and (f) MNah2.

Figure 4-12. In-structure response spectra for the 10-Hz structure subjected to empirical input motions with ScASA scaling (continued). Responses at the first and second floors for motions: (g) MNah3 and (h) MImp1.

Section 5

RESPONSE RESULTS: ARTIFICIAL MOTIONS WITH SMOOTH SPECTRA

This chapter presents results of evaluation-demand calculations performed using as inputs the eight artificial motions having smooth response spectra. As described in Chapter 3, each motion MArS1 has been generated to closely match a specified target response spectrum. As was produced for the empirical motions, the results obtained here include maximum structural inter-story forces, floor ZPAs, and ISS results.

Results are compared among the eight artificial motions to identify target spectra which result in substantially similar response demands. Target spectra that have very similar shapes, and that result in very similar demands, logically need not be considered separately for subsequent evaluation-demand comparisons.

The results of unique response calculations presented here are used in Chapter 7 to compare with evaluation demands obtained, for corresponding cases, from analyses using empirical motions and multiple artificial motions as inputs.

5.1 STRUCTURAL FORCES AND DISPLACEMENTS

5.1.1 Motion-Specific Results

Tables 5-1, 5-3, 5-5 and Tables 5-2, 5-4, 5-6 present results, respectively, of maximum structural forces and floor ZPAs for the eight cases of artificial motion input. Tables 5-1, 5-2 are for the 3-Hz structure, Tables 5-3, 5-4 apply to the 7-Hz structure, and Tables 5-5, 5-6 present results for the 10-Hz structure.

The reader is encouraged to examine these tables for similarities and differences in response demands among the various cases of artificial motion input. We here draw out two notable points for discussion. First, computed demands for the six Eastern U.S. motions are similar to one another, and computed demands for the two Western U.S. motions are similar to one another. For any given structure, this is seen most clearly in the results for ScSa scaling. Over the frequency range encompassed by the three structures, the target spectra for the two Western U.S. motions are identical. Hence, any differences observed in the demands for these

two motions is entirely due to random variation in the simulation process. The differences in demands for these two motions nowhere exceed 12%, but are less in most cases. So, it can be expected that errors on the order of 10% in random simulation. For cases where the target spectrum is not matched as closely as in this study, larger simulation-to-simulation variations can be expected. (In this case, scaling to envelope or meet specified criteria in fitting the target spectrum will be important to avert unconservative circumstances that could arise). Even though the simulated Eastern U.S. motions are all derived from different target spectra, the differences in demands among all motions is typically only on the order of 20%. (The differences can, however, be as high as 50% for isolated cases. Differences also decrease with increasing structural frequency). In most cases, differences in soil and rock results for a given target type of spectrum (i.e., T_{Er} versus T_{Es}, T_{Lr} versus T_{Ls}, and T_{L2r} versus T_{L2s}) generally have the same order of magnitude as differences caused by random noise in simulating a given target spectrum.

The second point we make reinforces the observation in Chapter 4 that Eastern U.S. motions and Western U.S. motions are fundamentally different in terms of their effects on structures and their effects on the relationship between base shear and the intensity of floor motions. *For the same magnitude of base shear*, Eastern U.S. motions will generally cause more intense floor motions than will Western U.S. motions. Again, this is due to the greater relative magnitude of second-mode contribution to overall response for the Eastern U.S. motions. To illustrate, a noteworthy case is seen in comparing results for motion MArS1(T_{Er}) versus motion MArS1(T_{Ws}), for the 3-Hz structure and ScSa3 scaling. The maximum base shear for the T_{Er} case is just slightly less than for the T_{Ws} case, and yet the floor ZPAs for T_{Er} exceed those for T_{Ws} in all floors (by no less than 24%, but by as much as 72%). Clearly, simplified understanding of the nature of structural response that has been acquired by the earthquake engineering profession, based on Western U.S. type inputs, cannot be readily applied to the Eastern U.S.

5.1.2 Response Statistics

Tables 5-7 to 5-9 present means and coefficients of variations for maximum force (and displacement) results and for ZPA results. These tables convey the level of consistency achieved in response demands among the alternative scaling bases. For each structure, it is seen that ScSa-type scaling generally results in the most consistent comparisons. ScPGA scaling results in very consistency for response comparisons in the 10-Hz structure, adequate consistency for the 7-Hz structure, and poor consistency (COV values as high as 53%) for the 3-Hz structure. In contrast, ScASA scaling produces good-to-adequate consistency in comparisons for all three structures. The highest COV in any response demand for ScASA scaling

is only 23%, and is observed for the highest-frequency (10-Hz) structure. The consistency in response comparisons is considerably better for the lower-frequency structures.

These statistical results verify the applicability of the ScASA approach for input scaling, as a consistent basis in comparing ground motions and the demands they produce.

5.2 IN-STRUCTURE RESPONSE SPECTRA

5.2.1 Motion-Specific Results

ISS results for the eight artificial motions MARs1 are presented in Figures 5-1 to 5-12. Results are shown for ScASA scaling. (Results for other scaling bases can be obtained by appropriately applying the scale factors in Table 2-6 to these ISS demands). Figures 5-1 to 5-4 show ISS results for the 3-Hz structure, Figures 5-5 to 5-8 show ISS results for the 7-Hz structure, and Figures 5-9 to 5-12 show ISS results for the 10-Hz structure,

The reader is encouraged to examine these plots for similarities and differences for related and contrasting cases of motion target spectra. We here make a few observations concerning these results. First, among the Eastern U.S. artificial motions, ISS demands exhibit relatively low variability, particularly in ISS shape, but also in ISS amplitude. Differences in ISS amplitudes result from random variations in input spectral amplitudes (at the structural frequency of interest) for a given value of ASA, and from differences in shapes of the target spectra. The low variability in response demands among the Eastern U.S. motions was anticipated in Chapters 1 and 3, due to the similarity in shapes of target spectra for all Eastern U.S. cases. For the Western U.S. motions, ISS results are nearly identical to one another for all structures and floor locations, which is as expected since they are derived from nearly identical target spectra.

A second point is that ISS shapes for the Western U.S. artificial motions are often significantly different than those for the Eastern U.S. artificial motions. This is true especially for the 7-Hz and 10-Hz structures, where the Western U.S. motions have little input energy at higher modal frequencies; and consequently, they result in ISS that are flat across higher frequencies (whereas the Eastern U.S. cases show bumps in ISS at the second-mode frequency). For the 3-Hz structure, the Western U.S. artificial motions do have significant input energy at the second modal frequency; hence, for this case, the ISS results are similar among the Eastern U.S. and Western U.S. cases.

The ISS results presented in Figures 5-1 to 5-12 represent demands that would be computed in seismic evaluation studies employing conventional methods for developing artificial ground-motion input. These simulated ISS demands will serve as the basis for comparative discussions in Chapter 7.

5.3 SELECTION OF CASES FOR SUBSEQUENT COMPARISONS

In making comparisons of target spectra in Chapter 2, three similar cases were identified, defining three groups: (1) Eastern U.S. spectra TEr, TEs, TL2r and TL2s, (2) Eastern U.S. spectra TLr and TLs, and (3) Western U.S. spectra TWr and TWs. To best focus subsequent comparisons, one motion from each of these groups can be selected in representing evaluation demands for that group of spectra. Demands should not be averaged among the motions in these groups, because demands produced in an actual seismic evaluation study will be based on only one input motion. Averaging demands may tend to show conservatism (i.e., broader ISS peaks) that may not be produced in practice.

The objectives here are (a) to verify that the demands produced among the motions for any group above are similar to one another, and (b) to select single motions that results in representative demands for each group, for use in subsequent comparisons. By considering the appropriate tables and figures in this chapter, the reader can verify similarity in demands produced by motions among each of the above groups. Results of forces, ZPAs, and ISS demands should be included for consideration.

For the first group of motions, ISS results are all similar, especially for the 7-Hz and 10-Hz structures. For the 3-Hz structure, only motion MArS1(TL2s) results in ISS demands notably different from the other motions in the group. For the second group of motions, ISS results are very similar each of the three structures. And, for the third group of similar motions, ISS demands are nearly identical for all structures. Similar conclusions can be drawn with respect to results of maximum forces and ZPAs.

Based on comparisons of results among motions for each of the three groups, we have selected the following three representative motions for use in subsequent comparisons: (1) MArS1(TL2r), (2) MArS1(TLr), and (3) MArS1(TWs).

Table 5-1

Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MARSl Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motion MARSl Matching Target:							
		TEr	TEs	TLr	TLs	TL2r	TL2s	TWr	TWs
No Scaling	1	3180.	7668.	5755.	11908.	3347.	6742.	24294.	21912.
	2	2957.	7166.	4943.	11003.	3116.	6323.	21345.	19295.
	3	2628.	6373.	4221.	9399.	2767.	5392.	16706.	15160.
	4	2118.	5218.	3185.	6795.	2150.	4251.	11679.	10818.
	5	1358.	3234.	1978.	3491.	1348.	2555.	6292.	5802.
ScPGA	1	6276.	8305.	8612.	10782.	7678.	9108.	24294.	21912.
	2	5836.	7760.	7397.	9962.	7149.	8542.	21345.	19295.
	3	5187.	6902.	6317.	8510.	6348.	7284.	16706.	15160.
	4	4180.	5651.	4766.	6152.	4933.	5742.	11679.	10818.
	5	2681.	3502.	2959.	3161.	3093.	3452.	6292.	5802.
ScSa3	1	20303.	20277.	19525.	20355.	20205.	21537.	22919.	20672.
	2	18880.	18948.	16770.	18808.	18812.	20199.	20137.	18203.
	3	16782.	16852.	14321.	16065.	16706.	17224.	15761.	14302.
	4	13522.	13798.	10806.	11614.	12981.	13578.	11018.	10206.
	5	8674.	8550.	6709.	5967.	8138.	8163.	5936.	5474.
ScASA	1	13989.	14189.	14918.	16317.	14595.	16369.	23113.	20799.
	2	13009.	13259.	12813.	15077.	13589.	15352.	20308.	18315.
	3	11564.	11793.	10942.	12878.	12067.	13091.	15894.	14390.
	4	9317.	9655.	8257.	9310.	9377.	10320.	11111.	10269.
	5	5977.	5983.	5126.	4783.	5879.	6205.	5986.	5507.

Table 5-2

Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion MArS1 Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motion MArS1 Matching Target:							
		TEr	TEs	TLr	TLs	TL2r	TL2s	TWr	TWs
No Scaling	1	.0954	.2042	.1791	.2912	.0879	.1539	.4274	.3751
	2	.1280	.2907	.2313	.3623	.1237	.2217	.6688	.5740
	3	.1198	.2737	.2018	.3903	.1178	.2194	.7366	.6521
	4	.1249	.2981	.1939	.4322	.1301	.2535	.7344	.6637
	5	.1757	.4182	.2579	.4568	.1744	.3308	.8117	.7489
ScPGA	1	.1883	.2212	.2679	.2637	.2017	.2079	.4274	.3751
	2	.2526	.3149	.3461	.3281	.2839	.2994	.6688	.5740
	3	.2365	.2964	.3020	.3533	.2702	.2964	.7366	.6521
	4	.2465	.3229	.2901	.3913	.2985	.3425	.7344	.6637
	5	.3469	.4530	.3859	.4136	.4000	.4469	.8117	.7489
ScSa3	1	.6093	.5401	.6075	.4978	.5307	.4916	.4032	.3539
	2	.8172	.7688	.7848	.6193	.7471	.7081	.6309	.5415
	3	.7650	.7238	.6847	.6671	.7110	.7010	.6949	.6152
	4	.7975	.7883	.6576	.7387	.7855	.8098	.6929	.6261
	5	1.1221	1.1060	.8749	.7809	1.0526	1.0568	.7657	.7065
ScASA	1	.4198	.3779	.4642	.3990	.3833	.3736	.4066	.3560
	2	.5631	.5380	.5996	.4965	.5396	.5382	.6363	.5448
	3	.5271	.5065	.5232	.5347	.5136	.5328	.7008	.6190
	4	.5495	.5516	.5025	.5922	.5674	.6155	.6987	.6300
	5	.7732	.7739	.6685	.6260	.7604	.8032	.7722	.7109

Table 5-3

Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motion MArS1 Matching Target:							
		TEr	TEs	TLr	TLs	TL2r	TL2s	TWr	TWs
No Scaling	1	3114.	6727.	5323.	10121.	3017.	5111.	11590.	11348.
	2	2780.	5977.	4661.	9160.	2690.	4278.	9906.	9677.
	3	2114.	4726.	3436.	7086.	2037.	3360.	7287.	7060.
	4	1880.	4185.	2990.	6197.	1802.	3050.	6326.	6073.
	5	918.	1860.	1316.	2748.	848.	1416.	2752.	2580.
ScPGA	1	6145.	7285.	7964.	9163.	6921.	6904.	11590.	11348.
	2	5487.	6473.	6974.	8293.	6172.	5780.	9906.	9677.
	3	4173.	5118.	5142.	6416.	4673.	4539.	7287.	7060.
	4	3710.	4533.	4474.	5610.	4135.	4120.	6326.	6073.
	5	1811.	2015.	1970.	2488.	1945.	1913.	2752.	2580.
ScSa7	1	10295.	9426.	10989.	11308.	10118.	9775.	10934.	10706.
	2	9193.	8375.	9622.	10234.	9022.	8183.	9345.	9129.
	3	6991.	6622.	7095.	7918.	6831.	6426.	6874.	6661.
	4	6216.	5865.	6173.	6923.	6045.	5833.	5968.	5730.
	5	3034.	2607.	2718.	3070.	2843.	2708.	2596.	2434.
ScASA	1	13699.	12447.	13796.	13867.	13156.	12409.	11027.	10772.
	2	12232.	11060.	12081.	12551.	11731.	10388.	9424.	9185.
	3	9303.	8745.	8907.	9710.	8882.	8158.	6932.	6702.
	4	8271.	7745.	7750.	8491.	7860.	7404.	6018.	5765.
	5	4037.	3442.	3412.	3765.	3697.	3438.	2618.	2449.

Table 5-4

Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motion MArS1 Matching Target:							
		TEr	TEs	TLr	TLs	TL2r	TL2s	TWr	TWs
No Scaling	1	.1605	.3355	.1844	.2879	.1462	.2400	.3542	.3471
	2	.1849	.3934	.2755	.4294	.1720	.3030	.5507	.5447
	3	.1906	.4041	.3132	.5694	.1826	.2771	.6493	.6382
	4	.2184	.4859	.3483	.7122	.2094	.3382	.7399	.7220
	5	.2732	.5545	.3933	.8136	.2528	.4242	.8091	.7564
ScPGA	1	.3167	.3634	.2760	.2607	.3354	.3243	.3542	.3471
	2	.3649	.4261	.4122	.3888	.3947	.4093	.5507	.5447
	3	.3762	.4376	.4687	.5156	.4189	.3743	.6493	.6382
	4	.4310	.5262	.5212	.6448	.4804	.4569	.7399	.7220
	5	.5392	.6005	.5886	.7366	.5799	.5731	.8091	.7564
ScSa7	1	.5305	.4702	.3808	.3217	.4903	.4591	.3342	.3275
	2	.6112	.5512	.5687	.4798	.5770	.5796	.5195	.5139
	3	.6302	.5662	.6467	.6362	.6124	.5300	.6125	.6020
	4	.7220	.6809	.7191	.7957	.7022	.6469	.6980	.6811
	5	.9033	.7770	.8121	.9090	.8478	.8114	.7633	.7136
ScASA	1	.7059	.6209	.4781	.3945	.6376	.5828	.3370	.3295
	2	.8133	.7280	.7140	.5884	.7503	.7357	.5239	.5170
	3	.8385	.7477	.8119	.7803	.7962	.6728	.6177	.6057
	4	.9608	.8991	.9028	.9758	.9131	.8211	.7039	.6853
	5	1.2020	1.0261	1.0195	1.1148	1.1023	1.0300	.7698	.7180

Table 5-5

Maximum Inter-story Structural Forces for the 10-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motion MArS1 Matching Target:							
		TEr	TEs	TLr	TLs	TL2r	TL2s	TWr	TWs
No Scaling	1	1678.	3292.	2399.	4310.	1569.	2640.	3845.	4112.
	2	1033.	1933.	1533.	2607.	940.	1566.	2282.	2442.
ScPGA	1	3312.	3565.	3590.	3902.	3599.	3566.	3845.	4112.
	2	2038.	2093.	2293.	2361.	2156.	2116.	2282.	2442.
ScSa10	1	4460.	4287.	4398.	4462.	4469.	4458.	4086.	4370.
	2	2744.	2517.	2809.	2700.	2678.	2645.	2425.	2595.
ScASA	1	7382.	6091.	6219.	5905.	6841.	6410.	3658.	3903.
	2	4543.	3576.	3972.	3572.	4099.	3803.	2171.	2318.

Table 5-6

Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion MArS1 Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motion MArS1 Matching Target:							
		TEr	TEs	TLr	TLs	TL2r	TL2s	TWr	TWs
No Scaling	1	.1868	.3623	.2743	.5127	.1732	.3094	.4171	.4401
	2	.2663	.5007	.4008	.6822	.2445	.4024	.5935	.6341
ScPGA	1	.3687	.3923	.4104	.4642	.3973	.4180	.4171	.4401
	2	.5256	.5423	.5998	.6177	.5609	.5436	.5935	.6341
ScSa10	1	.4965	.4717	.5028	.5308	.4934	.5225	.4433	.4677
	2	.7078	.6520	.7348	.7064	.6966	.6796	.6307	.6738
ScASA	1	.8219	.6703	.7110	.7024	.7552	.7512	.3969	.4178
	2	1.1716	.9265	1.0390	.9348	1.0662	.9771	.5647	.6018

Table 5-7

Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 3-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases

Scaling Basis	Floor No.	Mean Displ. (in)	Mean Force (kips)	COV of Displ. or Force	Mean ZPA (g)	COV of ZPA
No Scaling	1	.1178	10601.	.7244	.2268	.5195
	2	.1058	9519.	.7032	.3251	.5771
	3	.0870	7831.	.6523	.3389	.6540
	4	.0642	5777.	.6034	.3538	.6226
	5	.0362	3257.	.5440	.4218	.5414
ScPGA	1	.1347	12121.	.5344	.2691	.3036
	2	.1212	10911.	.5102	.3835	.3699
	3	.1006	9052.	.4516	.3929	.4528
	4	.0749	6740.	.3970	.4112	.4174
	5	.0430	3868.	.3329	.5009	.3296
ScSa3	1	.2303	20724.	.0473	.5042	.1670
	2	.2094	18845.	.0538	.7022	.1277
	3	.1778	16002.	.0666	.6953	.0586
	4	.1354	12190.	.1103	.7371	.0891
	5	.0800	7201.	.1711	.9332	.1699
ScASA	1	.1865	16786.	.1877	.3976	.0791
	2	.1691	15215.	.1687	.5570	.0723
	3	.1425	12827.	.1193	.5572	.1136
	4	.1078	9702.	.0830	.5884	.0956
	5	.0631	5681.	.0818	.7360	.0783

Table 5-8

Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 7-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases

Scaling Basis	Floor No.	Mean Displ. (in)	Mean Force (kips)	COV of Displ. or Force	Mean ZPA (g)	COV of ZPA
No Scaling	1	.0337	7044.	.4685	.2570	.3133
	2	.0278	6141.	.4630	.3567	.3874
	3	.0163	4638.	.4516	.4031	.4484
	4	.0160	4063.	.4419	.4718	.4488
	5	.0092	1805.	.4148	.5346	.4091
ScPGA	1	.0402	8415.	.2316	.3222	.1068
	2	.0333	7345.	.2209	.4364	.1523
	3	.0196	5551.	.2023	.4848	.2093
	4	.0192	4873.	.1897	.5653	.1996
	5	.0112	2184.	.1549	.6479	.1479
ScSa7	1	.0499	10444.	.0583	.4143	.1871
	2	.0414	9138.	.0669	.5501	.0729
	3	.0244	6927.	.0613	.6045	.0602
	4	.0240	6094.	.0575	.7057	.0578
	5	.0141	2751.	.0748	.8172	.0775
ScASA	1	.0604	12647.	.0902	.5108	.2673
	2	.0502	11082.	.1093	.6713	.1562
	3	.0296	8417.	.1205	.7339	.1149
	4	.0292	7413.	.1260	.8577	.1209
	5	.0172	3357.	.1538	.9978	.1580

Table 5-9

Motion-to-Motion Means and Coefficients of Variation of Structural Inter-story Maximum Forces and Displacements, and of Floor Zero-Period Accelerations, for the 10-Hz Structure Subjected to Artificial Motion Inputs MArS1 Scaled to Four Different Anchor Bases

Scaling Basis	Floor No.	Mean Displ. (in)	Mean Force (kips)	COV of Displ. or Force	Mean ZPA (g)	COV of ZPA
No Scaling	1	.0288	2981.	.3363	.3345	.3386
	2	.0173	1792.	.3283	.4656	.3308
ScPGA	1	.0357	3686.	.0636	.4135	.0664
	2	.0215	2223.	.0600	.5772	.0640
ScSa10	1	.0423	4374.	.0283	.4911	.0555
	2	.0255	2639.	.0441	.6852	.0455
ScASA	1	.0561	5801.	.2147	.6533	.2268
	2	.0339	3507.	.2240	.9102	.2228

Figure 5-1. In-structure response spectra for the 3-Hz structure subjected to artificial input motions MArS1 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArS1(TEr) and (b) MArS1(TEs).

Figure 5-2. In-structure response spectra for the 3-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (c) MArS1(TLr) and (d) MArS1(TLs).

Frequency (Hz)

Frequency (Hz)

Figure 5-3. In-structure response spectra for the 3-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (e) MArS1(TL2r) and (f) MArS1(TL2s).

Figure 5-4. In-structure response spectra for the 3-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (g) MArS1(TWr) and (h) MArS1(TWs).

Figure 5-5. In-structure response spectra for the 7-Hz structure subjected to artificial input motions MArS1 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArS1(TEr) and (b) MArS1(TEs).

ISS4(St7); Motion: MARSI(TLr)
(Floor 4, 7-Hz 4-Story Structure)

ISS4(St7); Motion: MARSI(TLs)
(Floor 4, 7-Hz 4-Story Structure)

ISS3(St7); Motion: MARSI(TLr)
(Floor 3, 7-Hz 4-Story Structure)

ISS3(St7); Motion: MARSI(TLs)
(Floor 3, 7-Hz 4-Story Structure)

ISS1(St7); Motion: MARSI(TLr)
(Floor 1, 7-Hz 4-Story Structure)

ISS1(St7); Motion: MARSI(TLs)
(Floor 1, 7-Hz 4-Story Structure)

Figure 5-6. In-structure response spectra for the 7-Hz structure subjected to artificial input motions MARSI with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (c) MARSI(TLr) and (d) MARSI(TLs).

Figure 5-7. In-structure response spectra for the 7-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (e) MArS1(TL2r) and (f) MArS1(TL2s).

Figure 5-8. In-structure response spectra for the 7-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (g) MArS1(TWr) and (h) MArS1(TWs).

Figure 5-9. In-structure response spectra for the 10-Hz structure subjected to artificial input motions MArS1 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArS1(TEr) and (b) MArS1(TEs).

Figure 5-10. In-structure response spectra for the 10-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (c) MArS1(TLr) and (d) MArS1(TLs).

Figure 5-11. In-structure response spectra for the 10-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (e) MArS1(TL2r) and (f) MArS1(TL2s).

Figure 5-12. In-structure response spectra for the 10-Hz structure subjected to artificial input motions MArS1 with ScASA scaling (continued). Responses at the first, third, and fifth floors for motions: (g) MArS1(TWr) and (h) MArS1(TWs).

Section 6

RESPONSE RESULTS: ARTIFICIAL MOTIONS WITH JAGGED SPECTRA

This chapter presents results of evaluation-demand calculations performed using, as inputs, the 40 artificial motions having jagged response spectra. As described in Chapter 3, these 40 motions are comprised of eight sets of five motions (MARJ1-5); the average spectral shape for any given motion set closely matches a specified target response spectrum, whereas the spectral shapes of individual motions model motion-to-motion variability. Results obtained for all 40 motions include maximum structural inter-story forces, floor ZPAs, and ISS results; average results (from the five motions in any given set) are also presented for all eight target spectra.

Results are presented among the five motions for each of the eight cases to demonstrate the variations in response modeled by the simulated motions. Average response results are also compared among the eight cases of target spectra. Results are compared among these eight sets to identify the target spectra which are most appropriate to consider separately in subsequent evaluation-demand comparisons.

The results of response calculations presented here are used in Chapter 7 to compare with evaluation demands obtained, for corresponding cases, from analyses using empirical motions as input.

6.1 STRUCTURAL FORCES AND DISPLACEMENTS

Results for maximum structural forces are presented in Tables 6-1 to 6-8 for the 3-Hz structure, Tables 6-17 to 6-24 for the 7-Hz structure, and Tables 6-33 to 6-40 for the 10-Hz structure. (Maximum structural displacements can be derived simply by dividing these maximum inter-story forces by appropriate element stiffnesses). Each table among these three sets of tables presents results for five artificial ground motions MARJn matching a given target spectrum among the set of eight targets. Results are presented for all applicable motion scaling approaches.

The reader is encouraged to examine these tables to become familiar with the magnitude of variabilities in structural responses resulting from the multiple artificial input motions.

Variabilities in the shape and amplitude of the response spectra for the artificial motions are similar to variabilities exhibited by real earthquake motions. Hence, seismic evaluation employing the multiple artificial motions will better represent expected variations in response demands.

It is important to keep in mind that the variability observed in these tables of structural forces is due to variabilities both in shape and amplitude of the input motion spectra. Individual motions within a given set have not been (independently) scaled to a common anchor basis; the motions are uniformly scaled by the same amount such that their average response spectrum matches their associated target spectrum. Thus, response variabilities observed in this chapter, among artificial motions for a given target spectrum, are not just due to variations in spectral shape, but also due to randomness in motion amplitudes. The COVs for structural forces noted in the tables are, therefore, dominated by these random variabilities, and do not serve to demonstrate consistency in different motion-scaling approaches.

Results for floor ZPAs are presented in Tables 6-9 to 6-16 for the 3-Hz structure, Tables 6-25 to 6-32 for the 7-Hz structure, and Tables 6-41 to 6-48 for the 10-Hz structure. Again, observation of these tables indicates the variations in ZPAs for different motion simulations, as well as the mean and COV of ZPAs for the simulations.

In examining the results in Tables 6-1 to 6-48, it is useful to make comparisons relative to various target spectra. As has been discussed in Chapters 4 and 5, for instance, the nature of structural response (e.g., distribution of forces with height, relative ratios of floor ZPAs to base shear, etc.) is fundamentally different for Eastern U.S. type motions versus Western U.S. type motions. Such difference can be seen by comparing, for a given structure, the results for an Eastern U.S. target spectrum (e.g., Tables 6-2 and 6-10 for target TEs) with corresponding results for a Western U.S. target spectrum (e.g., Tables 6-8 and 6-16 for target TWs).

6.2 IN-STRUCTURE RESPONSE SPECTRA

6.2.1 Motion-Specific Results for Given Target Spectrum

ISS results for artificial motions MArJn are presented in Figures 6-1 to 6-12. Results are shown for ScASA scaling. (Results for other scaling bases can be obtained by appropriately applying the scale factors in Table 2-6 to these ISS demands). Figures 6-1 to 6-4 show ISS results for the 3-Hz structure, Figures 6-5 to 6-8 show ISS results for the 7-Hz structure, and Figures 6-9 to 6-12 show ISS results for the 10-Hz structure. Each graph of ISS results, for any given case, shows responses for all five motion simulations on a single plot.

In examining these plots, the reader can clearly see the impact of the multiple input simulations on variations in ISS response demands for any given case. There is large variability with respect to amplitude, which is a direct consequence of the variability in amplitudes of the input response spectra. There is also notable variability in ISS shapes among the five simulations. In many instances, second-mode bumps in ISS are observed for some motions, but not others (which is due to the variability in response spectral shapes among the simulated motions). Still, however, the degree of variability in ISS shapes is not too great because of the dynamic response characteristics of the building. (Clearly, the variabilities in ISS shapes are not as great as variabilities observed in shapes of the associated input response spectra). In other words, the ability of the structure to filter input motion in a characteristic way, results in increased consistency in the shape of the output spectrum, as expected from random vibration theory.

6.2.2 Response Statistics for Given Target Spectra

Figure 6-13 to 6-24 present plots, corresponding to Figures 6-1 to 6-12, but now showing statistics of ISS demands resulting from the five input motion simulations. The mean ISS curve and corresponding mean plus one-sigma and mean minus one-sigma curves are presented for each response case. These plots facilitate observation of (a) the variability in ISS demands resulting from multiple input simulations, and (b) the similarities and differences in ISS results among the various cases of target response spectra.

6.3 SELECTION OF CASES FOR SUBSEQUENT COMPARISONS

As was done in Section 5.3, we again look for consistency in ISS demands for various target spectra, to meaningfully narrow the scope of subsequent response comparisons when assessing motion impacts in the following chapter. The most effective way of doing this is by comparing mean ISS curves for different target spectra, and for the same structure and floor location.

Examination of the results in Figures 6-13 to 6-24 leads us to a similar assessment, as to the comparative closeness of ISS results, to that drawn in Section 5.3. Consequently, we have selected the following three representative sets of motions for use in subsequent comparisons: (1) MArJ1-5(TL2r), (2) MArJ1-5(TLr), and (3) MArJ1-5(TWs).

Table 6-1

Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TEr):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	2930.	2083.	5960.	1039.	4523.	3307.	.5290
	2	2829.	1600.	5633.	884.	4455.	3080.	.5713
	3	2497.	1129.	4650.	733.	3996.	2601.	.5909
	4	2103.	1308.	3232.	602.	3037.	2056.	.4873
	5	1183.	916.	1756.	452.	1672.	1196.	.4050
ScPGA	1	5782.	4110.	11763.	2051.	8928.	6527.	.5290
	2	5583.	3158.	11118.	1746.	8792.	6079.	.5713
	3	4927.	2228.	9177.	1447.	7887.	5133.	.5909
	4	4150.	2582.	6378.	1187.	5994.	4058.	.4873
	5	2335.	1808.	3465.	891.	3301.	2360.	.4050
ScSa3	1	18707.	13297.	38055.	6636.	28883.	21116.	.5290
	2	18062.	10218.	35969.	5647.	28444.	19668.	.5713
	3	15941.	7207.	29689.	4683.	25517.	16607.	.5909
	4	13427.	8353.	20635.	3842.	19393.	13130.	.4873
	5	7554.	5849.	11211.	2884.	10679.	7635.	.4050
ScASA	1	12890.	9162.	26222.	4573.	19902.	14550.	.5290
	2	12445.	7041.	24784.	3891.	19599.	13552.	.5713
	3	10984.	4966.	20457.	3227.	17582.	11443.	.5909
	4	9251.	5756.	14218.	2647.	13363.	9047.	.4873
	5	5205.	4030.	7725.	1987.	7358.	5261.	.4050

Table 6-2

Maximum Inter-story Structural Forces for the 3-Hz Structure Sub-
jected to Artificial Motion Inputs MArJn(TEs) Scaled to Four Differ-
ent Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TEs):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	9817.	7713.	3616.	7425.	10326.	7779.	.3047
	2	9157.	7414.	2994.	6782.	9578.	7185.	.3258
	3	7656.	6890.	2872.	5916.	8231.	6313.	.2990
	4	5606.	5742.	2647.	4303.	6688.	4997.	.2800
	5	3068.	3280.	1627.	2288.	3866.	2826.	.2774
ScPGA	1	10632.	8353.	3916.	8042.	11183.	8425.	.3047
	2	9917.	8029.	3243.	7345.	10373.	7781.	.3258
	3	8291.	7461.	3110.	6407.	8914.	6837.	.2990
	4	6072.	6219.	2867.	4660.	7243.	5412.	.2800
	5	3322.	3552.	1762.	2477.	4187.	3060.	.2774
ScSa3	1	25958.	20395.	9562.	19635.	27304.	20571.	.3047
	2	24215.	19604.	7918.	17933.	25327.	18999.	.3258
	3	20244.	18218.	7595.	15643.	21765.	16693.	.2990
	4	14825.	15184.	7000.	11378.	17686.	13215.	.2800
	5	8112.	8672.	4303.	6049.	10222.	7472.	.2774
ScASA	1	18165.	14272.	6691.	13740.	19106.	14395.	.3047
	2	16945.	13718.	5540.	12549.	17723.	13295.	.3258
	3	14166.	12749.	5315.	10947.	15230.	11681.	.2990
	4	10374.	10626.	4898.	7962.	12376.	9247.	.2800
	5	5676.	6069.	3011.	4233.	7153.	5228.	.2774

Table 6-3

Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TLr):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	4491.	6503.	5727.	3410.	10368.	6100.	.3903
	2	4182.	5703.	5604.	2774.	9425.	5538.	.4007
	3	3582.	4530.	5736.	2346.	9276.	5094.	.4650
	4	2705.	3176.	4793.	1932.	7589.	4039.	.4968
	5	1462.	1646.	2860.	1217.	4269.	2291.	.4974
ScPGA	1	6721.	9730.	8569.	5103.	15513.	9127.	.3903
	2	6258.	8533.	8385.	4151.	14103.	8286.	.4007
	3	5360.	6779.	8583.	3511.	13880.	7622.	.4650
	4	4048.	4753.	7171.	2891.	11356.	6044.	.4968
	5	2188.	2463.	4279.	1821.	6388.	3428.	.4974
ScSa3	1	15237.	22061.	19427.	11569.	35171.	20693.	.3903
	2	14188.	19345.	19011.	9412.	31974.	18786.	.4007
	3	12151.	15369.	19460.	7959.	31468.	17281.	.4650
	4	9178.	10775.	16259.	6553.	25745.	13702.	.4968
	5	4961.	5584.	9701.	4128.	14483.	7772.	.4974
ScASA	1	11642.	16856.	14844.	8839.	26873.	15811.	.3903
	2	10840.	14781.	14526.	7191.	24430.	14354.	.4007
	3	9284.	11743.	14868.	6081.	24043.	13204.	.4650
	4	7012.	8233.	12423.	5007.	19671.	10469.	.4968
	5	3791.	4267.	7412.	3154.	11066.	5938.	.4974

Table 6-4

Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLs) Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TLs):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	5489.	8101.	29200.	11798.	7803.	12478.	.6894
	2	4173.	7495.	26730.	11275.	6796.	11294.	.7124
	3	3901.	6468.	22051.	10153.	5152.	9545.	.6908
	4	4007.	4665.	15606.	7721.	3942.	7188.	.6164
	5	2768.	2593.	8369.	4568.	2398.	4139.	.5443
ScPGA	1	4970.	7334.	26438.	10682.	7065.	11298.	.6894
	2	3778.	6786.	24201.	10209.	6153.	10225.	.7124
	3	3532.	5856.	19965.	9193.	4664.	8642.	.6908
	4	3628.	4224.	14130.	6991.	3569.	6508.	.6164
	5	2506.	2348.	7578.	4136.	2171.	3748.	.5443
ScSa3	1	9382.	13847.	49912.	20167.	13337.	21329.	.6894
	2	7132.	12811.	45689.	19273.	11617.	19304.	.7124
	3	6668.	11056.	37691.	17355.	8806.	16315.	.6908
	4	6849.	7974.	26676.	13198.	6737.	12287.	.6164
	5	4731.	4433.	14306.	7808.	4098.	7075.	.5443
ScASA	1	7521.	11100.	40010.	16166.	10691.	17098.	.6894
	2	5717.	10270.	36625.	15449.	9312.	15475.	.7124
	3	5345.	8862.	30214.	13912.	7059.	13078.	.6908
	4	5490.	6392.	21384.	10580.	5401.	9849.	.6164
	5	3793.	3553.	11468.	6259.	3285.	5672.	.5443

Table 6-5

Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TL2r):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	5807.	1342.	1824.	4322.	4453.	3550.	.4774
	2	5503.	1243.	1631.	3847.	3879.	3221.	.4905
	3	4719.	1119.	1380.	3474.	3138.	2766.	.4873
	4	3824.	931.	1146.	3233.	2264.	2279.	.4963
	5	2245.	533.	703.	2048.	1203.	1346.	.5140
ScPGA	1	13323.	3080.	4184.	9915.	10216.	8144.	.4774
	2	12627.	2852.	3742.	8826.	8899.	7389.	.4905
	3	10826.	2567.	3167.	7970.	7200.	6346.	.4873
	4	8773.	2135.	2628.	7417.	5195.	5230.	.4963
	5	5150.	1224.	1614.	4699.	2759.	3089.	.5140
ScSa3	1	35059.	8104.	11009.	26092.	26883.	21429.	.4774
	2	33226.	7504.	9846.	23225.	23418.	19444.	.4905
	3	28488.	6755.	8333.	20972.	18947.	16699.	.4873
	4	23086.	5618.	6916.	19516.	13669.	13761.	.4963
	5	13553.	3221.	4246.	12366.	7260.	8129.	.5140
ScASA	1	25325.	5854.	7952.	18847.	19419.	15479.	.4774
	2	24001.	5421.	7112.	16777.	16916.	14045.	.4905
	3	20578.	4880.	6019.	15149.	13686.	12062.	.4873
	4	16676.	4058.	4996.	14097.	9874.	9940.	.4963
	5	9790.	2327.	3067.	8932.	5245.	5872.	.5140

Table 6-6

Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TL2s):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	5816.	3886.	11758.	2039.	9338.	6567.	.5400
	2	5559.	3054.	11054.	1749.	9085.	6100.	.5770
	3	4903.	2160.	9143.	1419.	8029.	5131.	.5985
	4	4015.	2334.	6352.	1105.	6035.	3968.	.5143
	5	2237.	1588.	3331.	723.	3284.	2232.	.4483
ScPGA	1	7857.	5250.	15884.	2754.	12615.	8872.	.5400
	2	7509.	4125.	14932.	2363.	12273.	8241.	.5770
	3	6623.	2918.	12351.	1917.	10846.	6931.	.5985
	4	5424.	3152.	8581.	1493.	8153.	5361.	.5143
	5	3021.	2145.	4500.	976.	4436.	3016.	.4483
ScSa3	1	18580.	12415.	37560.	6512.	29830.	20980.	.5400
	2	17757.	9755.	35311.	5588.	29021.	19487.	.5770
	3	15662.	6899.	29207.	4533.	25648.	16390.	.5985
	4	12827.	7454.	20292.	3530.	19279.	12676.	.5143
	5	7145.	5072.	10642.	2309.	10491.	7132.	.4483
ScASA	1	14122.	9436.	28548.	4950.	22673.	15946.	.5400
	2	13497.	7415.	26838.	4247.	22058.	14811.	.5770
	3	11904.	5244.	22199.	3446.	19494.	12457.	.5985
	4	9749.	5666.	15423.	2683.	14653.	9635.	.5143
	5	5430.	3855.	8088.	1755.	7974.	5420.	.4483

Table 6-7

Maximum Inter-story Structural Forces for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWr) Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TWr):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	9036.	60272.	14922.	9846.	19353.	22686.	.8445
	2	7516.	54974.	13854.	7953.	17392.	20338.	.8708
	3	6429.	45641.	11742.	7330.	14417.	17112.	.8508
	4	4945.	32705.	9199.	6473.	10280.	12720.	.7996
	5	2723.	17039.	5162.	3801.	5327.	6810.	.7639
ScPGA	1	9036.	60272.	14922.	9846.	19353.	22686.	.8445
	2	7516.	54974.	13854.	7953.	17392.	20338.	.8708
	3	6429.	45641.	11742.	7330.	14417.	17112.	.8508
	4	4945.	32705.	9199.	6473.	10280.	12720.	.7996
	5	2723.	17039.	5162.	3801.	5327.	6810.	.7639
ScSa3	1	8525.	56860.	14078.	9289.	18257.	21402.	.8445
	2	7090.	51863.	13070.	7503.	16407.	19187.	.8708
	3	6065.	43058.	11077.	6915.	13601.	16143.	.8508
	4	4665.	30854.	8678.	6106.	9698.	12000.	.7996
	5	2569.	16075.	4870.	3586.	5025.	6425.	.7639
ScASA	1	8597.	57342.	14197.	9367.	18412.	21583.	.8445
	2	7150.	52303.	13181.	7566.	16546.	19349.	.8708
	3	6117.	43423.	11171.	6973.	13716.	16280.	.8508
	4	4705.	31115.	8752.	6158.	9780.	12102.	.7996
	5	2590.	16211.	4911.	3616.	5068.	6479.	.7639

Table 6-8

Maximum Inter-story Structural Forces for the 3-Hz Structure Sub-
jected to Artificial Motion Inputs MArJn(TWs) Scaled to Four Dif-
ferent Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TWs):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	26169.	7676.	32497.	29803.	15078.	22244.	.4223
	2	23851.	6879.	27840.	26715.	12846.	19626.	.4226
	3	19785.	5661.	22806.	22183.	10567.	16200.	.4233
	4	14325.	4022.	17157.	15938.	7783.	11845.	.4285
	5	7601.	2070.	9463.	8340.	4178.	6330.	.4369
ScPGA	1	26169.	7676.	32497.	29803.	15078.	22244.	.4223
	2	23851.	6879.	27840.	26715.	12846.	19626.	.4226
	3	19785.	5661.	22806.	22183.	10567.	16200.	.4233
	4	14325.	4022.	17157.	15938.	7783.	11845.	.4285
	5	7601.	2070.	9463.	8340.	4178.	6330.	.4369
ScSa3	1	24688.	7242.	30657.	28116.	14224.	20985.	.4223
	2	22501.	6490.	26265.	25203.	12118.	18515.	.4226
	3	18665.	5341.	21515.	20927.	9969.	15283.	.4233
	4	13514.	3794.	16186.	15036.	7342.	11174.	.4285
	5	7171.	1953.	8928.	7868.	3941.	5972.	.4369
ScASA	1	24839.	7286.	30846.	28289.	14312.	21114.	.4223
	2	22639.	6530.	26426.	25358.	12193.	18629.	.4226
	3	18780.	5374.	21648.	21056.	10030.	15377.	.4233
	4	13597.	3817.	16286.	15128.	7388.	11243.	.4285
	5	7215.	1965.	8983.	7916.	3966.	6009.	.4369

Table 6-9

Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TEr):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.0961	.0988	.1698	.0581	.0852	.1016	.3640
	2	.1116	.1153	.1678	.0561	.1105	.1123	.3148
	3	.1027	.0929	.2057	.0451	.1337	.1160	.4577
	4	.1305	.0577	.2053	.0386	.1797	.1224	.5348
	5	.1529	.1204	.2300	.0590	.2156	.1556	.4035
ScPGA	1	.1898	.1951	.3351	.1148	.1682	.2006	.3640
	2	.2203	.2276	.3311	.1108	.2181	.2216	.3148
	3	.2027	.1834	.4060	.0890	.2639	.2290	.4577
	4	.2576	.1140	.4052	.0763	.3547	.2416	.5348
	5	.3019	.2377	.4540	.1165	.4256	.3071	.4035
ScSa3	1	.6139	.6310	1.0840	.3713	.5442	.6489	.3640
	2	.7127	.7362	1.0712	.3584	.7055	.7168	.3148
	3	.6557	.5933	1.3136	.2880	.8539	.7409	.4577
	4	.8333	.3687	1.3111	.2468	1.1476	.7815	.5348
	5	.9765	.7691	1.4688	.3769	1.3768	.9936	.4035
ScASA	1	.4230	.4348	.7469	.2558	.3749	.4471	.3640
	2	.4911	.5073	.7381	.2469	.4861	.4939	.3148
	3	.4518	.4088	.9051	.1985	.5883	.5105	.4577
	4	.5742	.2540	.9034	.1700	.7907	.5385	.5348
	5	.6729	.5299	1.0120	.2597	.9487	.6846	.4035

Table 6-10

Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEs) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TEs):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.2280	.2436	.2312	.1296	.2950	.2255	.2380
	2	.3424	.2833	.2027	.1676	.3551	.2702	.2753
	3	.3247	.2754	.1527	.2303	.3882	.2743	.2928
	4	.3384	.3307	.1416	.2774	.3747	.2925	.2790
	5	.4064	.4280	.2069	.2934	.4922	.3654	.2790
ScPGA	1	.2470	.2638	.2504	.1404	.3195	.2442	.2380
	2	.3708	.3068	.2195	.1815	.3845	.2926	.2753
	3	.3517	.2983	.1654	.2494	.4205	.2970	.2928
	4	.3664	.3582	.1534	.3004	.4058	.3168	.2790
	5	.4401	.4635	.2241	.3178	.5330	.3957	.2790
ScSa3	1	.6030	.6441	.6113	.3427	.7800	.5962	.2380
	2	.9054	.7490	.5360	.4431	.9389	.7145	.2753
	3	.8587	.7283	.4038	.6089	1.0266	.7252	.2928
	4	.8947	.8745	.3745	.7335	.9907	.7736	.2790
	5	1.0745	1.1317	.5471	.7759	1.3014	.9661	.2790
ScASA	1	.4220	.4507	.4278	.2398	.5459	.4172	.2380
	2	.6336	.5241	.3751	.3101	.6570	.5000	.2753
	3	.6009	.5096	.2826	.4261	.7184	.5075	.2928
	4	.6261	.6120	.2620	.5133	.6933	.5413	.2790
	5	.7519	.7919	.3829	.5429	.9107	.6761	.2790

Table 6-11

Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TLr):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.0773	.1163	.2323	.1893	.2964	.1823	.4315
	2	.1044	.1711	.2517	.1573	.3519	.2073	.4166
	3	.1232	.1882	.2380	.1230	.3627	.2070	.4301
	4	.1634	.1997	.2569	.1071	.4413	.2337	.4907
	5	.1896	.2138	.3724	.1546	.5507	.2962	.4979
ScPGA	1	.1157	.1740	.3475	.2832	.4435	.2728	.4315
	2	.1563	.2560	.3766	.2353	.5266	.3102	.4166
	3	.1844	.2815	.3561	.1841	.5427	.3098	.4301
	4	.2445	.2989	.3844	.1603	.6603	.3497	.4907
	5	.2838	.3198	.5572	.2313	.8240	.4432	.4980
ScSa3	1	.2624	.3945	.7879	.6421	1.0056	.6185	.4315
	2	.3543	.5805	.8538	.5335	1.1939	.7032	.4166
	3	.4180	.6383	.8074	.4173	1.2304	.7023	.4301
	4	.5544	.6776	.8716	.3634	1.4969	.7928	.4907
	5	.6434	.7251	1.2633	.5245	1.8683	1.0049	.4979
ScASA	1	.2005	.3014	.6020	.4906	.7683	.4726	.4315
	2	.2707	.4435	.6523	.4076	.9122	.5373	.4166
	3	.3194	.4877	.6169	.3188	.9401	.5366	.4301
	4	.4236	.5177	.6659	.2776	1.1437	.6057	.4907
	5	.4916	.5541	.9652	.4007	1.4275	.7678	.4979

Table 6-12

Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLs) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TLs):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.2757	.2145	.5003	.3545	.2013	.3093	.3552
	2	.3368	.2491	.7317	.3912	.2407	.3899	.4613
	3	.2315	.2619	.8963	.4144	.2707	.4149	.5996
	4	.2040	.3129	.9966	.4745	.2377	.4452	.6539
	5	.3529	.3354	1.0802	.5914	.3196	.5359	.5407
ScPGA	1	.2497	.1942	.4530	.3210	.1822	.2800	.3552
	2	.3050	.2255	.6625	.3542	.2179	.3530	.4613
	3	.2096	.2371	.8115	.3752	.2451	.3757	.5996
	4	.1847	.2833	.9023	.4297	.2152	.4030	.6539
	5	.3195	.3037	.9780	.5354	.2893	.4852	.5407
ScSa3	1	.4713	.3666	.8552	.6060	.3440	.5286	.3552
	2	.5757	.4258	1.2508	.6686	.4114	.6665	.4613
	3	.3957	.4476	1.5320	.7084	.4627	.7093	.5996
	4	.3487	.5348	1.7035	.8111	.4063	.7609	.6539
	5	.6032	.5733	1.8463	1.0108	.5462	.9160	.5407
ScASA	1	.3778	.2938	.6855	.4858	.2758	.4237	.3552
	2	.4615	.3413	1.0026	.5360	.3298	.5342	.4613
	3	.3172	.3588	1.2281	.5678	.3709	.5686	.5996
	4	.2796	.4287	1.3655	.6502	.3257	.6100	.6539
	5	.4836	.4595	1.4800	.8103	.4379	.7343	.5407

Table 6-13

Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TL2r):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.1168	.0560	.0570	.1973	.0778	.1010	.5245
	2	.1821	.0495	.0789	.2133	.1088	.1265	.4889
	3	.1949	.0515	.0684	.2009	.1282	.1288	.4812
	4	.2121	.0514	.0680	.1589	.1411	.1263	.4704
	5	.2893	.0688	.0924	.2619	.1532	.1731	.5112
ScPGA	1	.2681	.1284	.1307	.4527	.1786	.2317	.5245
	2	.4179	.1136	.1810	.4893	.2496	.2903	.4889
	3	.4473	.1181	.1570	.4608	.2940	.2954	.4812
	4	.4865	.1178	.1560	.3645	.3238	.2897	.4704
	5	.6637	.1578	.2121	.6008	.3514	.3972	.5112
ScSa3	1	.7054	.3379	.3441	1.1913	.4700	.6097	.5245
	2	1.0997	.2989	.4763	1.2876	.6567	.7638	.4889
	3	1.1769	.3107	.4131	1.2127	.7737	.7774	.4812
	4	1.2802	.3101	.4106	.9590	.8522	.7624	.4704
	5	1.7465	.4154	.5581	1.5809	.9248	1.0451	.5112
ScASA	1	.5096	.2441	.2485	.8605	.3395	.4404	.5245
	2	.7943	.2159	.3441	.9301	.4743	.5517	.4889
	3	.8501	.2244	.2984	.8760	.5589	.5616	.4812
	4	.9248	.2240	.2966	.6928	.6155	.5507	.4704
	5	1.2616	.3000	.4031	1.1420	.6680	.7550	.5112

Table 6-14

Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TL2s):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.1603	.1590	.2782	.0904	.1527	.1681	.3622
	2	.1954	.1949	.2821	.0897	.1986	.1921	.3178
	3	.1928	.1622	.3854	.0796	.2711	.2182	.4751
	4	.2478	.1071	.4048	.0702	.3608	.2381	.5580
	5	.2891	.2090	.4420	.0944	.4239	.2917	.4493
ScPGA	1	.2165	.2148	.3759	.1222	.2062	.2271	.3622
	2	.2640	.2632	.3811	.1212	.2683	.2596	.3178
	3	.2605	.2192	.5206	.1075	.3663	.2948	.4751
	4	.3348	.1447	.5468	.0948	.4874	.3217	.5580
	5	.3906	.2823	.5972	.1275	.5726	.3940	.4493
ScSa3	1	.5121	.5080	.8888	.2889	.4876	.5371	.3622
	2	.6242	.6225	.9012	.2866	.6344	.6138	.3178
	3	.6160	.5183	1.2311	.2542	.8662	.6971	.4751
	4	.7917	.3422	1.2930	.2241	1.1525	.7607	.5580
	5	.9236	.6676	1.4121	.3014	1.3540	.9318	.4493
ScASA	1	.3892	.3861	.6756	.2196	.3706	.4082	.3622
	2	.4745	.4731	.6850	.2178	.4822	.4665	.3178
	3	.4682	.3939	.9357	.1932	.6583	.5299	.4751
	4	.6017	.2601	.9828	.1703	.8760	.5782	.5580
	5	.7020	.5074	1.0733	.2291	1.0291	.7082	.4493

Table 6-15

Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWr) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TWr):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.2486	.7568	.3580	.3261	.4032	.4186	.4217
	2	.2635	1.2811	.4442	.3379	.4982	.5650	.6500
	3	.2576	1.7223	.4769	.2928	.5730	.6645	.8149
	4	.2895	2.0327	.5259	.3544	.6542	.7713	.8344
	5	.3539	2.2163	.6636	.4929	.6790	.8811	.7697
ScPGA	1	.2486	.7568	.3580	.3261	.4032	.4186	.4217
	2	.2635	1.2811	.4442	.3379	.4982	.5650	.6500
	3	.2576	1.7223	.4769	.2928	.5730	.6645	.8149
	4	.2895	2.0327	.5259	.3544	.6542	.7713	.8344
	5	.3539	2.2163	.6636	.4929	.6790	.8811	.7697
ScSa3	1	.2345	.7140	.3378	.3076	.3804	.3949	.4217
	2	.2486	1.2085	.4190	.3188	.4700	.5330	.6500
	3	.2430	1.6248	.4499	.2762	.5405	.6269	.8149
	4	.2731	1.9177	.4961	.3343	.6172	.7277	.8344
	5	.3338	2.0909	.6261	.4650	.6406	.8313	.7697
ScASA	1	.2365	.7200	.3406	.3103	.3836	.3982	.4217
	2	.2507	1.2188	.4226	.3215	.4740	.5375	.6500
	3	.2450	1.6386	.4537	.2786	.5451	.6322	.8149
	4	.2754	1.9339	.5003	.3371	.6224	.7339	.8344
	5	.3367	2.1086	.6314	.4689	.6460	.8383	.7697

Table 6-16

Zero-Period Accelerations of Structural Floor Responses for the 3-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWs) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TWs):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.4630	.1869	.7217	.4778	.3642	.4427	.3926
	2	.6618	.2002	.9475	.6336	.4335	.5753	.4330
	3	.7580	.2172	.9819	.8144	.4317	.6406	.4322
	4	.8826	.2522	1.0371	.9867	.4664	.7250	.4279
	5	.9993	.2671	1.2215	1.0819	.5364	.8212	.4384
ScPGA	1	.4630	.1869	.7217	.4778	.3642	.4427	.3926
	2	.6618	.2002	.9475	.6336	.4335	.5753	.4330
	3	.7580	.2172	.9819	.8144	.4317	.6406	.4322
	4	.8826	.2522	1.0371	.9867	.4664	.7250	.4279
	5	.9993	.2671	1.2215	1.0819	.5364	.8212	.4384
ScSa3	1	.4368	.1764	.6809	.4507	.3436	.4177	.3926
	2	.6244	.1889	.8939	.5977	.4089	.5428	.4330
	3	.7151	.2049	.9263	.7683	.4072	.6044	.4322
	4	.8326	.2379	.9784	.9308	.4400	.6840	.4279
	5	.9427	.2520	1.1524	1.0207	.5060	.7748	.4384
ScASA	1	.4395	.1774	.6850	.4535	.3457	.4202	.3926
	2	.6282	.1901	.8994	.6014	.4114	.5461	.4330
	3	.7195	.2062	.9320	.7730	.4097	.6081	.4322
	4	.8377	.2394	.9844	.9365	.4427	.6882	.4279
	5	.9485	.2535	1.1594	1.0269	.5091	.7795	.4384

Table 6-17

Maximum Inter-story Structural Forces for the 7-Hz Structure Sub-
jected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Dif-
ferent Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TEr):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	1745.	2893.	6359.	1678.	3582.	3251.	.5263
	2	1389.	2500.	5406.	1440.	3243.	2796.	.5285
	3	1337.	1833.	4235.	1178.	2681.	2253.	.4975
	4	1270.	1656.	3743.	1049.	2391.	2022.	.4818
	5	670.	775.	1732.	481.	1107.	953.	.4608
ScPGA	1	3444.	5709.	12551.	3312.	7069.	6417.	.5263
	2	2742.	4935.	10670.	2842.	6402.	5518.	.5285
	3	2639.	3618.	8358.	2325.	5291.	4446.	.4975
	4	2506.	3268.	7387.	2070.	4720.	3990.	.4818
	5	1322.	1530.	3418.	950.	2185.	1881.	.4608
ScSa7	1	5769.	9564.	21025.	5548.	11842.	10750.	.5263
	2	4593.	8267.	17875.	4761.	10724.	9244.	.5285
	3	4420.	6062.	14002.	3896.	8863.	7448.	.4975
	4	4199.	5475.	12374.	3467.	7907.	6684.	.4818
	5	2215.	2563.	5727.	1592.	3660.	3151.	.4608
ScASA	1	7677.	12727.	27978.	7382.	15758.	14304.	.5263
	2	6112.	11000.	23785.	6336.	14270.	12301.	.5285
	3	5882.	8066.	18632.	5184.	11793.	9911.	.4975
	4	5587.	7285.	16466.	4614.	10522.	8895.	.4818
	5	2947.	3411.	7620.	2118.	4870.	4193.	.4608

Table 6-18

Maximum Inter-story Structural Forces for the 7-Hz Structure Sub-
jected to Artificial Motion Inputs MArJn(TEs) Scaled to Four Differ-
ent Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TEs):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	8854.	10509.	7635.	3982.	10472.	8290.	.2904
	2	7751.	9068.	6898.	3281.	9111.	7222.	.2963
	3	5860.	6743.	5306.	2347.	6635.	5378.	.2983
	4	5103.	5836.	4652.	2017.	5715.	4665.	.2982
	5	2305.	2556.	2186.	894.	2509.	2090.	.2933
ScPGA	1	9589.	11381.	8268.	4313.	11341.	8978.	.2904
	2	8395.	9821.	7470.	3554.	9867.	7821.	.2963
	3	6347.	7303.	5747.	2542.	7186.	5825.	.2983
	4	5527.	6320.	5038.	2185.	6189.	5052.	.2982
	5	2496.	2768.	2367.	968.	2718.	2263.	.2933
ScSa7	1	12406.	14725.	10697.	5580.	14673.	11616.	.2904
	2	10861.	12707.	9665.	4598.	12766.	10119.	.2963
	3	8211.	9449.	7435.	3288.	9297.	7536.	.2983
	4	7150.	8178.	6519.	2827.	8008.	6536.	.2982
	5	3230.	3581.	3063.	1253.	3516.	2928.	.2933
ScASA	1	16384.	19445.	14127.	7369.	19377.	15340.	.2904
	2	14343.	16780.	12764.	6072.	16859.	13364.	.2963
	3	10844.	12478.	9819.	4342.	12277.	9952.	.2983
	4	9443.	10799.	8609.	3733.	10575.	8632.	.2982
	5	4265.	4729.	4045.	1654.	4643.	3867.	.2933

Table 6-19

Maximum Inter-story Structural Forces for the 7-Hz Structure Sub-
jected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Dif-
ferent Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TLr):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	1253.	2735.	5244.	3767.	13527.	5305.	.8129
	2	1052.	2246.	4346.	3328.	11358.	4466.	.8098
	3	827.	1626.	3554.	2686.	8306.	3400.	.7711
	4	745.	1400.	3281.	2376.	7170.	2994.	.7542
	5	352.	600.	1634.	1078.	3163.	1365.	.7323
ScPGA	1	1875.	4092.	7847.	5637.	20241.	7938.	.8129
	2	1575.	3360.	6503.	4980.	16995.	6683.	.8098
	3	1238.	2433.	5318.	4019.	12428.	5087.	.7711
	4	1115.	2095.	4910.	3555.	10728.	4480.	.7542
	5	527.	897.	2446.	1613.	4732.	2043.	.7323
ScSa7	1	2587.	5646.	10827.	7778.	27928.	10953.	.8129
	2	2173.	4636.	8972.	6871.	23450.	9221.	.8098
	3	1708.	3357.	7338.	5546.	17148.	7019.	.7711
	4	1538.	2890.	6774.	4905.	14802.	6182.	.7542
	5	726.	1238.	3374.	2226.	6529.	2819.	.7323
ScASA	1	3247.	7089.	13593.	9765.	35062.	13751.	.8129
	2	2728.	5821.	11264.	8627.	29440.	11576.	.8098
	3	2144.	4214.	9213.	6963.	21529.	8812.	.7711
	4	1931.	3629.	8505.	6158.	18584.	7761.	.7542
	5	912.	1554.	4236.	2794.	8197.	3539.	.7323

Table 6-20

Maximum Inter-story Structural Forces for the 7-Hz Structure Sub-
jected to Artificial Motion Inputs MArJn(TLs) Scaled to Four Differ-
ent Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TLs):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	7492.	8033.	13581.	11116.	7230.	9490.	.2607
	2	6502.	6968.	11315.	10072.	6177.	8207.	.2538
	3	4638.	5150.	8895.	7648.	4699.	6206.	.2805
	4	4019.	4464.	7863.	6641.	4170.	5431.	.2840
	5	1803.	2088.	3665.	2892.	1959.	2481.	.2825
ScPGA	1	6783.	7273.	12296.	10064.	6546.	8593.	.2607
	2	5887.	6308.	10244.	9119.	5593.	7430.	.2538
	3	4199.	4663.	8053.	6924.	4255.	5619.	.2805
	4	3639.	4041.	7119.	6013.	3775.	4917.	.2840
	5	1633.	1890.	3318.	2619.	1774.	2247.	.2825
ScSa7	1	8371.	8975.	15174.	12420.	8078.	10604.	.2607
	2	7265.	7785.	12642.	11253.	6902.	9169.	.2538
	3	5182.	5754.	9938.	8545.	5251.	6934.	.2805
	4	4491.	4987.	8785.	7420.	4659.	6068.	.2840
	5	2015.	2333.	4095.	3231.	2189.	2772.	.2825
ScASA	1	10266.	11006.	18608.	15231.	9907.	13004.	.2607
	2	8909.	9547.	15503.	13800.	8464.	11245.	.2538
	3	6354.	7057.	12187.	10479.	6439.	8503.	.2805
	4	5507.	6116.	10773.	9099.	5714.	7442.	.2840
	5	2471.	2861.	5022.	3963.	2684.	3400.	.2825

Table 6-21

Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TL2r):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	2655.	2351.	1871.	7108.	2436.	3284.	.5873
	2	2199.	1925.	1735.	6189.	2029.	2815.	.6015
	3	1696.	1348.	1415.	4524.	1531.	2103.	.5784
	4	1561.	1158.	1288.	3903.	1346.	1851.	.5585
	5	754.	497.	596.	1715.	624.	837.	.5333
ScPGA	1	6092.	5394.	4293.	16309.	5590.	7535.	.5873
	2	5044.	4416.	3980.	14199.	4655.	6459.	.6015
	3	3891.	3092.	3246.	10379.	3513.	4824.	.5784
	4	3582.	2656.	2956.	8954.	3089.	4247.	.5585
	5	1731.	1141.	1367.	3936.	1431.	1921.	.5333
ScSa7	1	8905.	7885.	6275.	23840.	8172.	11015.	.5873
	2	7374.	6456.	5818.	20756.	6805.	9442.	.6015
	3	5689.	4520.	4745.	15173.	5136.	7053.	.5784
	4	5236.	3883.	4320.	13089.	4516.	6209.	.5585
	5	2530.	1668.	1999.	5753.	2092.	2809.	.5333
ScASA	1	11579.	10253.	8160.	30999.	10625.	14323.	.5873
	2	9589.	8395.	7565.	26989.	8849.	12277.	.6015
	3	7397.	5878.	6169.	19729.	6678.	9170.	.5784
	4	6808.	5049.	5618.	17019.	5872.	8073.	.5585
	5	3290.	2169.	2599.	7481.	2720.	3652.	.5333

Table 6-22

Maximum Inter-story Structural Forces for the 7-Hz Structure Sub-
jected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Dif-
ferent Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TL2s):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	2862.	4887.	11202.	2820.	6127.	5580.	.5517
	2	2328.	4224.	9546.	2433.	5572.	4821.	.5501
	3	2186.	3003.	7355.	1968.	4513.	3805.	.5222
	4	2058.	2697.	6463.	1747.	4006.	3394.	.5065
	5	1064.	1253.	2918.	797.	1833.	1573.	.4791
ScPGA	1	3866.	6602.	15132.	3810.	8276.	7537.	.5517
	2	3145.	5706.	12895.	3287.	7527.	6512.	.5501
	3	2953.	4057.	9936.	2658.	6097.	5140.	.5222
	4	2780.	3643.	8731.	2360.	5412.	4585.	.5065
	5	1437.	1693.	3941.	1077.	2476.	2125.	.4791
ScSa7	1	5474.	9348.	21425.	5394.	11718.	10672.	.5517
	2	4454.	8079.	18258.	4655.	10657.	9220.	.5501
	3	4182.	5744.	14068.	3764.	8633.	7278.	.5222
	4	3936.	5158.	12363.	3342.	7662.	6492.	.5065
	5	2035.	2397.	5580.	1524.	3506.	3008.	.4791
ScASA	1	6949.	11866.	27198.	6847.	14875.	13547.	.5517
	2	5653.	10256.	23177.	5909.	13528.	11704.	.5501
	3	5308.	7292.	17858.	4778.	10958.	9239.	.5222
	4	4996.	6547.	15693.	4242.	9727.	8241.	.5065
	5	2583.	3043.	7084.	1935.	4450.	3819.	.4791

Table 6-23

Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWr) Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TWr):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	11104.	15520.	11497.	11934.	7314.	11474.	.2274
	2	9514.	12469.	9762.	10199.	5840.	9557.	.2232
	3	7063.	9089.	7180.	7664.	4228.	7045.	.2246
	4	6109.	7859.	6194.	6684.	3679.	6105.	.2235
	5	2635.	3391.	2658.	2990.	1618.	2658.	.2212
ScPGA	1	11104.	15520.	11497.	11934.	7314.	11474.	.2274
	2	9514.	12469.	9762.	10199.	5840.	9557.	.2232
	3	7063.	9089.	7180.	7664.	4228.	7045.	.2246
	4	6109.	7859.	6194.	6684.	3679.	6105.	.2235
	5	2635.	3391.	2658.	2990.	1618.	2658.	.2212
ScSa7	1	10476.	14641.	10847.	11259.	6900.	10824.	.2274
	2	8976.	11763.	9210.	9621.	5509.	9016.	.2232
	3	6664.	8575.	6774.	7230.	3989.	6646.	.2246
	4	5763.	7414.	5843.	6306.	3471.	5759.	.2235
	5	2485.	3199.	2507.	2821.	1527.	2508.	.2212
ScASA	1	10565.	14765.	10939.	11354.	6958.	10916.	.2274
	2	9052.	11863.	9288.	9703.	5556.	9092.	.2232
	3	6720.	8647.	6831.	7291.	4022.	6702.	.2246
	4	5812.	7477.	5893.	6359.	3500.	5808.	.2235
	5	2507.	3227.	2529.	2845.	1540.	2529.	.2212

Table 6-24

Maximum Inter-story Structural Forces for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWs) Scaled to Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TWs):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	15183.	5230.	17375.	12578.	7405.	11554.	.3972
	2	12955.	4158.	15120.	10323.	6114.	9734.	.4209
	3	9596.	2929.	11871.	7429.	4441.	7253.	.4508
	4	8295.	2500.	10454.	6373.	3831.	6291.	.4595
	5	3576.	1057.	4737.	2713.	1647.	2746.	.4807
ScPGA	1	15183.	5230.	17375.	12578.	7405.	11554.	.3972
	2	12955.	4158.	15120.	10323.	6114.	9734.	.4209
	3	9596.	2929.	11871.	7429.	4441.	7253.	.4508
	4	8295.	2500.	10454.	6373.	3831.	6291.	.4595
	5	3576.	1057.	4737.	2713.	1647.	2746.	.4807
ScSa7	1	14324.	4934.	16392.	11866.	6986.	10900.	.3972
	2	12222.	3922.	14264.	9739.	5768.	9183.	.4209
	3	9053.	2763.	11199.	7008.	4190.	6843.	.4508
	4	7826.	2358.	9862.	6012.	3615.	5935.	.4595
	5	3374.	997.	4469.	2560.	1553.	2591.	.4807
ScASA	1	14412.	4964.	16493.	11939.	7029.	10967.	.3972
	2	12297.	3946.	14352.	9798.	5804.	9239.	.4209
	3	9109.	2780.	11268.	7051.	4216.	6885.	.4508
	4	7874.	2373.	9923.	6049.	3637.	5971.	.4595
	5	3395.	1004.	4496.	2575.	1563.	2606.	.4807

Table 6-25

Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TEr):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.1575	.1038	.2988	.0744	.1288	.1526	.5114
	2	.1640	.1614	.3630	.1065	.1842	.1958	.4467
	3	.1240	.1761	.3439	.0948	.2083	.1894	.4581
	4	.1316	.1853	.4252	.1195	.2668	.2257	.4983
	5	.1938	.2324	.5120	.1440	.3244	.2813	.4606
ScPGA	1	.3108	.2048	.5897	.1468	.2542	.3013	.5114
	2	.3237	.3186	.7165	.2102	.3635	.3865	.4467
	3	.2448	.3475	.6788	.1871	.4112	.3739	.4581
	4	.2597	.3658	.8392	.2359	.5266	.4454	.4983
	5	.3826	.4587	1.0105	.2842	.6404	.5553	.4606
ScSa7	1	.5207	.3431	.9879	.2459	.4259	.5047	.5114
	2	.5423	.5337	1.2002	.3521	.6090	.6475	.4467
	3	.4100	.5822	1.1372	.3134	.6888	.6263	.4581
	4	.4351	.6128	1.4058	.3952	.8822	.7462	.4983
	5	.6409	.7684	1.6928	.4761	1.0727	.9302	.4606
ScASA	1	.6928	.4566	1.3145	.3271	.5667	.6716	.5114
	2	.7216	.7101	1.5971	.4686	.8104	.8616	.4467
	3	.5456	.7747	1.5132	.4170	.9166	.8334	.4581
	4	.5790	.8154	1.8706	.5258	1.1740	.9930	.4983
	5	.8528	1.0225	2.2525	.6335	1.4275	1.2377	.4606

Table 6-26

Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEs) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TEs):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.3132	.3452	.2308	.1843	.3275	.2802	.2212
	2	.4354	.4848	.3608	.2198	.5103	.4022	.2597
	3	.4838	.5875	.4401	.2132	.5965	.4642	.2995
	4	.5818	.6859	.5329	.2329	.6670	.5401	.3025
	5	.6815	.7473	.6495	.2615	.7484	.6176	.2949
ScPGA	1	.3392	.3739	.2499	.1996	.3547	.3035	.2212
	2	.4715	.5250	.3907	.2381	.5527	.4356	.2597
	3	.5239	.6363	.4766	.2309	.6460	.5027	.2995
	4	.6301	.7428	.5772	.2523	.7223	.5849	.3025
	5	.7380	.8093	.7034	.2832	.8105	.6689	.2949
ScSa7	1	.4389	.4837	.3234	.2582	.4589	.3926	.2212
	2	.6101	.6793	.5056	.3080	.7150	.5636	.2597
	3	.6779	.8233	.6166	.2987	.8358	.6505	.2995
	4	.8152	.9611	.7468	.3264	.9346	.7568	.3025
	5	.9548	1.0471	.9101	.3663	1.0486	.8654	.2949
ScASA	1	.5796	.6388	.4270	.3410	.6061	.5185	.2212
	2	.8056	.8970	.6676	.4068	.9443	.7443	.2597
	3	.8952	1.0872	.8143	.3945	1.1037	.8590	.2995
	4	1.0765	1.2692	.9862	.4310	1.2342	.9994	.3025
	5	1.2610	1.3828	1.2018	.4838	1.3848	1.1428	.2949

Table 6-27

Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TLr):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.0736	.1050	.2743	.1594	.4507	.2126	.6458
	2	.0792	.1304	.3528	.1780	.6262	.2733	.7282
	3	.0708	.1465	.3311	.2134	.7303	.2984	.7783
	4	.0851	.1661	.3405	.2682	.8458	.3411	.7824
	5	.1027	.1781	.4830	.3187	.9282	.4022	.7293
ScPGA	1	.1101	.1571	.4105	.2385	.6744	.3181	.6458
	2	.1185	.1951	.5278	.2663	.9370	.4090	.7282
	3	.1060	.2192	.4954	.3194	1.0928	.4465	.7783
	4	.1273	.2486	.5095	.4013	1.2656	.5104	.7824
	5	.1537	.2666	.7227	.4769	1.3889	.6018	.7293
ScSa7	1	.1519	.2168	.5664	.3291	.9306	.4390	.6458
	2	.1635	.2692	.7283	.3675	1.2928	.5643	.7282
	3	.1462	.3024	.6835	.4407	1.5078	.6161	.7783
	4	.1756	.3430	.7029	.5538	1.7462	.7043	.7824
	5	.2121	.3678	.9972	.6581	1.9164	.8303	.7293
ScASA	1	.1908	.2721	.7111	.4132	1.1683	.5511	.6458
	2	.2052	.3380	.9144	.4614	1.6231	.7084	.7282
	3	.1836	.3797	.8581	.5532	1.8930	.7735	.7783
	4	.2205	.4306	.8825	.6952	2.1923	.8842	.7824
	5	.2662	.4618	1.2520	.8262	2.4059	1.0424	.7293

Table 6-28

Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLs) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TLs):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.3703	.3470	.5385	.3874	.2214	.3729	.2716
	2	.4966	.4069	.6882	.5242	.3270	.4886	.2490
	3	.4455	.4513	.7424	.6477	.3873	.5348	.2544
	4	.4761	.5298	.8866	.7793	.4719	.6288	.2725
	5	.5266	.6076	1.0768	.8674	.5776	.7312	.2861
ScPGA	1	.3352	.3142	.4876	.3507	.2004	.3376	.2716
	2	.4496	.3684	.6231	.4746	.2961	.4424	.2490
	3	.4033	.4086	.6722	.5864	.3507	.4842	.2544
	4	.4311	.4797	.8027	.7056	.4273	.5693	.2725
	5	.4768	.5501	.9749	.7854	.5229	.6620	.2861
ScSa7	1	.4137	.3878	.6017	.4328	.2473	.4167	.2716
	2	.5548	.4546	.7690	.5857	.3654	.5459	.2490
	3	.4977	.5043	.8295	.7237	.4327	.5976	.2544
	4	.5319	.5920	.9906	.8707	.5273	.7025	.2725
	5	.5883	.6789	1.2031	.9692	.6453	.8170	.2861
ScASA	1	.5073	.4755	.7379	.5308	.3033	.5110	.2716
	2	.6804	.5575	.9430	.7182	.4481	.6694	.2490
	3	.6104	.6184	1.0172	.8875	.5307	.7328	.2544
	4	.6523	.7260	1.2148	1.0678	.6466	.8615	.2725
	5	.7215	.8325	1.4754	1.1886	.7914	1.0019	.2861

Table 6-29

Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TL2r):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.1419	.0974	.0982	.2235	.1025	.1327	.3640
	2	.1790	.1264	.1112	.3446	.1398	.1802	.4730
	3	.1472	.1324	.1091	.4052	.1374	.1863	.5915
	4	.1755	.1392	.1451	.4563	.1577	.2148	.5654
	5	.2229	.1480	.1748	.5126	.1883	.2493	.5369
ScPGA	1	.3255	.2236	.2253	.5127	.2352	.3044	.3640
	2	.4107	.2899	.2552	.7906	.3207	.4134	.4730
	3	.3377	.3039	.2504	.9297	.3151	.4274	.5915
	4	.4026	.3193	.3329	1.0469	.3618	.4927	.5654
	5	.5115	.3395	.4010	1.1761	.4320	.5720	.5369
ScSa7	1	.4758	.3268	.3294	.7494	.3438	.4450	.3640
	2	.6004	.4238	.3730	1.1557	.4688	.6044	.4730
	3	.4936	.4442	.3661	1.3590	.4607	.6247	.5915
	4	.5885	.4668	.4867	1.5304	.5289	.7203	.5654
	5	.7477	.4963	.5861	1.7193	.6315	.8362	.5369
ScASA	1	.6187	.4249	.4283	.9745	.4471	.5787	.3640
	2	.7806	.5511	.4850	1.5028	.6096	.7858	.4730
	3	.6419	.5776	.4760	1.7671	.5990	.8123	.5915
	4	.7652	.6070	.6328	1.9900	.6877	.9365	.5654
	5	.9722	.6453	.7621	2.2356	.8211	1.0873	.5369

Table 6-30

Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TL2s):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.2296	.1671	.4820	.1140	.2083	.2402	.5295
	2	.2528	.2650	.5987	.1657	.3058	.3176	.4653
	3	.1983	.2934	.6091	.1567	.3503	.3216	.4950
	4	.2160	.3109	.7421	.1996	.4509	.3839	.5214
	5	.3082	.3759	.8719	.2375	.5370	.4661	.4846
ScPGA	1	.3101	.2257	.6511	.1540	.2813	.3245	.5295
	2	.3415	.3580	.8088	.2239	.4131	.4291	.4653
	3	.2679	.3963	.8228	.2117	.4732	.4344	.4950
	4	.2918	.4201	1.0026	.2697	.6091	.5186	.5214
	5	.4163	.5078	1.1779	.3208	.7254	.6297	.4846
ScSa7	1	.4391	.3195	.9219	.2181	.3983	.4594	.5295
	2	.4836	.5068	1.1452	.3169	.5849	.6075	.4653
	3	.3793	.5611	1.1650	.2998	.6700	.6150	.4950
	4	.4131	.5947	1.4195	.3818	.8624	.7343	.5214
	5	.5895	.7190	1.6678	.4543	1.0271	.8915	.4846
ScASA	1	.5574	.4056	1.1702	.2768	.5057	.5832	.5295
	2	.6139	.6434	1.4537	.4023	.7425	.7712	.4653
	3	.4815	.7123	1.4789	.3806	.8505	.7807	.4950
	4	.5244	.7550	1.8019	.4847	1.0947	.9321	.5214
	5	.7483	.9127	2.1171	.5767	1.3038	1.1317	.4846

Table 6-31

Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWr) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TWr):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.3253	.6134	.3504	.3832	.3054	.3956	.2831
	2	.5066	.7516	.5312	.5804	.4145	.5569	.1998
	3	.6136	.8264	.6331	.6658	.4120	.6302	.2101
	4	.7177	.9220	.7310	.7819	.4237	.7152	.2276
	5	.7766	.9985	.7851	.8796	.4697	.7819	.2244
ScPGA	1	.3253	.6134	.3504	.3832	.3054	.3956	.2831
	2	.5066	.7516	.5312	.5804	.4145	.5569	.1998
	3	.6136	.8264	.6331	.6658	.4120	.6302	.2101
	4	.7177	.9220	.7310	.7819	.4237	.7152	.2276
	5	.7766	.9985	.7851	.8796	.4697	.7819	.2244
ScSa7	1	.3069	.5787	.3306	.3615	.2881	.3732	.2831
	2	.4780	.7091	.5011	.5476	.3911	.5254	.1998
	3	.5789	.7796	.5973	.6281	.3887	.5945	.2101
	4	.6771	.8698	.6896	.7376	.3997	.6748	.2276
	5	.7326	.9420	.7406	.8298	.4431	.7376	.2244
ScASA	1	.3095	.5836	.3334	.3646	.2906	.3763	.2831
	2	.4820	.7151	.5054	.5522	.3944	.5298	.1998
	3	.5838	.7862	.6023	.6334	.3920	.5995	.2101
	4	.6828	.8772	.6954	.7439	.4031	.6805	.2276
	5	.7389	.9500	.7469	.8369	.4469	.7439	.2244

Table 6-32

Zero-Period Accelerations of Structural Floor Responses for the 7-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWs) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TWs):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.4562	.2156	.5965	.4562	.2618	.3973	.3523
	2	.6941	.2525	.8651	.5962	.3486	.5513	.4066
	3	.8360	.2750	.9614	.6772	.3999	.6299	.4100
	4	.9750	.2978	1.1824	.7555	.4511	.7324	.4445
	5	1.0539	.3120	1.3886	.7995	.4849	.8078	.4788
ScPGA	1	.4562	.2156	.5965	.4562	.2618	.3973	.3523
	2	.6941	.2525	.8651	.5962	.3486	.5513	.4066
	3	.8360	.2750	.9614	.6772	.3999	.6299	.4100
	4	.9750	.2978	1.1824	.7555	.4511	.7324	.4445
	5	1.0539	.3120	1.3886	.7995	.4849	.8078	.4788
ScSa7	1	.4304	.2034	.5627	.4304	.2470	.3748	.3523
	2	.6548	.2382	.8161	.5625	.3289	.5201	.4066
	3	.7887	.2594	.9069	.6388	.3773	.5942	.4100
	4	.9199	.2809	1.1155	.7127	.4256	.6909	.4445
	5	.9943	.2944	1.3100	.7542	.4575	.7621	.4788
ScASA	1	.4330	.2047	.5662	.4330	.2485	.3771	.3523
	2	.6588	.2396	.8212	.5659	.3309	.5233	.4066
	3	.7935	.2610	.9125	.6428	.3796	.5979	.4100
	4	.9255	.2827	1.1224	.7171	.4282	.6952	.4445
	5	1.0004	.2962	1.3181	.7589	.4603	.7668	.4788

Table 6-33

Maximum Inter-story Structural Forces for the 10-Hz Structure
Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four
Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TEr):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	1305.	1632.	2695.	952.	1660.	1649.	.3535
	2	721.	1018.	1579.	637.	1044.	1000.	.3310
ScPGA	1	2575.	3222.	5319.	1879.	3277.	3254.	.3535
	2	1422.	2009.	3116.	1256.	2060.	1973.	.3310
ScSa10	1	3467.	4339.	7163.	2530.	4412.	4382.	.3535
	2	1916.	2706.	4196.	1692.	2775.	2657.	.3310
ScASA	1	5739.	7182.	11857.	4188.	7304.	7254.	.3535
	2	3171.	4479.	6946.	2801.	4593.	4398.	.3310

Table 6-34

Maximum Inter-story Structural Forces for the 10-Hz Structure
 Subjected to Artificial Motion Inputs MArJn(TEs) Scaled to Four
 Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TEs):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	3002.	4134.	3335.	2529.	4017.	3403.	.1783
	2	1882.	2629.	2156.	1522.	2549.	2148.	.1925
ScPGA	1	3251.	4477.	3612.	2739.	4351.	3686.	.1783
	2	2038.	2847.	2335.	1649.	2761.	2326.	.1925
ScSa10	1	3909.	5383.	4343.	3293.	5231.	4432.	.1783
	2	2450.	3423.	2807.	1982.	3319.	2797.	.1925
ScASA	1	5555.	7650.	6171.	4679.	7433.	6298.	.1783
	2	3482.	4865.	3989.	2817.	4717.	3974.	.1925

Table 6-35

Maximum Inter-story Structural Forces for the 10-Hz Structure
 Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four
 Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TLr):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	643.	1007.	3551.	2357.	4756.	2463.	.6261
	2	324.	580.	1947.	1492.	2893.	1447.	.6449
ScPGA	1	963.	1506.	5313.	3526.	7117.	3685.	.6261
	2	485.	868.	2913.	2232.	4329.	2165.	.6449
ScSa10	1	1179.	1845.	6509.	4320.	8719.	4514.	.6261
	2	594.	1064.	3568.	2734.	5303.	2653.	.6449
ScASA	1	1668.	2609.	9204.	6108.	12328.	6383.	.6261
	2	840.	1504.	5046.	3867.	7499.	3751.	.6449

Table 6-36

Maximum Inter-story Structural Forces for the 10-Hz Structure
Subjected to Artificial Motion Inputs MArJn(TLs) Scaled to Four
Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TLs):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	3871.	3702.	4401.	6432.	2703.	4222.	.2924
	2	2502.	2166.	2908.	4204.	1644.	2685.	.3223
ScPGA	1	3505.	3352.	3985.	5824.	2447.	3822.	.2924
	2	2266.	1961.	2633.	3806.	1488.	2431.	.3223
ScSa10	1	4008.	3833.	4557.	6660.	2798.	4371.	.2924
	2	2591.	2243.	3011.	4353.	1702.	2780.	.3223
ScASA	1	5304.	5073.	6030.	8814.	3703.	5785.	.2924
	2	3429.	2968.	3985.	5760.	2252.	3679.	.3223

Table 6-37

Maximum Inter-story Structural Forces for the 10-Hz Structure
 Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four
 Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TL2r):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	1607.	721.	1344.	3172.	881.	1545.	.5650
	2	931.	461.	818.	2033.	575.	963.	.5815
ScPGA	1	3688.	1654.	3084.	7276.	2021.	3545.	.5650
	2	2135.	1058.	1876.	4664.	1319.	2210.	.5815
ScSa10	1	4579.	2054.	3830.	9036.	2510.	4402.	.5650
	2	2651.	1313.	2329.	5791.	1638.	2745.	.5815
ScASA	1	7010.	3144.	5863.	13831.	3842.	6738.	.5650
	2	4058.	2010.	3566.	8865.	2507.	4201.	.5815

Table 6-38

Maximum Inter-story Structural Forces for the 10-Hz Structure
 Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four
 Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TL2s):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	2055.	2540.	4169.	1509.	2637.	2582.	.3443
	2	1129.	1581.	2443.	1001.	1634.	1558.	.3252
ScPGA	1	2776.	3431.	5631.	2038.	3562.	3488.	.3443
	2	1526.	2136.	3300.	1353.	2207.	2104.	.3252
ScSa10	1	3471.	4289.	7039.	2547.	4452.	4360.	.3443
	2	1907.	2670.	4125.	1691.	2759.	2630.	.3252
ScASA	1	4990.	6167.	10121.	3663.	6402.	6269.	.3443
	2	2742.	3838.	5931.	2431.	3967.	3782.	.3252

Table 6-39

Maximum Inter-story Structural Forces for the 10-Hz Structure
 Subjected to Artificial Motion Inputs MArJn(TWr) Scaled to
 Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TWr):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	2346.	6697.	3028.	4940.	3423.	4087.	.3812
	2	1251.	4057.	1645.	3036.	2141.	2426.	.4166
ScPGA	1	2346.	6697.	3028.	4940.	3423.	4087.	.3812
	2	1251.	4057.	1645.	3036.	2141.	2426.	.4166
ScSa10	1	2494.	7117.	3218.	5250.	3637.	4343.	.3812
	2	1329.	4312.	1748.	3226.	2275.	2578.	.4166
ScASA	1	2232.	6372.	2881.	4700.	3256.	3888.	.3812
	2	1190.	3860.	1565.	2889.	2037.	2308.	.4166

Table 6-40

Maximum Inter-story Structural Forces for the 10-Hz Structure
Subjected to Artificial Motion Inputs MArJn(TWs) Scaled to
Four Different Anchor Bases

Scale Basis	Elem. No.	Computed Maximum Inter-Story Forces (kips) for Artificial Ground Motions MArJn(TWs):					Mean Force (kips)	COV of Force
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	4659.	2172.	7613.	3086.	2826.	4071.	.4790
	2	2682.	1244.	4788.	1605.	1590.	2382.	.5443
ScPGA	1	4659.	2172.	7613.	3086.	2826.	4071.	.4790
	2	2682.	1244.	4788.	1605.	1590.	2382.	.5443
ScSa10	1	4951.	2308.	8090.	3280.	3003.	4326.	.4790
	2	2850.	1322.	5088.	1706.	1690.	2531.	.5443
ScASA	1	4422.	2062.	7226.	2929.	2683.	3864.	.4790
	2	2546.	1181.	4545.	1524.	1510.	2261.	.5443

Table 6-41

Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEr) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TEr):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.2252	.1843	.3014	.1008	.1631	.1950	.3422
	2	.1865	.2664	.4134	.1655	.2713	.2606	.3346
ScPGA	1	.4446	.3637	.5949	.1989	.3218	.3848	.3422
	2	.3681	.5257	.8158	.3267	.5355	.5144	.3346
ScSa10	1	.5987	.4898	.8012	.2678	.4334	.5182	.3422
	2	.4957	.7080	1.0987	.4399	.7211	.6927	.3346
ScASA	1	.9910	.8107	1.3262	.4434	.7174	.8577	.3422
	2	.8205	1.1719	1.8187	.7282	1.1936	1.1466	.3346

Table 6-42

Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TEs) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TEs):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.4033	.4137	.3874	.2782	.4248	.3815	.1392
	2	.4937	.6817	.5557	.3925	.6591	.5565	.1919
ScPGA	1	.4368	.4480	.4196	.3013	.4601	.4132	.1392
	2	.5347	.7383	.6018	.4251	.7138	.6027	.1919
ScSa10	1	.5252	.5387	.5045	.3623	.5532	.4968	.1392
	2	.6429	.8877	.7236	.5111	.8582	.7247	.1919
ScASA	1	.7463	.7655	.7169	.5148	.7861	.7059	.1392
	2	.9135	1.2614	1.0283	.7263	1.2196	1.0298	.1919

Table 6-43

Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLr) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TLr):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.0856	.1214	.4620	.2392	.4900	.2797	.6022
	2	.0868	.1507	.4945	.3881	.7536	.3747	.6439
ScPGA	1	.1281	.1817	.6913	.3579	.7332	.4185	.6022
	2	.1299	.2255	.7399	.5807	1.1276	.5607	.6439
ScSa10	1	.1570	.2226	.8469	.4385	.8982	.5126	.6022
	2	.1592	.2763	.9064	.7114	1.3813	.6869	.6439
ScASA	1	.2220	.3147	1.1975	.6201	1.2701	.7249	.6022
	2	.2251	.3907	1.2816	1.0060	1.9532	.9713	.6439

Table 6-44

Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TLs) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TLs):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.4541	.4159	.5796	.6184	.2807	.4698	.2573
	2	.6433	.5620	.7577	1.0949	.4264	.6969	.3249
ScPGA	1	.4111	.3766	.5248	.5599	.2542	.4253	.2573
	2	.5824	.5089	.6860	.9914	.3861	.6310	.3249
ScSa10	1	.4702	.4306	.6001	.6403	.2907	.4864	.2573
	2	.6661	.5819	.7845	1.1337	.4415	.7215	.3249
ScASA	1	.6222	.5699	.7942	.8474	.3846	.6437	.2573
	2	.8814	.7701	1.0382	1.5003	.5843	.9549	.3249

Table 6-45

Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2r) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TL2r):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.1807	.0796	.1432	.3386	.0926	.1670	.5579
	2	.2406	.1189	.2115	.5250	.1498	.2492	.5800
ScPGA	1	.4145	.1827	.3286	.7769	.2126	.3831	.5579
	2	.5521	.2728	.4852	1.2046	.3437	.5717	.5800
ScSa10	1	.5147	.2268	.4081	.9648	.2639	.4757	.5579
	2	.6856	.3388	.6025	1.4958	.4268	.7099	.5800
ScASA	1	.7879	.3472	.6246	1.4768	.4040	.7281	.5579
	2	1.0494	.5186	.9223	2.2897	.6533	1.0866	.5800

Table 6-46

Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TL2s) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TL2s):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.3400	.2888	.4619	.1567	.2629	.3021	.3305
	2	.2923	.4135	.6393	.2602	.4246	.4060	.3286
ScPGA	1	.4593	.3902	.6240	.2116	.3552	.4081	.3305
	2	.3949	.5585	.8636	.3516	.5736	.5484	.3286
ScSa10	1	.5742	.4877	.7800	.2646	.4440	.5101	.3305
	2	.4937	.6982	1.0795	.4395	.7170	.6856	.3286
ScASA	1	.8255	.7013	1.1215	.3804	.6384	.7334	.3305
	2	.7098	1.0039	1.5522	.6319	1.0309	.9857	.3286

Table 6-47

Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWr) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TWr):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.2848	.7387	.3587	.5016	.3545	.4476	.3612
	2	.3243	1.0539	.4275	.7886	.5613	.6311	.4156
ScPGA	1	.2848	.7387	.3587	.5016	.3545	.4476	.3612
	2	.3243	1.0539	.4275	.7886	.5613	.6311	.4156
ScSa10	1	.3026	.7850	.3812	.5330	.3767	.4757	.3612
	2	.3447	1.1200	.4543	.8380	.5965	.6707	.4156
ScASA	1	.2709	.7028	.3412	.4772	.3373	.4259	.3612
	2	.3086	1.0027	.4067	.7503	.5340	.6005	.4156

Table 6-48

Zero-Period Accelerations of Structural Floor Responses for the 10-Hz Structure Subjected to Artificial Motion Inputs MArJn(TWs) Scaled to Four Different Anchor Bases

Scale Basis	Floor No.	Computed Maximum Floor Accelerations (g) for Artificial Ground Motions MArJn(TWs):					Mean ZPA (g)	COV of ZPA
		n=1	n=2	n=3	n=4	n=5		
No Scaling	1	.5136	.2512	.8340	.3838	.3329	.4631	.4407
	2	.6968	.3232	1.2474	.4163	.4132	.6194	.5460
ScPGA	1	.5136	.2512	.8340	.3838	.3329	.4631	.4407
	2	.6968	.3232	1.2474	.4163	.4132	.6194	.5460
ScSa10	1	.5458	.2669	.8862	.4079	.3538	.4921	.4407
	2	.7405	.3434	1.3256	.4424	.4391	.6582	.5460
ScASA	1	.4875	.2384	.7916	.3643	.3160	.4396	.4407
	2	.6614	.3067	1.1840	.3952	.3922	.5879	.5460

Figure 6-1. In-structure response spectra for the 3-Hz structure subjected to five artificial input motions MARJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MARJ1-5(TEr) and (b) MARJ1-5(TEs).

Figure 6-2. In-structure response spectra for the 3-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).

Figure 6-3. In-structure response spectra for the 3-Hz structure subjected to five artificial input motions MARJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MARJ1-5(TL2r) and (f) MARJ1-5(TL2s).

Figure 6-4. In-structure response spectra for the 3-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TWr) and (h) MArJ1-5(TWs).

Frequency (Hz)

Frequency (Hz)

Figure 6-5. In-structure response spectra for the 7-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MArJ1-5(TEr) and (b) MArJ1-5(TEs).

Figure 6-6. In-structure response spectra for the 7-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).

Figure 6-7. In-structure response spectra for the 7-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MArJ1-5(TL2r) and (f) MArJ1-5(TL2s).

Figure 6-8. In-structure response spectra for the 7-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TWr) and (h) MArJ1-5(TWs).

Figure 6-9. In-structure response spectra for the 10-Hz structure subjected to five artificial input motions MARJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MARJ1-5(Ter) and (b) MARJ1-5(TEs).

Figure 6-10. In-structure response spectra for the 10-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).

Figure 6-11. In-structure response spectra for the 10-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MArJ1-5(TL2r) and (f) MArJ1-5(TL2s).

Figure 6-12. In-structure response spectra for the 10-Hz structure subjected to five artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TW_r) and (h) MArJ1-5(TW_s).

Statistics of ISS5(S13) Results
[Mean $\pm$ σ for MARJ1-5(TER)]

Statistics of ISS5(S13) Results
[Mean $\pm$ σ for MARJ1-5(TES)]

Statistics of ISS3(S13) Results
[Mean $\pm$ σ for MARJ1-5(TER)]

Statistics of ISS3(S13) Results
[Mean $\pm$ σ for MARJ1-5(TES)]

Statistics of ISS1(S13) Results
[Mean $\pm$ σ for MARJ1-5(TER)]

Statistics of ISS1(S13) Results
[Mean $\pm$ σ for MARJ1-5(TES)]

Figure 6-13. ISS statistics for the 3-Hz structure subjected to artificial input motions MARJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MARJ1-5(TER) and (b) MARJ1-5(TES).

Figure 6-14. ISS statistics for the 3-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).

Figure 6-15. ISS statistics for the 3-Hz structure subjected to artificial input motions MARJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MARJ1-5(TL2r) and (f) MARJ1-5(TL2s).

Figure 6-16. ISS statistics for the 3-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TWr) and (h) MArJ1-5(TWs).

Figure 6-17. ISS statistics for the 7-Hz structure subjected to artificial input motions MARJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MARJ1-5(TEr) and (b) MARJ1-5(TEs).

Frequency (Hz)

Frequency (Hz)

Figure 6-18. ISS statistics for the 7-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).

Frequency (Hz)

Frequency (Hz)

Figure 6-19. ISS statistics for the 7-Hz structure subjected to artificial input motions MARJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MARJ1-5(TL2r) and (f) MARJ1-5(TL2s).

Frequency (Hz)

Frequency (Hz)

Figure 6-20. ISS statistics for the 7-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TWr) and (h) MArJ1-5(TWs).

Figure 6-21. ISS statistics for the 10-Hz structure subjected to artificial input motions MarJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (a) MarJ1-5(TEr) and (b) MarJ1-5(TEs).

Figure 6-22. ISS statistics for the 10-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (c) MArJ1-5(TLr) and (d) MArJ1-5(TLs).

Figure 6-23. ISS statistics for the 10-Hz structure subjected to artificial input motions MARJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (e) MARJ1-5(TL2 τ) and (f) MARJ1-5(TL2s).

Figure 6-24. ISS statistics for the 10-Hz structure subjected to artificial input motions MArJ1-5 with ScASA scaling. Responses at the first, third, and fifth floors for motions: (g) MArJ1-5(TWr) and (h) MArJ1-5(TWs).

Section 7

MOTION IMPACTS ON IN-STRUCTURE DEMAND SPECTRA

This chapter compares results of seismic evaluation demands produced for the three cases of motion inputs considered in this study: (1) empirical ground-motion records, (2) artificial motions MArS1 simulated to have response spectra smoothly matching their respective target spectra, and (3) multiple artificial motions MArJn simulated to have jagged response spectra that, when averaged, match their respective targets. The comparisons and discussion help clarify the expected impacts, of alternative approaches for developing seismic input, on evaluation results.

Observations made in this chapter are based on comparison of in-structure-spectra demands. The reader may verify, by appropriate comparisons of the tables in Chapters 5, 6 and 7 (for respective cases), that these observations are also generally valid with respect to structural forces (and displacements) and floor ZPAs.

7.1 COMPARISONS OF EMPIRICAL VERSUS ARTIFICIAL MOTIONS WITH SMOOTH SPECTRA

Figures 7-1 to 7-6 present comparisons of ISS demands for empirical motions versus those obtained for artificial motions having smooth response spectra. As discussed in previous chapters, the most consistent basis for making comparisons in this study is in consideration of demands for cases where the empirical motion spectra and target spectra of the artificial motions are most similar. On this basis, the following comparative cases are judged to be the most appropriate to consider: (1) results for empirical motions MSag1, MSag2 and MNah3 against corresponding results for motion(s) simulated to match target spectrum TL2r; (2) results for empirical motion MSag3 against results for motion(s) simulated to match target spectrum TLr; and (3) results for empirical motion MImp1 against results for motion(s) simulated to match target spectrum TWs. These cases are also consistent with respect site condition (rock/soil); i.e., all motions for a given case are of the same category. Cases 1 and 2 are for Eastern U.S. type motions and Case 3 is for Western U.S. type motions.

The graphs in Figures 7-1 and 7-2 are for the five-story, 3-Hz structure. For the Case-1 comparison, it is noted that the artificial motion-input produces ISS demands, in the vicinity

of the structure's fundamental-mode frequency, that are generally similar of conservative relative to corresponding ISS demands for the three empirical motions. Near the vicinity of the structure's higher-mode frequencies, however, the ISS demands produced for the artificial motion input are generally unconservative with respect to results for the three empirical motions. The locations of peaks in ISS for the empirical motions vary notably over this (higher) frequency range. For the Case-2 comparison, ISS demands for the artificial input are somewhat lower than those for empirical input near the fundamental-mode frequency, but at higher frequencies, the results are very similar for the different inputs. For the Case-3 comparison, the ISS demands for empirical and artificial input are both quite similar.

Figures 7-3 and 7-4 present results for the four-story (5-DOF), 7-Hz structure. The Case-1 comparison shows that ISS demands for the artificial input are substantially similar to those for the empirical motions, in the vicinity of the structure's fundamental-mode frequency. Over higher frequencies, the artificial motion input is still somewhat unconservative with respect to empirical-motion demands, although not as much so as observed for the 3-Hz structure. In addition, the peaks in empirical-motion ISS at the structure's second-mode frequency are here more-consistently located than observed for the 3-Hz structure. For the Case-2 comparison, ISS demands are mostly very similar for the empirical and artificial inputs; for the first floor, over higher frequencies, the artificial-motion results are notably more conservative than for the empirical motion. The Case-1 comparison again reveals (as for the 3-Hz structure) very similar results for ISS demands among the artificial and empirical inputs. The only difference worthy of note here is that the artificial input produces an ISS bump at the structure's second-mode frequency, for the first floor, whereas such a bump is absent from corresponding results for the empirical motion.

In Figures 7-5 and 7-6 comparative ISS demands are presented for the two-story, 10-Hz structure. In comparing results for Case 1, it is seen that ISS demands for the empirical motions are still notably conservative, with respect to results seen for the artificial input, in the vicinity of the structure's second-mode frequency (particularly at the first-floor level). In the vicinity of the structure's fundamental-mode frequency, the ISS demands are very much the same among the empirical and artificial motions. For the Case-2 comparison, the demands produced for the artificial input are notably conservative, over nearly all frequencies, with respect to demands seen for the empirical motion input. And, for the Case-3 comparison, the artificial-motion input results in generally greater demands in the vicinity of the structure's fundamental-mode frequency, and very similar ISS demands across higher frequencies, relative to results produced for the empirical motion input.

It is important to make a couple of points regarding all of the above comparisons. First, to a large degree it can be said that the results for empirical and artificial motion inputs, for corresponding cases, are substantially similar. In some instances, the empirical motion input(s) result in the higher demands; in many instances, however, the artificial motion input produces the higher result. The relative nature of the demand varies depending on the specific structure considered. These observed differences, in part, have to do with variations in the shape of input spectra, across the broad frequency range of 3 Hz to 10 Hz, when anchored to a scalar value of average spectral acceleration. The impact, on relative levels of demand, resulting from the shape variations, therefore, changes from structure to structure, i.e., with predominant frequency of the structures, as observed in the preceding comparisons. Another source of explanation for the observed differences in results for the artificial and empirical motions has to do with some inconsistency in the shape of the target spectrum versus the spectral shape(s) of the empirical motions. Although the shapes are roughly similar for corresponding cases, the target spectrum (derived from the UHS) generally is not matched precisely by any specific empirical motion.

An additional point to be made from the preceding comparisons is that, if anything, the artificial motions demonstrate the tendency to exhibit greater relative conservatisms at lower frequencies, compared to relative conservatisms (or occasional under-conservatisms) at higher frequencies. It was hypothesized in Chapter 1 that the artificial motions might be deficient in their ability to produce adequate evaluation demands over lower frequencies. The observations noted as aforementioned, however, do not support this hypothesis.

7.2 COMPARISONS OF EMPIRICAL VERSUS ARTIFICIAL MOTIONS WITH JAGGED SPECTRA

Figures 7-7 to 7-12 present comparisons of ISS demands for empirical motions versus those obtained for multiple artificial motions having jagged response spectra. In these comparisons, the average ISS demand (for any given case), among the demands produced for the five artificial motions, is presented. Figures 7-7 and 7-8, Figures 7-9 and 7-10, and Figures 7-11 and 7-12, respectively, show comparative results for the 3-Hz structure, the 7-Hz structure, and the 10-Hz structure.

We shall not delve into the particulars of these comparisons for each of the three comparative cases, because the observations concerning relative conservatisms for real versus artificial motion input are virtually the same (with the same explanations) as those discussed above for artificial motions with smooth spectra. The reason for such similarity in comparisons is clarified in the next section.

It is worth mentioning here, however, that the occasional, spurious PSD gaps seen for isolated simulations of multiple artificial motions (as noted in Chapter 3), have no apparent effect on the average evaluation demands produced from these motions.

7.3 COMPARISONS AMONG ALTERNATIVE SIMULATION APPROACHES

Figures 7-13 to 7-18 present comparisons of ISS demands among the two alternative procedures for developing and using artificial motion input. Figures 7-13 and 7-14, Figures 7-15 and 7-16, and Figures 7-17 and 7-18, respectively, show comparative results for the 3-Hz structure, the 7-Hz structure, and the 10-Hz structure.

Consistently, these comparisons show that the average demands produced for the multiple artificial motions having jagged spectra are very similar to corresponding demands produced for the single artificial motion having smooth response spectrum. Hence, this is the reason that observations concerning comparative levels of conservatism with respect to empirical motions were essentially the same (in Section 7.1 and 7.2) for the two alternative motion-simulation approaches. The minor differences in demands produced for the two alternative simulation approaches is seen in ISS peaks. In most cases, the single artificial motion produces somewhat higher ISS peaks than does the average of multiple artificial motions, although for at least one instance (Case-1 comparison for the 3-Hz structure) the opposite is true.

It was anticipated earlier that average linear demands produced for the multiple artificial motions having jagged spectra would be nearly similar (although not exactly so) to those produced for single artificial motions having smooth spectra (and matching the same designated target spectrum). The similarity in results observed here, however, does not suggest that implementing multiple artificial motions for seismic evaluation study is unnecessary. This is because, demands on NPP components that may experience significant non-linear response, and/or demands on NPP systems, can be expected to be more sensitive to spectral-shape variations.

Although the average linear ISS demands produced here for multiple artificial motions having realistic jagged spectra are nearly the same as those produced, correspondingly, for a single artificial motion having a smooth response spectrum, the variations in ISS demands produced for the multiple artificial motions (as presented in Chapter 6) convey significant information not found for the single artificial-motion result.

7.4 COMPARISONS AMONG EASTERN U.S. AND WESTERN U.S. MOTIONS

A point worthy of separate consideration has to do with comparison of demands produced for Eastern U.S. type and Western U.S. type motions. Such comparison is relevant because seismic margin assessments for Eastern U.S. NPPs often use motion input representative of Western U.S. earthquake motions.

Contrasting results observed in Figures 7-1 with corresponding results in Figure 7-2, Figures 7-3 with Figure 7-4, and Figure 7-5 with Figure 7-6, it is clear that the Western U.S. motions result in consistently lower demands, across high frequencies, as compared to Eastern U.S. motions. This observation suggests that if sufficient conservatism is not introduced in selection of the Western U.S. type seismic margin earthquake, linear effects on high-frequency equipment mounted in Eastern U.S. NPPs can be significantly under-estimated. Conversely, if sufficient demands over the high-frequency range are produced for evaluation of an Eastern U.S. NPP, using Western U.S. type input, it is more likely than not that the ISS evaluation demands in the vicinity of structural predominant vibration frequencies may be considerably over-conservative. In either case, the nature of response evaluated for the Eastern U.S. NPP may be significantly different than what is expected in response to an actual Eastern U.S. earthquake of SME magnitude. (Refer to the discussions in earlier chapters concerning fundamental differences in response for Eastern U.S. and Western U.S. NPP structures).

It is clear that the best understanding of the potential severe-accident response of a nuclear power plant is obtained when the most representative severe-accident motion input is used. Consequently, the common practice of using Western U.S. type motion input to characterize the seismic threat to an Eastern U.S. NPP, for seismic evaluation and design purposes, needs to be either changed or more-carefully scrutinized relative to the particular application.

Figure 7-1. Comparisons of ISS demands in St3 produced for empirical motions with those produced for artificial motions MArS1. (a) Case-1 comparison, (b) Case-2 comparison.

Figure 7-2. Comparisons of ISS demands in St3 produced for empirical motions with those produced for artificial motions MArS1 (continued). (c) Case-3 comparison.

Figure 7-3. Comparisons of ISS demands in St7 produced for empirical motions with those produced for artificial motions MArS1. (a) Case-1 comparison, (b) Case-2 comparison.

Figure 7-4. Comparisons of ISS demands in St7 produced for empirical motions with those produced for artificial motions MArS1 (continued). (c) Case-3 comparison.

Figure 7-5. Comparisons of ISS demands in St10 produced for empirical motions with those produced for artificial motions MArS1. (a) Case-1 comparison, (b) Case-2 comparison.

Figure 7-6. Comparisons of ISS demands in St10 produced for empirical motions with those produced for artificial motions MArS1 (continued). (c) Case-3 comparison.

Figure 7-7. Comparisons of ISS demands in St3 produced for empirical motions with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.

Figure 7-8. Comparisons of ISS demands in St3 produced for empirical motions with those produced for the average of multiple artificial motions MArJl-5 (continued). (c) Case-3 comparison.

Figure 7-9. Comparisons of ISS demands in St7 produced for empirical motions with those produced for the average of multiple artificial motions MArJl-5. (a) Case-1 comparison, (b) Case-2 comparison.

Figure 7-10. Comparisons of ISS demands in St7 produced for empirical motions with those produced for the average of multiple artificial motions MArJl-5 (continued). (c) Case-3 comparison.

ISS2(St10); Empirical Vs MArJ1-5
(Motions [MSag1, MSag2, MNah3] Vs MArJ1-5(TL2r))

ISS2(St10); Empirical Vs MArJ1-5
(Motion MSag3 Versus MArJ1-5(TLr))

ISS1(St10); Empirical Vs MArJ1-5
(Motions [MSag1, MSag2, MNah3] Vs MArJ1-5(TL2r))

ISS1(St10); Empirical Vs MArJ1-5
(Motion MSag3 Versus MArJ1-5(TLr))

Figure 7-11. Comparisons of ISS demands in St10 produced for empirical motions with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.

ISS2(St10); Empirical Vs MArJ1-5
(Motion MImpl Versus MArJ1-5(TWs))

ISS1(St10); Empirical Vs MArJ1-5
(Motion MImpl Versus MArJ1-5(TWs))

Figure 7-12. Comparisons of ISS demands in St10 produced for empirical motions with those produced for the average of multiple artificial motions MArJ1-5 (continued). (c) Case-3 comparison.

Figure 7-13. Comparisons of ISS demands in St3 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.

Figure 7-14. Comparisons of ISS demands in St3 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5 (continued). (c) Case-3 comparison.

Figure 7-15. Comparisons of ISS demands in St7 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.

Figure 7-16. Comparisons of ISS demands in St7 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5 (continued). (c) Case-3 comparison.

Figure 7-17. Comparisons of ISS demands in St10 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5. (a) Case-1 comparison, (b) Case-2 comparison.

Figure 7-18. Comparisons of ISS demands in St10 produced for artificial motion MArS1 with those produced for the average of multiple artificial motions MArJ1-5 (continued). (c) Case-3 comparison.

Section 8

SUMMARY AND CONCLUSIONS

This report has documented Phase-2 research concerning the impacts of ground motion characterization on seismic evaluation studies. The specific objective of this study has been to investigate potential effects of the use artificial input time histories on typical seismic evaluation demands. For this purpose, two alternative approaches for simulating artificial motions were considered: the first (conventional) approach was based on simulation of a single motion with smooth response spectrum matching a given target spectrum, whereas the second was based on simulation of five artificial motions with jagged spectra that, when averaged, matched the given target spectrum. Eight target spectra were considered: six of these represented input specifically applicable for Eastern U.S. sites, and two of these represented input specifically applicable for Western U.S. sites.

The basic approach in this study has been to compare demands, representative of the types of results computed in actual seismic evaluation studies, for similar cases of empirical and artificial motion inputs that have been scaled to consistent levels. The evaluation results considered include maximum structural forces (and displacements), in-structure ZPA levels, and in-structure response spectra. All results have been obtained assuming linear response.

The results of comparisons considered in this study lead to development of the following conclusions:

1. Single artificial motions simulated to match Eastern U.S. target spectra have no apparent tendency to possess gaps in the energy content found in their power spectral densities. In simulating multiple artificial motions to match, on average, a given response spectrum, while maintaining realistic variations in spectral amplitude and shape, situations can be introduced that tend to produce gaps in PSDs of (isolated cases of) individual motions. Such cases arise, however, only when the target spectrum is matched very closely with a small number of motions. In addition, the spurious PSD gaps that sometimes result are found over high frequencies, and primarily for simulation of Western U.S. type motions. Furthermore, such gaps were not observed to result in deficient overall (average) response demands.

Consequently, from the observations in this study, it may be concluded that artificial motions possess PSDs generally representative of those found in real earthquake motions, for the frequency range of interest.

2. Evaluation demands computed for single artificial motions are generally similar to corresponding demands computed for empirical motions. In a limited number of comparisons with results produced for artificial motions matching Eastern U.S. target spectra, the response over higher-mode frequencies was notable under-estimated in comparison to demands produced for empirical motions. This discrepancy, however, is largely attributed to variations in the empirical motion spectra, for a given motion anchor basis, relative to the shape of the target spectrum, and to inconsistencies between the spectral shapes of individual motions and of the uniform hazard spectrum. Average evaluation demands computed for multiple artificial motions result in similar comparisons with empirical-based demands, as observed for corresponding cases of single artificial-motion input.
3. Average linear evaluation demands produced for the multiple artificial motions are similar to those produced for corresponding cases of single artificial-motion input. It is expected, however, that non-linear evaluation demands, and demands on nuclear-power-plant systems, would have greater sensitivity to this difference in characterization of motion input.
4. Fundamental differences have been observed in structural responses and ISS demands for Eastern U.S. motion inputs relative to Western U.S. motion inputs. The Eastern U.S. motions generally excite a greater degree of higher-mode response. This leads to an entirely different distribution of seismic forces than observed for Western U.S. motions and than typically assumed in seismic evaluation and design practice. The greater contribution from higher-modes leads to floor motions that are significantly greater, for a given base shear, than those observed for Western U.S. motions.

The observations made in this study support the following conclusions and recommendations. First, to produce high-frequency ISS evaluation demands adequately representative of Eastern U.S. motions, Western U.S. motions need to be scaled to levels that produce overly conservative demands in the vicinity of the fundamental-mode frequency of a structure. On the other hand, if the Western U.S. motions are not sufficiently conservative, inadequate high-frequency demands will be obtained. In either case, the use of Western U.S. motions to characterize the input to Eastern U.S. power plants, leads to misunderstanding as to the nature of seismic severe-accident

response of the NPP. Consequently, it is recommended that inputs representative of Eastern U.S. motions be used in seismic evaluation studies of Eastern U.S. NPPs.

Second, because structure and equipment responses to Eastern U.S. motions are fundamentally different than for Western U.S. motions, general understanding derived from the application of structural dynamics for Western U.S. motion inputs cannot be readily applied to the case of Eastern U.S. motions, without specific verification. Consequently, methods, criteria, and results or rules-of-thumb developed for Western U.S. motions should be either re-developed for application to Eastern U.S. motions, or at least carefully scrutinized.

Third, simplified understanding of characteristic dynamic response to earthquakes is often developed from single-degree-of-freedom (SDOF) (linear or nonlinear) response models. Because significant higher-mode response is characteristic for typical Eastern U.S. input, a SDOF model is inherently incapable of capturing simultaneous effects at the fundamental and higher modes. For instance, the consistent observation of high floor motions for a given base shear (relative to similar results observed for Western U.S. motions) is directly related to higher-mode response, and to be adequately captured, requires a multiple-degree-of-freedom (MDOF) structural model. Consequently, parameter studies used to develop simplified understanding, for design or evaluation purposes concerning Eastern U.S. buildings, need to either implement MDOF structural models directly or equivalently correct results obtained for SDOF models.

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