Code Requirements for the Selection and Scaling of Ground Motion Records

COSMOS Annual Meeting
November 18, 2005

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Presentation Topics

- Background
  - Building Codes and Source Documents
  - Response Spectra
- Code Selection and Scaling Requirements
  - Historical Perspective
  - *ASCE 7-05*
- Code-Compatible Scaling Method (Kircher)
- Scaled Records – ATC-63 (R-factor Project)
- Summary and Conclusion

Current Model Building Codes

- National:
  - *2003 IBC* - *2003 International Building Code*, International Code Council, Birmingham AL.
  - *2003 NFPA 5000* - *2003 Building Construction and Safety Code, NFPA 5000*, National Fire Protection Association, Quincy MA.
- Regional:
  - *2001 CBC* - *2001 California Building Code*, California Building Standards Commission, based on the *1997 Uniform Building Code (1997 UBC)*, International Conference of Building Officials, Whittier, CA.

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Sources of Building Code Seismic Criteria

- National:
  - *NEHRP Provisions* - *2003 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*, Federal Emergency Management Agency, FEMA 450.
  - *ASCE 7* - *Minimum Design Loads for Buildings and Other Structures*, SEI/ASCE 7-02, American Society of Civil Engineers, Reston, VA, 2003.
- Regional:
  - SEAOC *Blue Book* - *Recommended Lateral Force Requirements and Commentary, Seismology Committee*, Structural Engineers Association of California, 1996 Sixth Edition and 1999 Seventh Edition.

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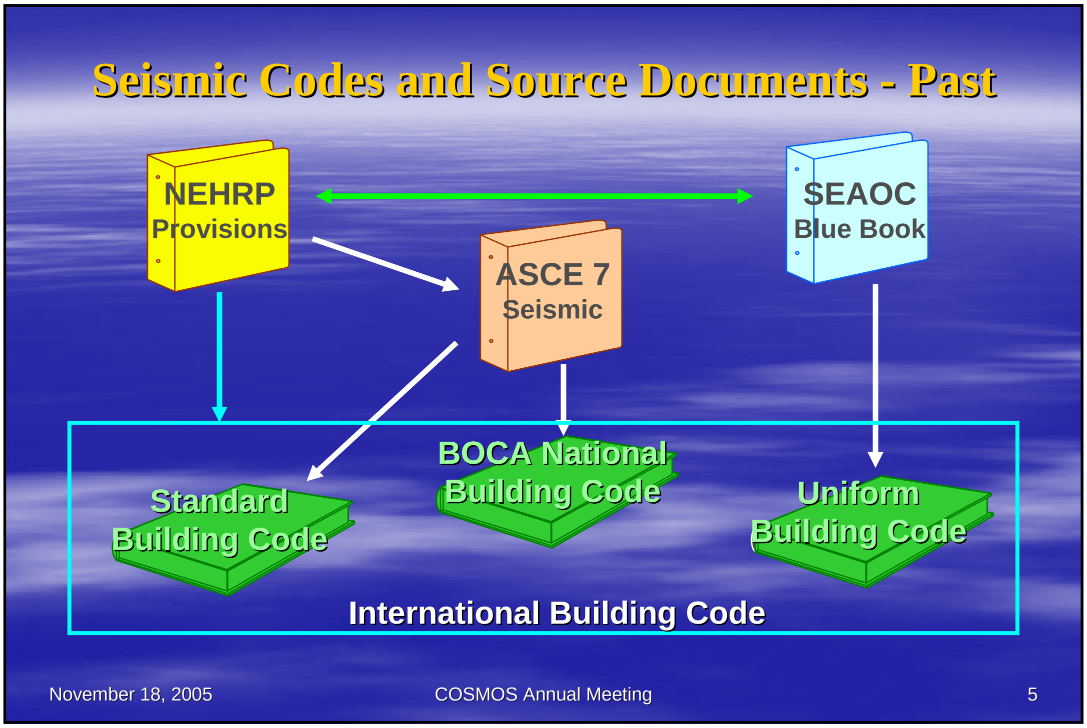
Seismic Codes and Source Documents - Past
NEHRP Provisions
SEAOC Blue Book
ASCE 7 Seismic
BOCA National Building Code
Standard Building Code
Uniform Building Code
International Building Code
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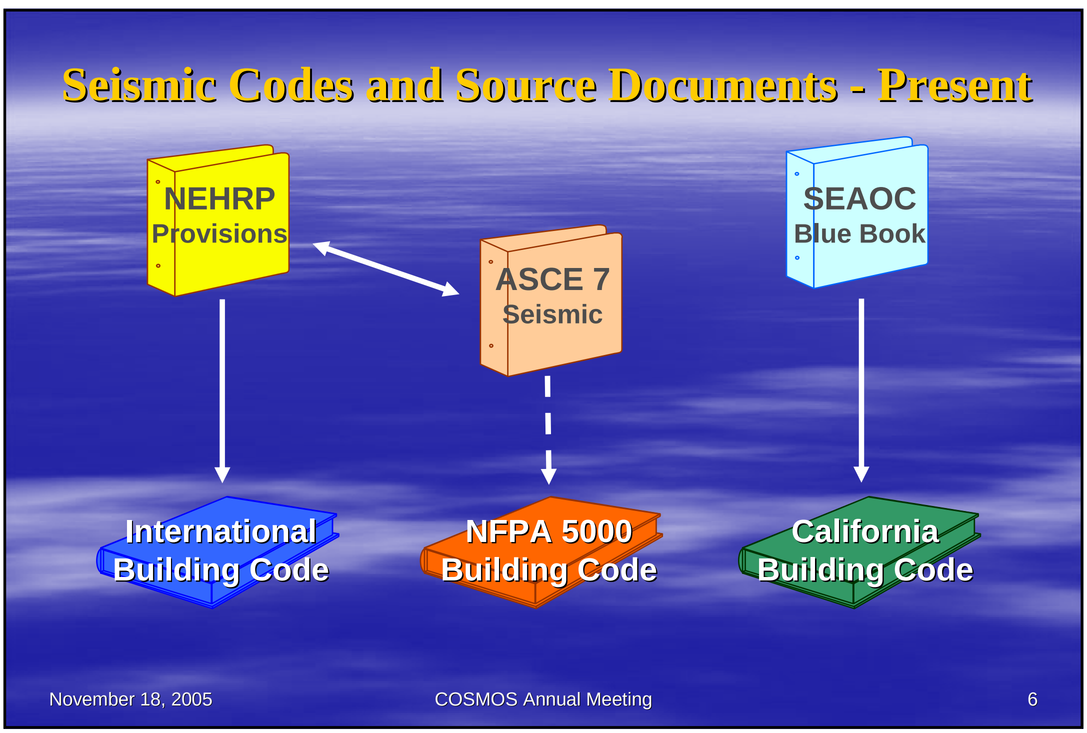
Seismic Codes and Source Documents - Present
NEHRP Provisions
SEAOC Blue Book
ASCE 7 Seismic
International Building Code
NFPA 5000 Building Code
California Building Code
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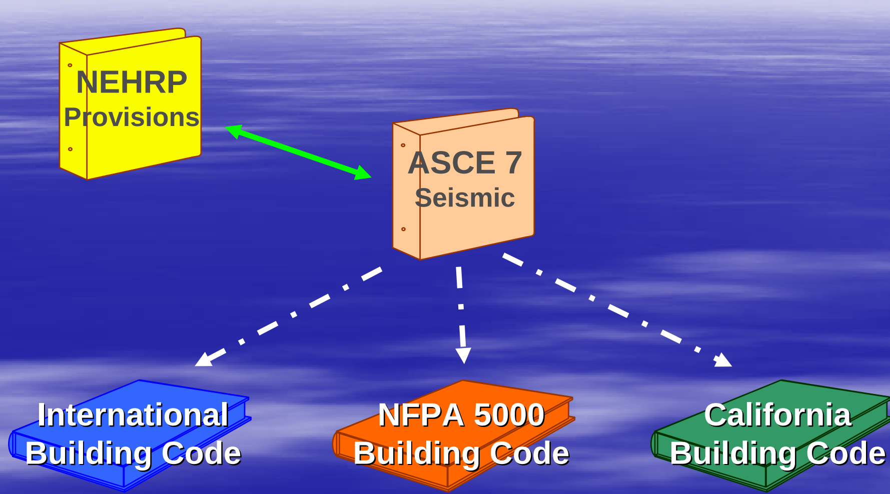
Seismic Codes and Source Documents – Future



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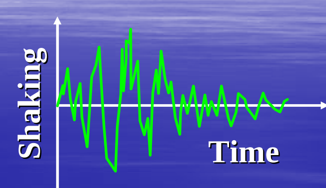
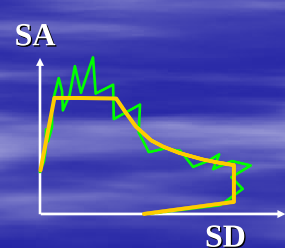
Ground Shaking Characterization

- Ground Motion Time Histories
  - Acceleration (including PGA)
  - Velocity (including PGV)
  - Displacement (including (PGD)



- Elastic Response Spectra
  - Peak response of a collection of linear single-degree-of-freedom systems with 5% viscous damping
  - “Smooth” spectra used for design (to represent many different possible ground motion time histories)



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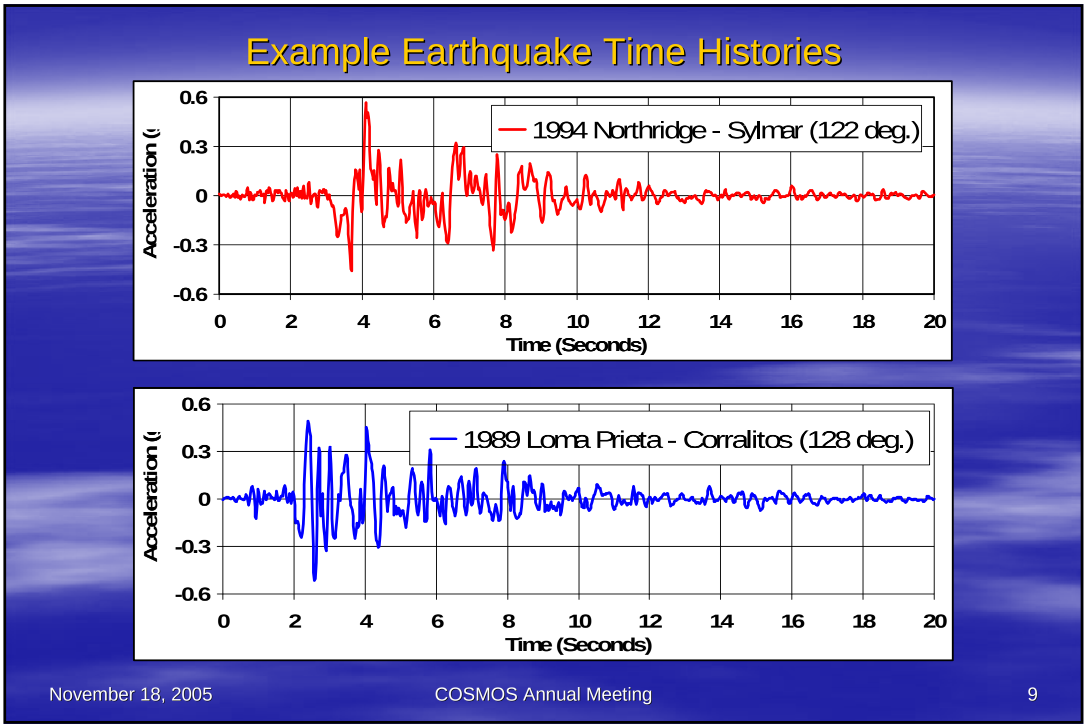
Example Earthquake Time Histories
1994 Northridge - Sylmar (122 deg.)
Acceleration (
Time (Seconds)
1989 Loma Prieta - Corralitos (128 deg.)
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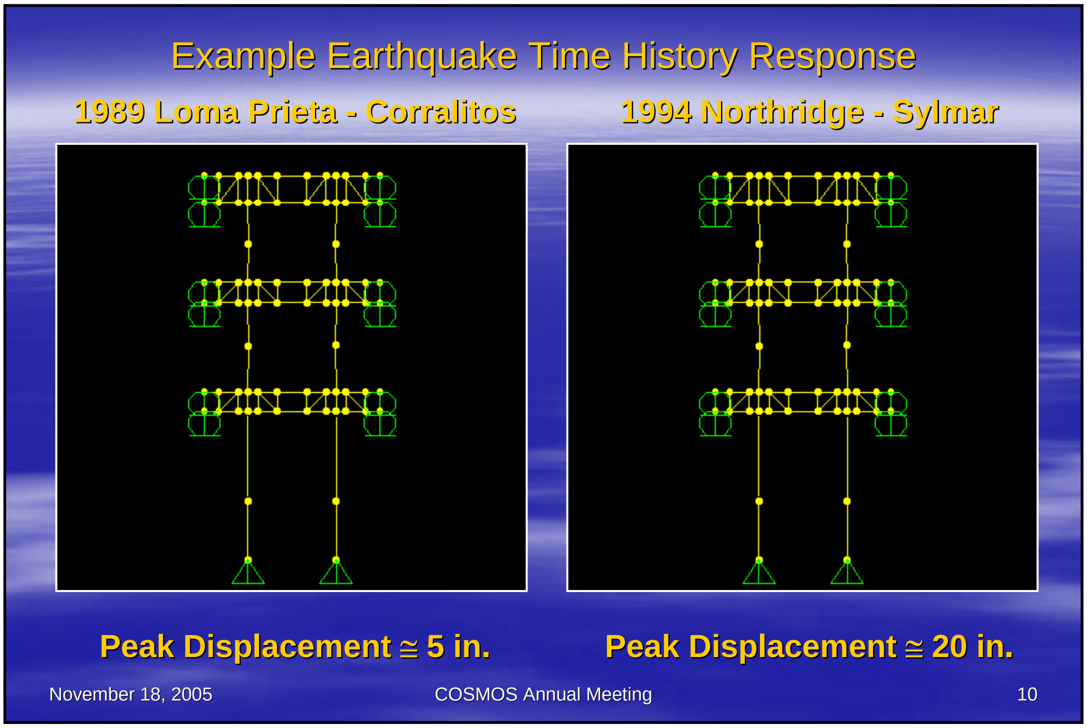
Example Earthquake Time History Response
1989 Loma Prieta - Corralitos
1994 Northridge - Sylmar
Peak Displacement ≅ 5 in.
Peak Displacement ≅ 20 in.
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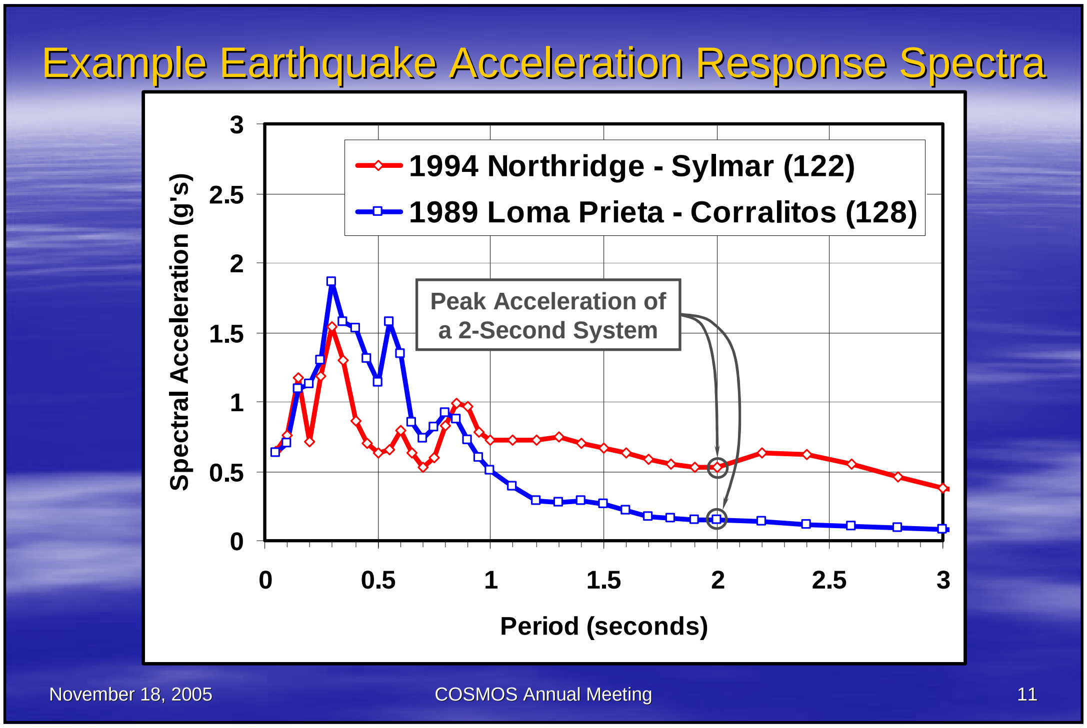
Example Earthquake Acceleration Response Spectra
1994 Northridge - Sylmar (122)
1989 Loma Prieta - Corralitos (128)
Peak Acceleration of a 2-Second System
Spectral Acceleration (g's)
Period (seconds)
0
0.5
1
1.5
2
2.5
3
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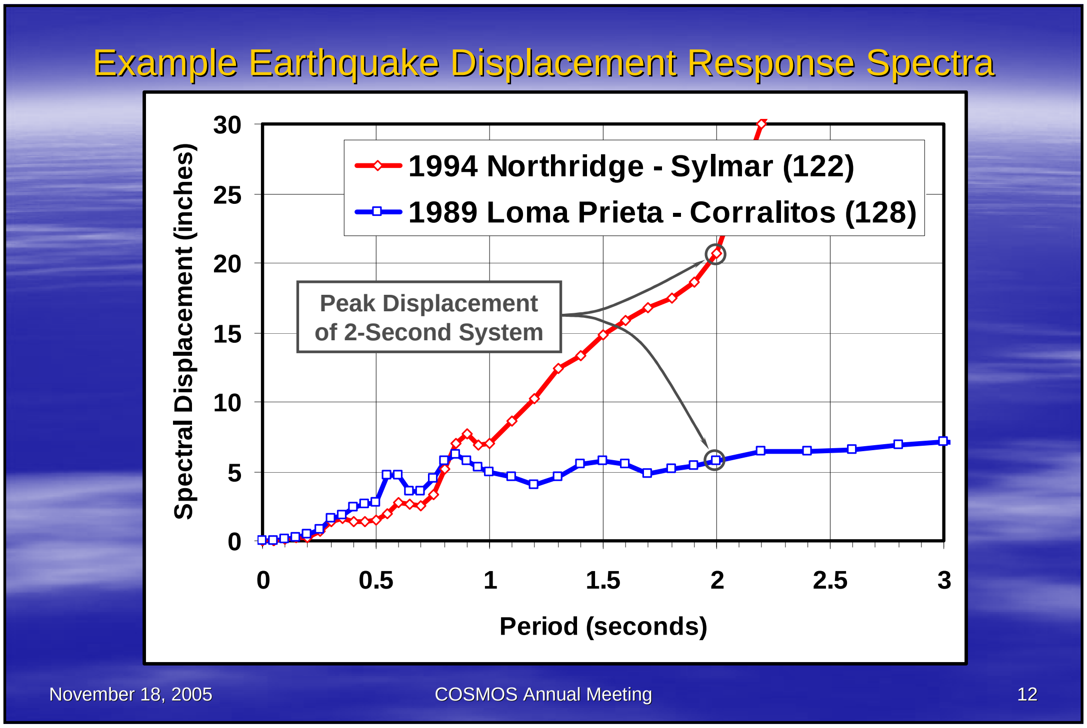
Example Earthquake Displacement Response Spectra
1994 Northridge - Sylmar (122)
1989 Loma Prieta - Corralitos (128)
Peak Displacement of 2-Second System
Spectral Displacement (inches)
Period (seconds)
0
5
10
15
20
25
30
0.5
1
1.5
2
2.5
3
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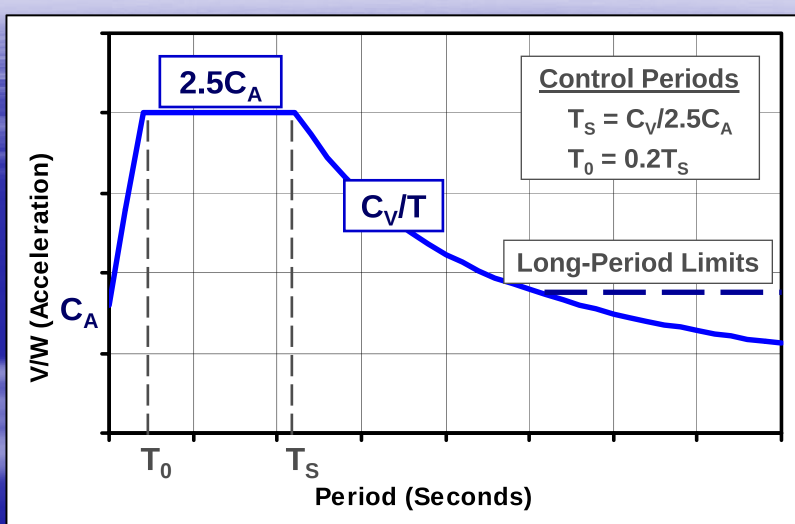
1997 UBC/2001 CBC Design Spectrum



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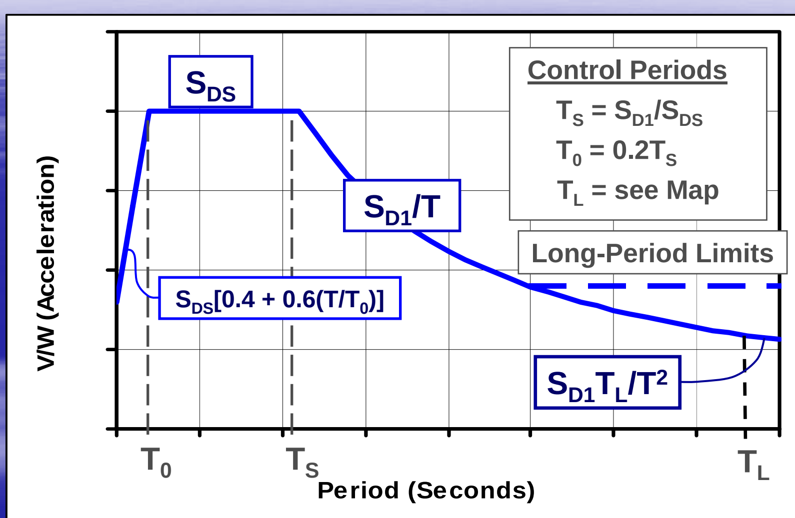
ASCE 7-05 Design Spectrum Shape



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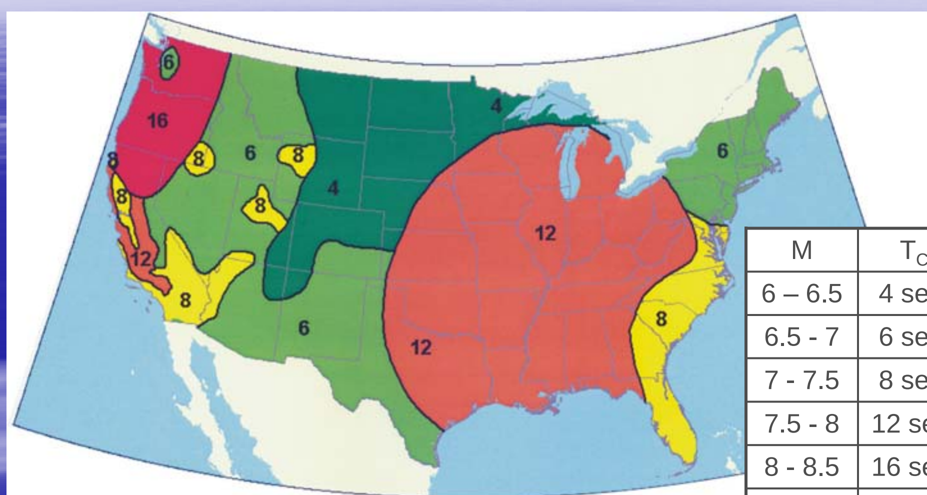
Map of Displacement Domain Transition Period, T_L



M	T_C
6 – 6.5	4 sec.
6.5 - 7	6 sec.
7 - 7.5	8 sec.
7.5 - 8	12 sec.
8 - 8.5	16 sec.
8.5 - 9+	20 sec.

Map Source: Crouse et al., "Development of Seismic Ground-Motion Criteria for the ASCE 7 Standard," *8NCEE*

Historical Perspective

- Base-Isolated Structures
  - *1990 SEAOC Blue Book,* Appendix 1L (Hart/Kircher/Romstad), Section F2b Time Histories
  - *1991 UBC,* Division III, Section 2375 (d) 2 Time Histories
  - *1994 NEHRP Provisions,* Section 2.6.4.4.2 Time Histories
- Seismic Retrofit Design Guidelines:
  - ATC-40 – *Seismic evaluation and retrofit of concrete buildings*, California Seismic Safety Commission, SSC 96-01
  - ATC-33 – *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, *FEMA-273*, October 1997 (aka *FEMA 356)*
- Conventional (Fixed-Base) Structures:
  - *2000 NEHRP Provisions* – Section 5.6.2 Ground Motion

1990 SEAOC Blue Book

- General - Section F2c. "Time Histories. Ground motion time histories developed for the specific site shall be representative of actual earthquake ground motions. Response spectra from time histories, either individually or in combination, shall approximate the site-specific design spectra …. "
- Base Isolation - Appendix 1L, Section D5b. "Time history may be used for design of any … and shall be use for design of all seismic-isolated structures …"
  - located on a soft soil profile (site factor S_4), or
  - with limited displacement capacity (e.g., moat wall limits MCE displacement to less than 1.5 times DBE displacement), or
  - with an Isolation System that has highly nonlinear and/or rate-dependent properties, weak restoring force, etc.

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1990 SEAOC Blue Book

- Base Isolation - Appendix 1L, Section F2b. "Time Histories. Pairs of horizontal ground motion time history components shall be selected from not less than three recorded events. These motions shall be scaled such that the square root sum of the squares of the 5%-damped spectrum of the scaled horizontal components does not fall below 1.3 times the 5%-damped spectrum of the DBE (or MCE) by more than 10% in the period range of … T_I minus 1.0 seconds to T_I plus 2.0 seconds.
  - (1) The duration of the time histories shall be consistent with the magnitude and source characteristics of the DBE (or MCE).
  - (2) Time histories developed for sites within 15 km of a major active fault shall incorporate near-fault phenomena."

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1990 SEAOC Blue Book

- Base Isolation - Appendix 1L, Section F5d. "Time History Analysis.
  - (1) Time history analysis shall be performed with at least three appropriate pairs of horizontal time history components …
  - (2) Each pair of time histories shall be applied simultaneously to the model, considering the most disadvantageous location of mass eccentricity.
  - (3) The maximum response of the parameter of interest calculated by the three time history analyses shall be used for design."
- *1994 UBC* (*1994 NEHRP Provisions*) and later editions thereof:
  - "If seven or more time-history analyses are performed, then the average value of the response parameter of interest may be used for design."

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ATC-40 – Selection of Acceleration Time Histories

- Not less than three pairs of horizontal components (set of seven is recommended and required for averaging response results)
- Selection of Recorded Earthquakes:
  - Magnitude, source characteristics and site-source distance consistent with magnitude, source characteristics and distance, respectively, that dominates hazard at site.
  - Site characteristics same as site conditions of building.
  - When appropriate recorded time history are not available, simulated ground motion time history pairs may be used to make up the total number.
- Each pair of components should have appropriate duration (considering site-source distance, basin effects, etc.) and contain near-source pulses (for sites within 10 km of active faults).

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ATC-40 – Scaling of Acceleration Time Histories

- Each pair of components should be scaled in the time domain such that the average value of the spectra of all scaled time histories matches the site response spectrum over the period range of interest.
- Period range of interest includes periods at or near "effective period" of the performance point (period corresponding to peak nonlinear response) and periods of higher modes, if such are being considered in the analysis.
- *Commentary* – "*A ground motion expert should assist the structural engineer in the selection and scaling of appropriate time histories.*"

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ATC-40 Earthquake Ground Motion Records

- Two sets of 10 earthquake records identified as suitable candidates for time history analysis of buildings (at soil sites) with ground shaking of 0.2 g, or greater, EPA:
  - Records at soil sites greater than 10 km from sources
  - Records at soil sites near sources.
- Selection criteria (used to identify candidate records):
  - Free-field station (or ground floor of small building)
  - Stiff or medium stiff soil site conditions
  - Large-magnitude earthquake ($M \geq 6.5$)
  - Peak ground acceleration of at least 0.2g (before scaling)
- Ground motion expert (for record selection) – Bill Joyner (USGS)

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ATC-40 – Candidate Records at Soil Sites Greater than 10 km from Sources

Table 4-9. Earthquake Records at Soil Sites Greater Than 10 Km from Sources

	Earthquake Source			Earthquake Recording	
No.	Magnitude	Year	Earthquake	Station Name	Owner
1	7.1	1949	Western Washington	Station 325	USGS[1]
2	6.5	1954	Eureka, California	Station 022	USGS
3	6.6	1971	San Fernando, California	Station 241	USGS
4	6.6	1971	San Fernando, California	Station 458	USGS
5	7.1	1989	Loma Prieta, California	Hollister, South & Pine	CDMG[2]
6	7.1	1989	Loma Prieta, California	Gilroy #2	CDMG
7	7.5	1992	Landers, California	Yermo	CDMG
8	7.5	1992	Landers, California	Joshua Tree	CDMG
9	6.7	1994	Northridge, California	Moorpark	CDMG
10	6.7	1994	Northridge, California	Century City LACC North	CDMG

1. USGS: United State Geological Survey
2. CDMG: California Division of Mines and Geology

ATC-40 – Candidate Records at Soil Sites Near Sources

Table 4-10. Earthquake Records at Soil Sites Near Sources

	Earthquake Source			Earthquake Recording	
No.	Magnitude	Year	Earthquake	Station Name	Owner
1	6.5	1979	Imperial Valley, California	El Centro Array Station 6	USGS[1]
2	6.5	1979	Imperial Valley, California	El Centro Array Station 7	USGS
3	7.1	1989	Loma Prieta, California	Corralitos	CDMG[2]
4	7.1	1989	Loma Prieta, California	Capitola	CDMG
5	6.9	1992	Cape Mendocino, California	Petrolia	CDMG
6	6.7	1994	Northridge, California	Newhall Fire Station	CDMG
7	6.7	1994	Northridge, California	Sylmar Hospital	CDMG
8	6.7	1994	Northridge, California	Sylmar Converter Station	LADWP[3]
9	6.7	1994	Northridge, California	Sylmar Converter Sta. East	LADWP
10	6.7	1994	Northridge, California	Rinaldi Treatment Plant	LADWP

1. USGS: United States Geological Survey
2. CDMG: California Division of Mines and Geology
3. LADWP: Los Angeles Department of Water and Power

ASCE 7-05

- Chapter 16 – Seismic Response History Procedures (Generic)
  - Section 16.1.3.1 – Two-Dimensional Analysis (i.e. 1 horizontal)
  - Section 16.1.3.2 – Three-dimensional Analysis (horizontal pair)
    - Not less than three pairs (nor less seven pairs for averaging of response results) of actual recorded events (if available)
    - Magnitude, fault distance and source mechanism consistent with those that control MCE
    - Equal scaling of the two components of each horizontal pair
    - Average of the SRSS spectra (of each horizontal pair) not less than 1.3 times the design spectrum by more than 10% at each period between 0.2T and 1.5T
- Chapter 17 – Seismically Isolated Structures
  - Section 17.3.2 – Ground Motion Histories – Same as Section 16.1.3.2, except period range of $0.5T_D$ to $1.25T_M$

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Code-Consistent Time History Scaling Procedure

Definitions (Input Data):

n	Number of horizontal time history pairs to be scaled (i.e., 3 pairs minimum, 7 pairs if average response is to be used for design).
PGV_{ji}	Peak ground velocity, PGV, of time history, TH_{ji}.
RS_{ji}	Response spectrum (5% damping) of time history, TH_{ji}.
TRS	Target response spectrum defined as 1.3 times the DBE (or 1.3 times the MCE).
T_I	Period of isolated structure in seconds.

Definitions (Calculated Data):

ARS	Response spectrum shape of time histories taken as the mean of composite response spectra, CRS_i, normalized by composite peak ground velocity, $CPGV_i$.
$CPGV_i$	Composite peak ground velocity of the ith horizontal time history pair.
CRS_i	Composite response spectrum of the ith horizontal time history pair.
M_{ARS}	Response spectrum multiplier used to fit the response spectrum shape, ARS, to the target response spectrum, TRS.
STH_{ji}	Scaled time history of the ith pair in the jth horizontal direction.

Calculation Steps:

1. For each pair of earthquake components, calculate the composite spectrum, CRS_i, and the composite peak ground velocity, $CPGV_i$:

$$CRS_i = \sqrt{(RS_{1i}^2 + RS_{2i}^2)} \qquad CPGV_i = \sqrt{(PGV_{1i}^2 + PGV_{2i}^2)}$$

2. Find the average value of composite spectra normalized by composite peak ground velocity:

$$ARS = \frac{1}{n}\sum \frac{CRS_i}{CPGV_i}$$

3. Determine the response spectrum multiplier, M_{ARS}, that is required to increase (or decrease) the response spectrum shape, ARS, such that it does not fall below the target response spectrum, TRS, by more than 10% in the period range of T_I - 1 second to T_I + 2 seconds:

$$M_{ARS} = \frac{TRS}{ARS} \qquad (t = T_I - 1 \text{ second to } T_I + 2)$$

4. For each pair of earthquake time histories, scale both horizontal components by the ratio of the response spectrum multiplier to the composite peak ground velocity:

$$STH_{1i} = \left(\frac{M_{ARS}}{CPGV_i}\right)TH_{1i} \qquad STH_{2i} = \left(\frac{M_{ARS}}{CPGV_i}\right)TH_{2i}$$

- Procedure initially developed (by Kircher) for nonlinear time history analysis of base-isolated hospitals in the early 1990's
- Procedure "normalizes" records by PGV to account for differences in magnitude, distance, etc. of records
- Period range: T_I - 1 second to T_I + 2 seconds based on *1991 UBC (should be updated to match current Code criteria)*
- Random orientation of horizontal components should be rotated to fault normal/fault parallel directions for scaling to spectra that incorporate effects of directivity, etc. (i.e., for sites near active faults).

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ATC-63 – Selection and Scaling of Records

- Project Application – Scaled records must be broadly applicable to many different sites across the U.S. (and to all structure types).
- Selection criteria (e.g., for set of “soil/non-near-fault” records)
  - Soil Sites – (stiff or medium soil site conditions)
  - Sites not near-source (station >= 10 km from fault rupture)
  - Free-field instrument stations (or ground floor of small buildings)
  - Large-magnitude events (M ≥ 6.5) – consistent with MCE
  - Strong-motion records (PGA ≥ ≈0.2 g, PGV ≥ ≈15 cm/sec., before scaling) – consistent with MCE
  - No more than two records from each event (e.g., records with largest PGV) – too avoid record bias by event
- Scale records using “Code” method (with PGV normalization) – except match median value of the spectra of scaled records to 100% of MCE demand (arbitrarily set at $S_{M1} = F_vS_1 = 0.9$ g).

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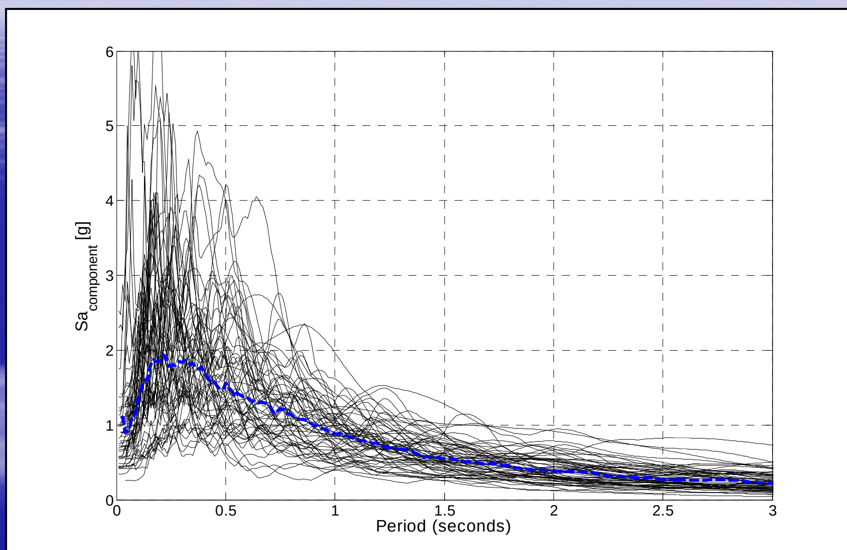
ATC-63 - Median and Individual Spectra of 60 Components Scaled (by “Code” method) to match MCE Spectrum at $S_{M1} = 0.9$g



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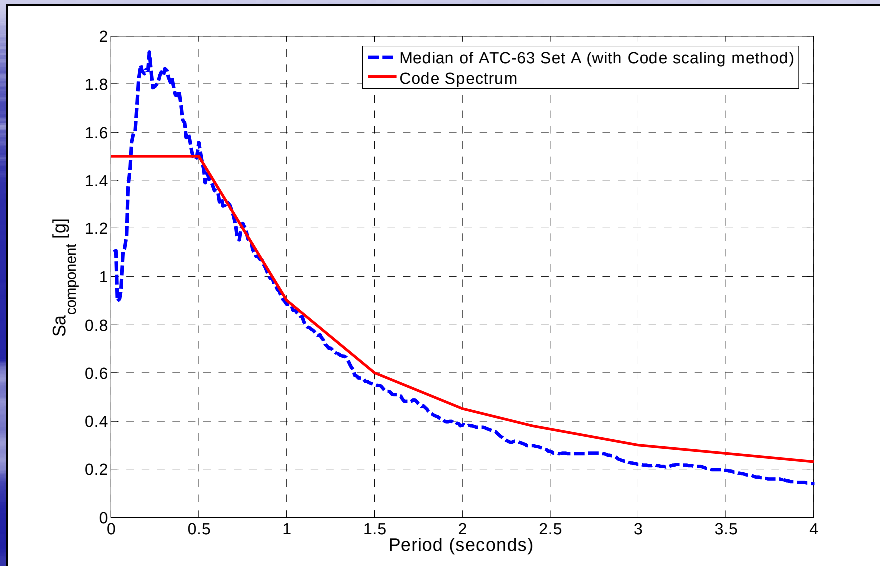
ATC-63 – Comparison of Median Spectrum of 60 Scaled Components and MCE Spectrum (S_{M1} = 0.9g)



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Summary and Conclusion

- Seismic Codes, such as *ASCE 7-05*, have well established methods for selecting and scaling earthquake records (aka time histories) to match DBE and/or MCE design response spectra
  - Methods have evolved slightly, but are essentially the same as those first developed by SEAOC for base-isolated structures (as contained in Appendix 1L of the 1990 SEAOC *Blue Book*)
- Primary difficulty with (time-domain) scaling records is the requirement to envelop (within 10%) design response spectra over a broad range of periods (and frequency-domain scaling is not considered a desirable alternative to time-domain scaling)
  - Possible solution (when a sufficiently large number of records are used – e.g., at least 7 records) – Scale records to match a specific period of interest (e.g., S_{M1} or dominant period of structure) and use more liberal matching criteria at other periods

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