NORTHRIDGE 20 SYMPOSIUM

Ground Motion Prediction Equations: Developments and Advancements since 1994

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Ground motion prediction equations

- GMPEs
- "Ground motion models"
- Used to be named "Attenuation" relations
- Scaling models of ground motions with respect to magnitude, distance, site conditions, …
- For active tectonic regions, the models are mainly based on "observations", i.e., recorded ground motions

Some key milestones in development of GMPEs

- 1964 Luis Esteva & Emilio Rosenblueth

$$a = c\exp(\alpha M)R^{-\beta}$$

- 1970 Esteva

$$a = c_1 e^{c_2 M}(R + c_3)^{-c_4}$$

- 1978 Sadigh, et al.

$$\ln y = \ln A + BM_s + E\ln[R + d\exp(fM_s)]$$

- 1981 Campbell

$$\mathrm{PGA} = a\exp(bM)[R + c_1\exp(c_2 M)]^{-d}$$

- 1981 Joyner and Boore

$$\log y = \alpha + \beta \mathrm{M} - \log r + br$$

$$\text{where } r = (d^2 + h^2)^{1/2}$$

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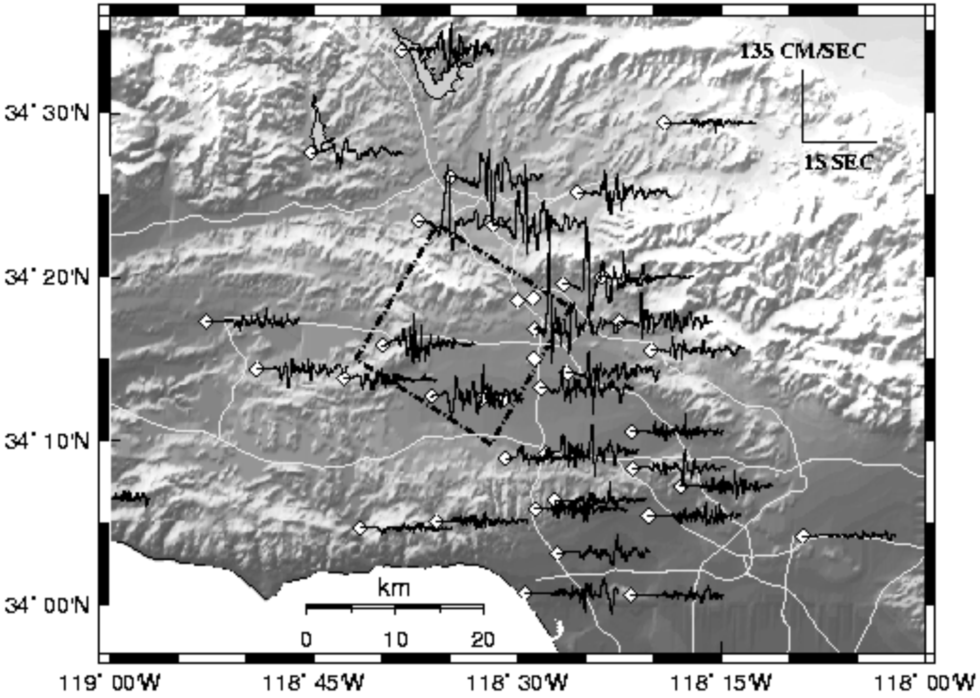
1994 Northridge earthquake

- Provided a well-recorded set of ground motions
- Still one of the important Reverse faulting EQs that provided a contrast between hanging wall and footwall ground motions



Source: http://pasadena.wr.usgs.gov/office/wald/CUREe.html

What we knew in 1994

- Distance measure: Distance to the fault (Joyner & Boore distance, seismogenic distance)
- Soil condition was considered important
  - It was mainly classified as "hard rock", "stiff soil", "rock", "soil"
  - Boore et al. just started using scaling with V_{S30}
- Style of faulting was recognized as important
- Concept of "magnitude saturation" was acceptable by some researchers

Following the Northridge EQ

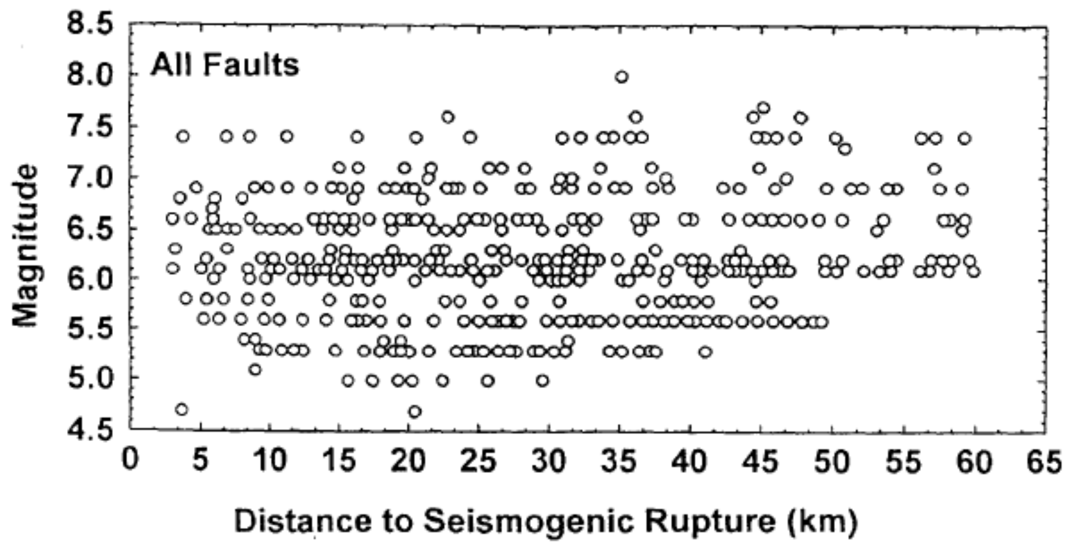
- Major advances in the development of GMPEs have been through the NGA project(s)
- **NGA** = **N**ext **G**eneration **A**ttenuation relations
- PEER compiled a very comprehensive **database** of ground motions recorded in **shallow crustal earthquakes in active tectonic regions**

NGA-West1 & NGA-West2

- NGA-West1 Initiated October 2003
- In 2008, NGA-West1 GMPEs were finalized
- In 2008 USGS adopted the NGA-West1 GMPEs for the US National Seismic Hazard Maps
- NGA-West2 is a follow-up of NGA-West1

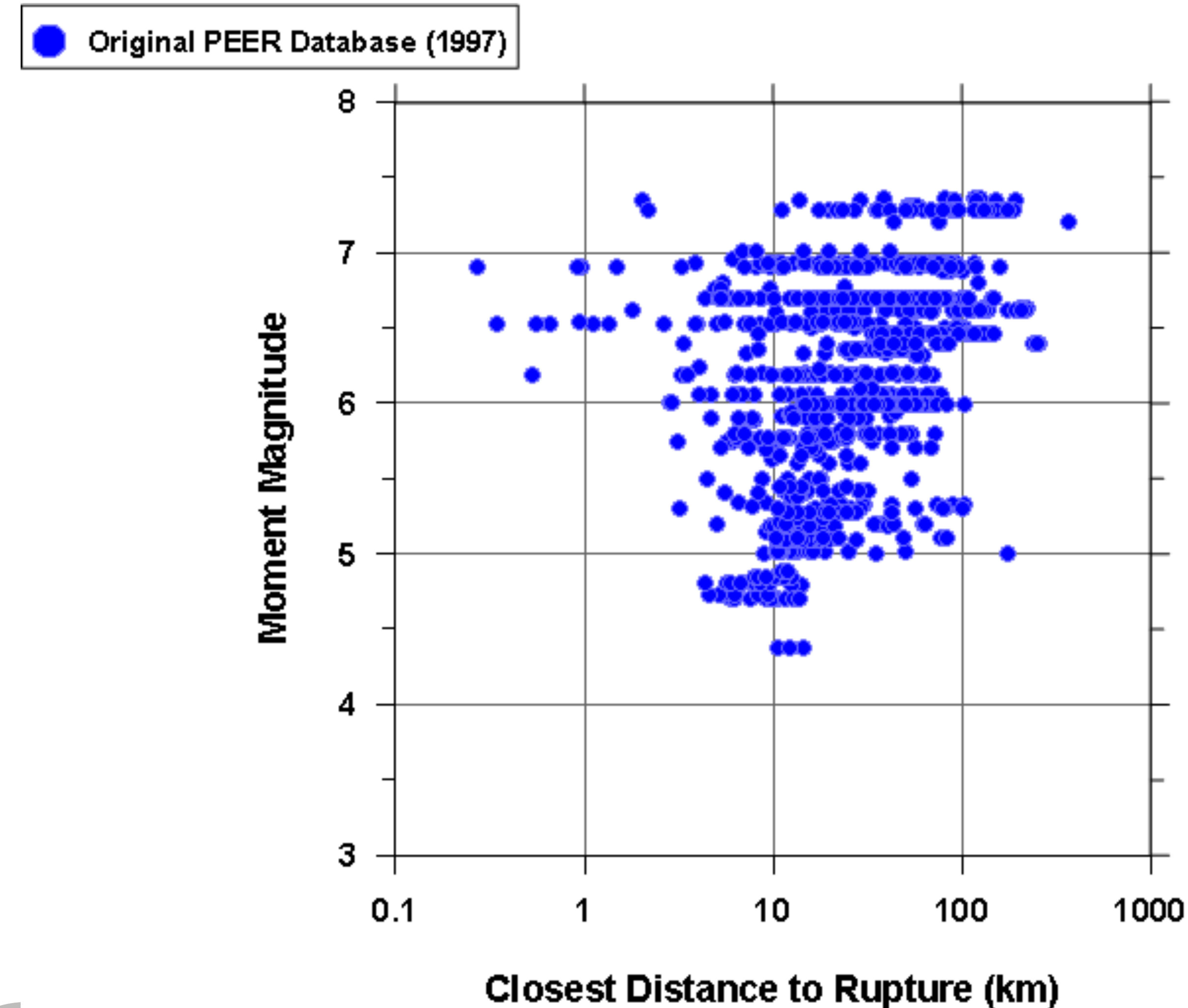
In 1994, a typical database was

- Horizontal components: **645 recordings** in 47 EQs
- Vertical components: **225 recordings** in 26 EQs



Reference: Campbell and Bozorgnia, 1994

Evolution of ground motion database since 1994



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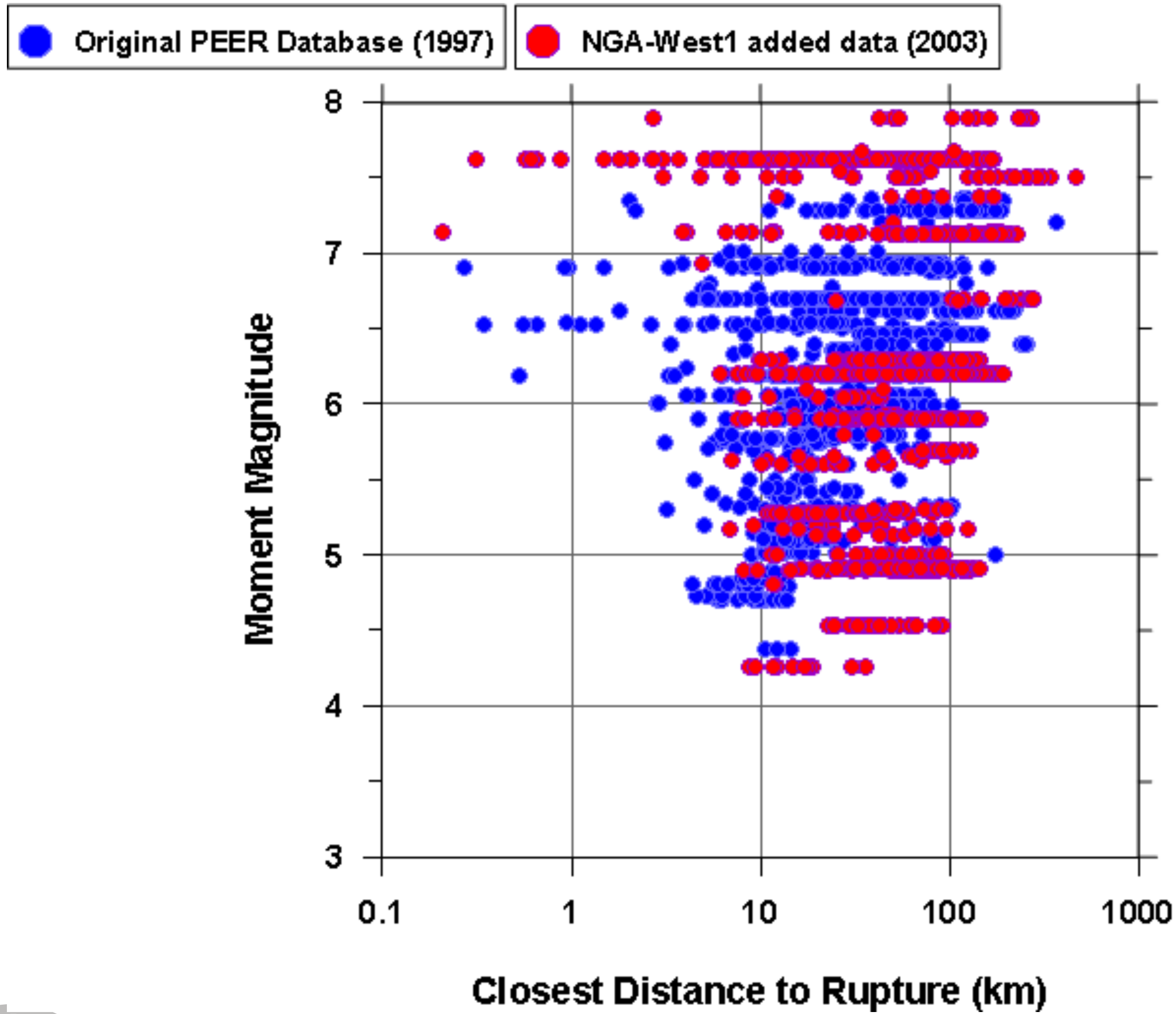
Evolution of ground motion database since 1994



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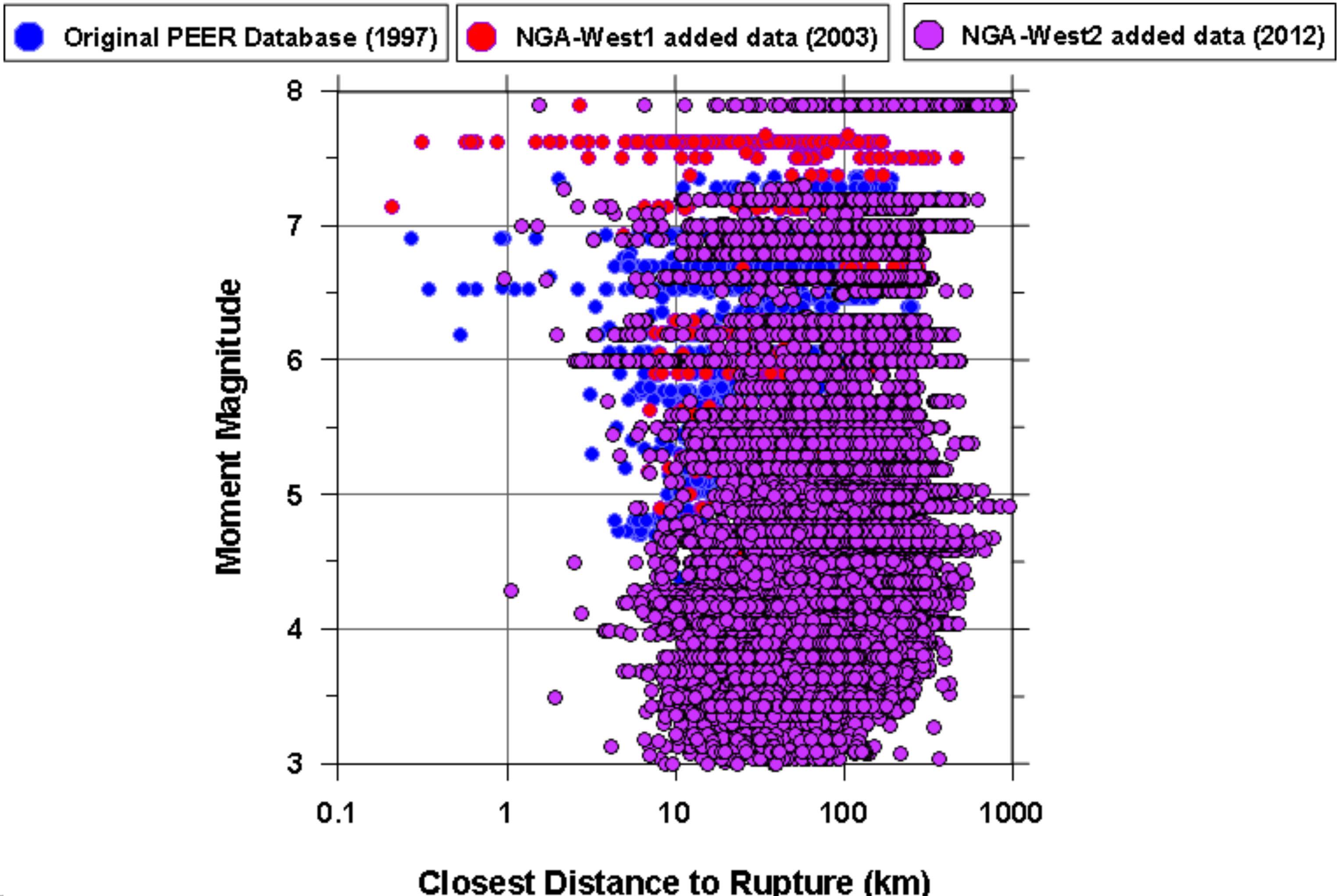
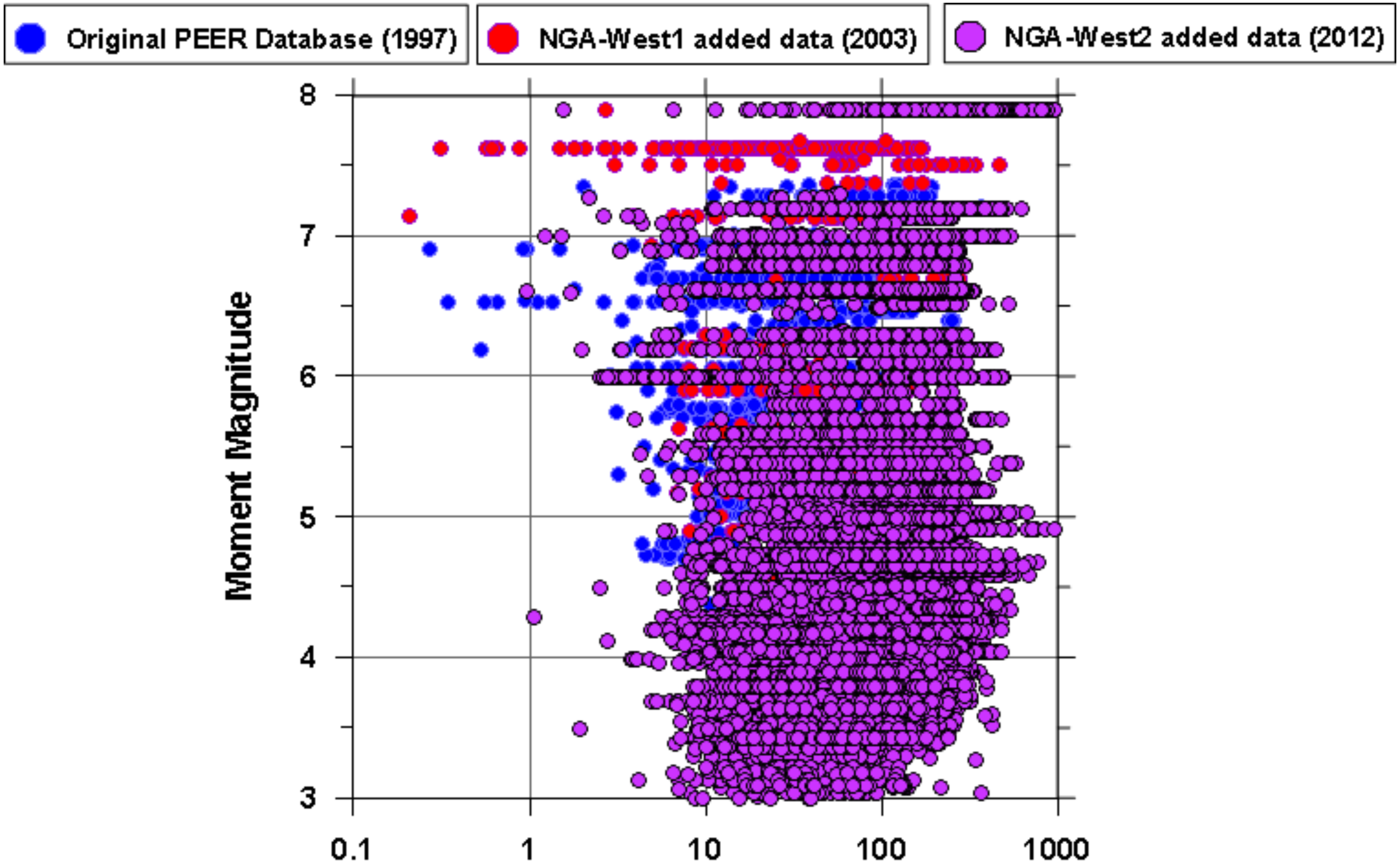
Evolution of ground motion database since 1994



Evolution of ground motion database since 1994



NGA-West2 database includes over 21,000 three-component recordings… (over 63,000 records)

Database evolution: As an example

- Campbell and Bozorgnia selected databases:
  - 1994 database: **645 recordings** (from 47 EQs)
  - 2014 database: **15,521 recordings** (from 322 EQs)
  - Database size **increased by a factor of 24**

Availability of databases in 1994 vs 2014

- In 1994: Most of the ground motion databases were not public
  - Individual teams had their own databases
- In 2014: NGA databases are shared among the GMPE developers and also available to the public
  - Full transparency
  - Much higher quality
  - Avoiding duplication
  - Making it available for other applications

2014 NGA-West2 database “flatfiles”

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Record Sequence Number	EQID	Earthquake Name	YEAR	MODY	HRMN	Station Name	Station Sequence Number	Station ID No.	Earthquake Magnitude	Magnitude Type	Magnitude Uncertainty: Kagan Model	Magnitude Uncertainty: Statistical
2	1	0001	Helena, Montana-01	1935	1031	1838	Carroll College	197	2022	6.00	Mw	0.3000	-999
3	2	0002	Helena, Montana-02	1935	1031	1918	Helena Fed Bldg	198	2229	6.00	U	0.3000	-999
4	3	0003	Humbolt Bay	1937	0207	0442	Ferndale City Hall	133	1023	5.80	Mw	0.3000	-999
5	4	0004	Imperial Valley-01	1938	0606	0242	El Centro Array #9	75	117	5.00	U	0.3000	-999
6	5	0005	Northwest Calif-01	1938	0912	0610	Ferndale City Hall	133	1023	5.50	Mw	0.3000	-999
7	6	0006	Imperial Valley-02	1940	0519	0437	El Centro Array #9	75	117	6.95	Mw	0.3000	0.072
8	7	0007	Northwest Calif-02	1941	0209	0945	Ferndale City Hall	133	1023	6.60	U	0.3000	-999
9	8	0008	Northern Calif-01	1941	1003	1614	Ferndale City Hall	133	1023	6.40	U	0.3000	-999
10	9	0009	Borrego	1942	1021	1622	El Centro Array #9	75	117	6.50	U	0.3000	-999
11	10	0010	Imperial Valley-03	1951	0124	0717	El Centro Array #9	75	117	5.60	U	0.3000	-999
12	11	0011	Northwest Calif-03	1951	1008	0411	Ferndale City Hall	133	1023	5.80	Mw	0.3000	-999
13	12	0012	Kern County	1952	0721	1153	LA - Hollywood Stor FF	326	24303	7.36	Mw	0.3000	0.145
14	13	0012	Kern County	1952	0721	1153	Pasadena - CIT Athenaeum	499	80053	7.36	Mw	0.3000	0.145
15	14	0012	Kern County	1952	0721	1153	Santa Barbara Courthouse	92	283	7.36	Mw	0.3000	0.145
16	15	0012	Kern County	1952	0721	1153	Taft Lincoln School	148	1095	7.36	Mw	0.3000	0.145
17	16	0013	Northern Calif-02	1952	0922	1141	Ferndale City Hall	133	1023	5.20	Mw	0.3000	-999
18	17	0014	Southern Calif	1952	1122	0746	San Luis Obispo	147	1083	6.00	U	0.3000	-999
19	18	0015	Imperial Valley-04	1953	0614	0417	El Centro Array #9	75	117	5.50	U	0.3000	-999
20	19	0016	Central Calif-01	1954	0425	2033	Hollister City Hall	135	1028	5.30	U	0.3000	-999
21	20	0017	Northern Calif-03	1954	1221	1956	Ferndale City Hall	133	1023	6.50	U	0.3000	-999
22	21	0018	Imperial Valley-05	1955	1217	0607	El Centro Array #9	75	117	5.40	U	0.3000	-999

- Data and Metadata can be downloaded

In 1994

- Typical functional form of GMPEs

$$\ln Y = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_V \ln \frac{V_S}{V_A}$$

$$b_1 = \begin{cases} b_{1SS} & \text{for strike-slip earthquakes;} \\ b_{1RS} & \text{for reverse-slip earthquakes;} \\ b_{1ALL} & \text{if mechanism is not specified.} \end{cases}$$

$$r = \sqrt{r_{jb}^2 + h^2}$$

In 2014

$$\ln Y = \begin{cases} \ln PGA; & PSA < PGA \text{ and } T < 0.25 \text{ s} \\ f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed} + f_{hyp} + f_{dip} + f_{atn}; & \text{otherwise} \end{cases}$$

$$f_{mag} = \begin{cases} c_0 + c_1\mathbf{M}; & \mathbf{M} \le 4.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M}-4.5); & 4.5 < \mathbf{M} \le 5.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M}-4.5) + c_3(\mathbf{M}-5.5); & 5.5 < \mathbf{M} \le 6.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M}-4.5) + c_3(\mathbf{M}-5.5) + c_4(\mathbf{M}-6.5); & \mathbf{M} > 6.5 \end{cases}$$

$$f_{dis} = (c_5 + c_6\mathbf{M})\ln\left(\sqrt{R_{RUP}^2 + c_7^2}\right)$$

$$f_{flt} = f_{flt,F} f_{flt,M}$$

$$f_{flt,F} = c_8 F_{RV} + c_9 F_{NM}$$

$$f_{flt,M} = \begin{cases} 0; & \mathbf{M} \le 4.5 \\ \mathbf{M} - 4.5; & 4.5 < \mathbf{M} \le \\ 1; & \mathbf{M} > 5.5 \end{cases}$$

$$f_{hng} = c_{10} f_{hng,R_X} f_{hng,R_{RUP}} f_{hng,M} f_{hng,Z} f_{hng,\delta}$$

$$f_{hng,R_X} = \begin{cases} 0; & R_X < 0 \\ f_1(R_X); & 0 \le R_X < R_1 \\ \max[f_2(R_X), 0]; & R_X \ge R_1 \end{cases}$$

$$f_1(R_X) = h_1 + h_2(R_X/R_1) + h_3(R_X/R_1)^2$$

$$f_2(R_X) = h_4 + h_5\left(\frac{R_X - R_1}{R_2 - R_1}\right) + h_6\left(\frac{R_X - R_1}{R_2 - R_1}\right)^2$$

$$R_1 = W\cos(\delta)$$

$$R_2 = 62\mathbf{M} - 350$$

$$f_{hng,R_{RUP}} = \begin{cases} 1; & R_{RUP} = 0 \\ (R_{RUP} - R_{JB}) / R_{RUP}; & R_{RUP} > 0 \end{cases}$$

$$\begin{cases} 0; & \mathbf{M} \le 5.5 \end{cases}$$

$$f_{site} = f_{site,G} + S_J f_{site,J}$$

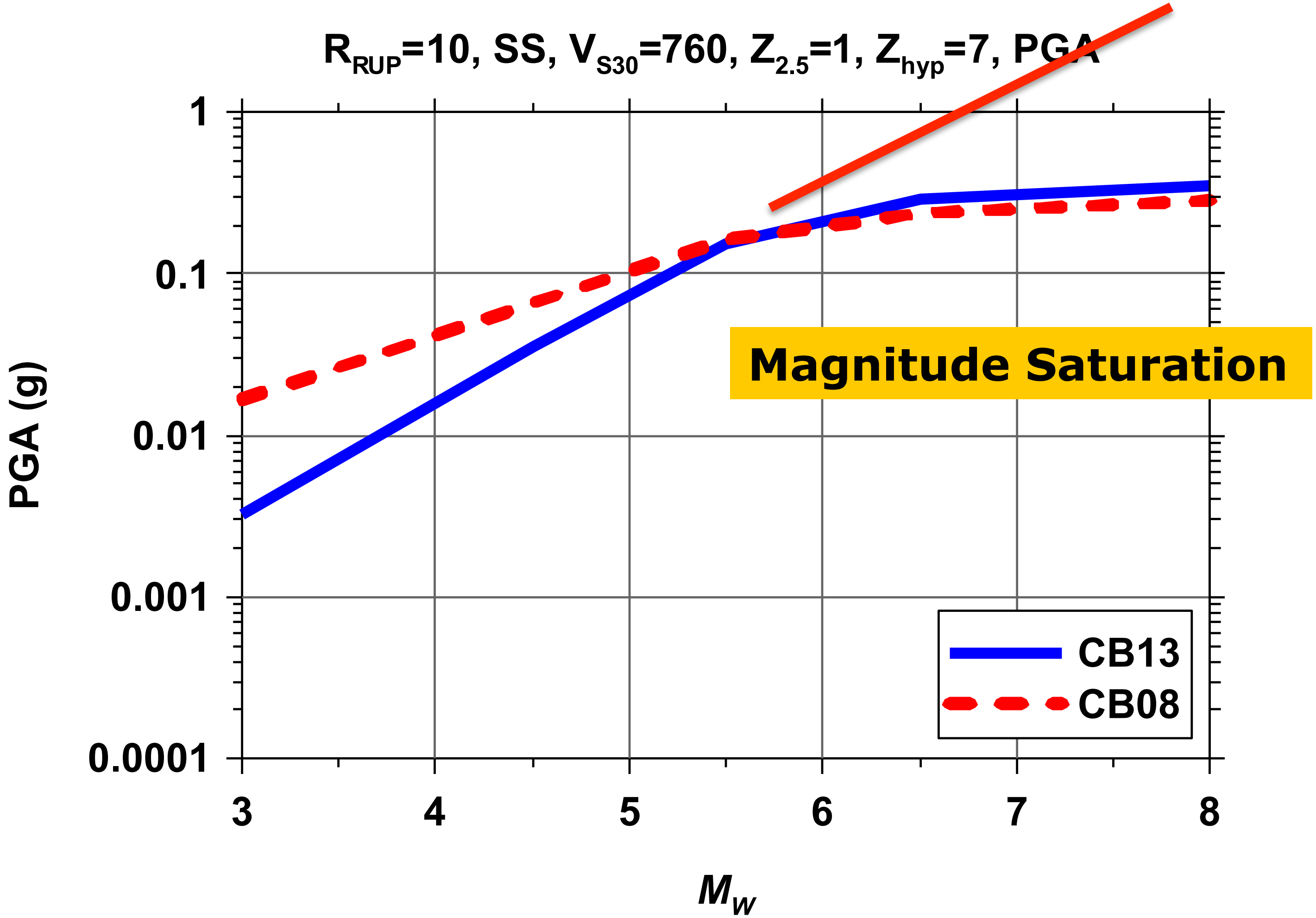
$$f_{site,G} = \begin{cases} c_{11}\ln\left(\frac{V_{S30}}{k_1}\right) + k_2\left\{\ln\left[A_{1100} + c\left(\frac{V_{S30}}{k_1}\right)^n\right] - \ln \right. \\ (c_{11} + k_2 n)\ln\left(\frac{V_{S30}}{k_1}\right); \end{cases}$$

$$f_{site,J} = \begin{cases} (c_{12} + k_2 n)\left[\ln\left(\frac{V_{S30}}{k_1}\right) - \ln\left(\frac{200}{k_1}\right)\right]; \\ (c_{13} + k_2 n)\ln\left(\frac{V_{S30}}{k_1}\right); \end{cases}$$

In 2014

- **Most** GMPEs are applicable to:
  - M: 3 to 8.5 (strike-slip)
  - Distance: 0 to 300km
  - Hanging wall and footwall sites
  - Soil V_{S30}: 150-1500 m/sec
  - Soil nonlinearity
  - Deep basins
  - Strike-slip, Reverse, Normal faulting mechanisms
  - Period: 0-10 seconds

In 2014: Magnitude "saturation" at short periods is now a common feature

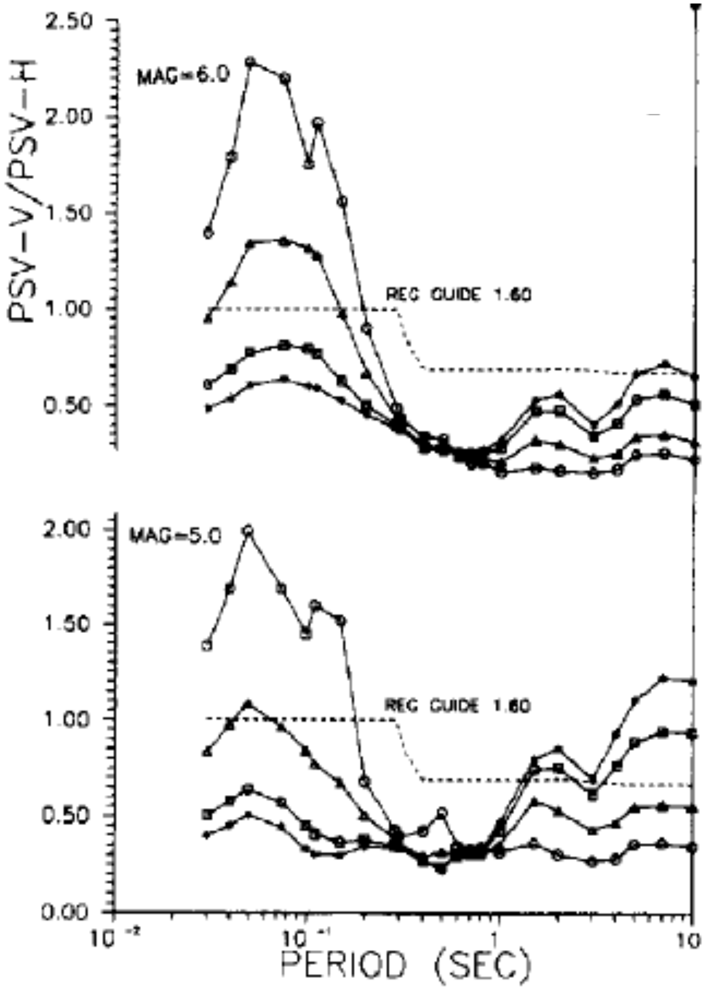


In 1994

- After the Northridge EQ, vertical ground motion attracted attention of engineers because of:
  - High vertical accelerations recorded and,
  - Collapse of bridges and a department store

In 1994 we knew…

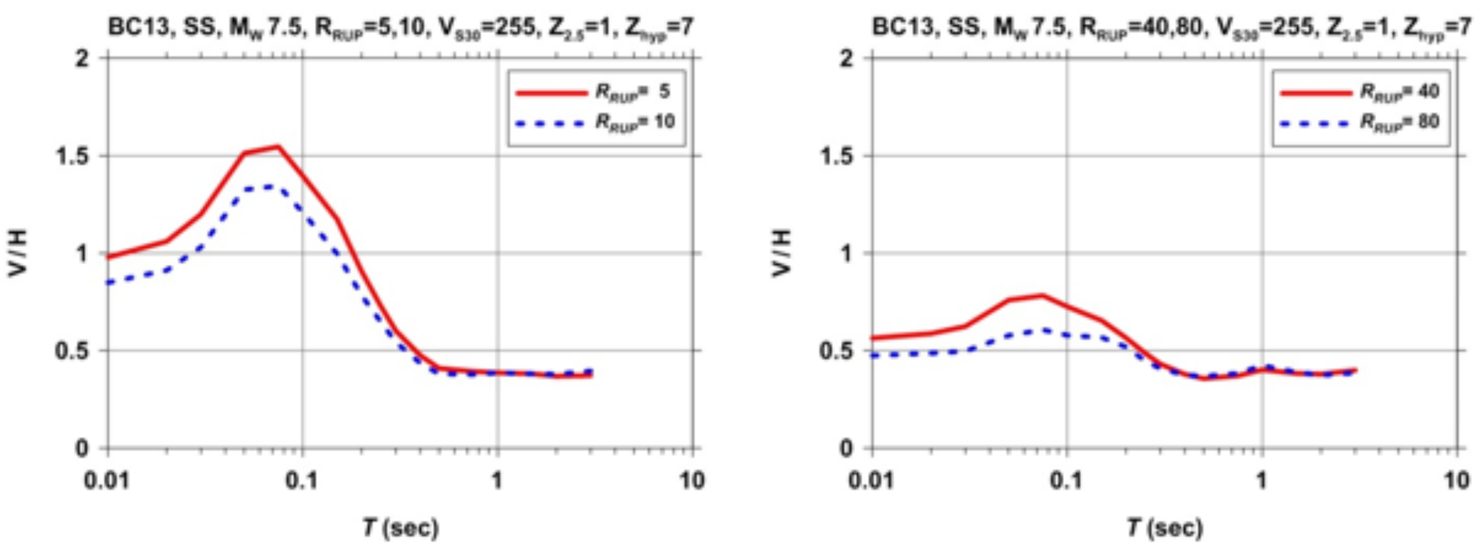
- Vertical / Horizontal spectral ratio (V/H)
  - Is a strong function of distance and period
  - Should not use 2/3 as a scaling factor for V/H



Reference: Niazi & Bozorgnia, 1992

In 2014

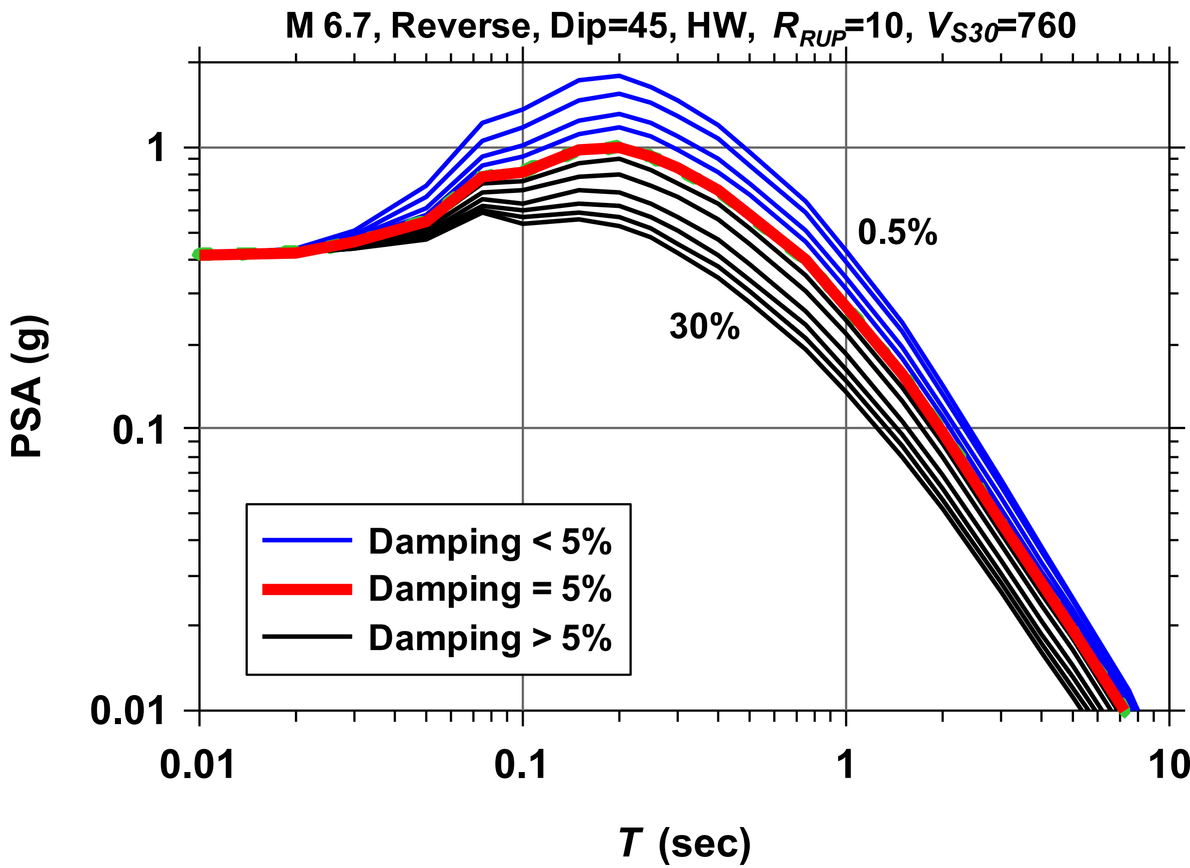
- We have a set of vertical GMPEs as part of NGA-West2
- Qualitatively consistent with previous work
- Much more robust predictions



In 2014: We have robust damping scaling model for response spectra

- To scale horizontal and vertical GMPEs for damping other than 5%:

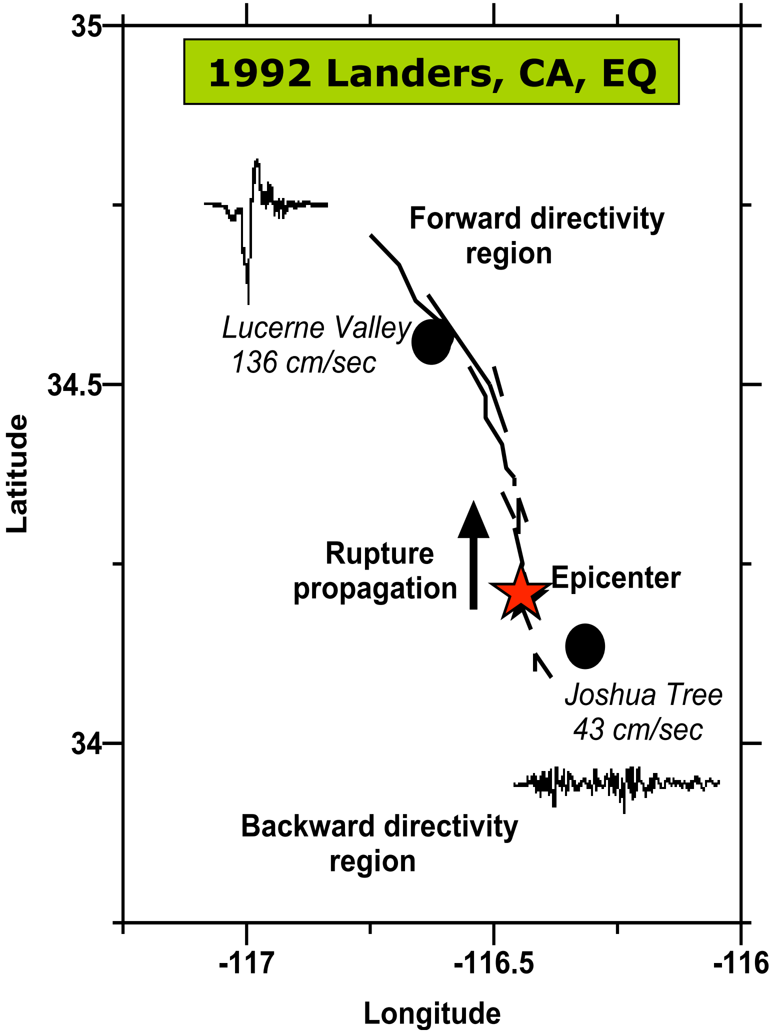
  0.5% to **30%**



Reference: Rezaeian et al. (2012)

In 2014: Directivity

- We have five directivity models developed in NGA-West2
  - Wide-band and narrow-band models
- This effort will continue



In 2014: Directionality of ground motion

- We now know:
- Only for the cases when the site is **within 5 km of the fault** and **spectral period is longer than 0.5 sec**, is the orientation of maximum rotated spectral ordinate is more likely to be closer to the **strike-normal** than the strike-parallel direction
- Beyond these ranges, the **angle** of the maximum rotated motion **is random**

Ref: Shahi and Baker, PEER report 2013/10

In 2014: After decades, new NEHRP site factors are proposed

Table 11.4-1 Site Coefficient, F_a

Site Class	Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at Short Period					
	$S_S \leq 0.25$	$S_S = 0.5$	$S_S = 0.75$	$S_S = 1.0$	$S_S = 1.25$	$S_S \geq 1.5$
A	0.8	0.8	0.8	0.8	0.8	0.8
B	~~1.0~~ 0.9	~~1.0~~ 0.9	~~1.0~~ 0.9	~~1.0~~ 0.9	~~1.0~~ 0.9	0.9
C	~~1.2~~ 1.3	~~1.2~~ 1.3	~~1.1~~ 1.2	~~1.0~~ 1.2	~~1.0~~ 1.2	1.2
D	1.6	1.4	1.2	1.1	1.0	1.0
E	~~2.5~~ 2.4	1.7	~~1.2~~ 1.3	~~0.9~~ 1.1	~~0.9~~ 1.0	0.8
F	See Section 11.4.7					

Note: Use straight-line interpolation for intermediate values of S_S. At the Site Class B-C boundary, F_a = 1.0 for all S_s levels. If site classes A or B are established without the use of on-site measurements of shear wave velocity, use F_a = 1.0.

Courtesy: Jon Stewart & Emel Seyhan

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In 2014: New NEHRP site factors are proposed

Table 11.4-2 Site Coefficient, F_v

Site Class	Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at 1-s Period					
	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 = 0.5$	$S_1 \geq 0.6$
A	0.8	0.8	0.8	0.8	0.8	0.8
B	~~1.0~~ 0.8	~~1.0~~ 0.8	~~1.0~~ 0.8	~~1.0~~ 0.8	~~1.0~~ 0.8	0.8
C	~~1.7~~ 1.5	~~1.6~~ 1.5	1.5	~~1.4~~ 1.5	~~1.3~~ 1.5	1.4
D	2.4	~~2.0~~ 2.2	~~1.8~~ 2.0	~~1.6~~ 1.9	~~1.5~~ 1.8	1.7
E	~~3.5~~ 4.2	~~3.2~~ 3.3	2.8	2.4	~~2.4~~ 2.2	2.0
F	See Section 11.4.7					

Note: Use straight-line interpolation for intermediate values of S_1. At the Site Class B-C boundary, F_v = 1.0 for all S_1 levels. <u>If site classes A or B are established without the use of on-site measurements of shear wave velocity, use F_v = 1.0.</u>

Courtesy: Jon Stewart & Emel Seyhan

1994 vs 2014

- In 1994: Interactions among GMPE developers were relatively small

- In 2014: There are great constructive interactions among:
  - GMPE developers
  - Other junior and senior researchers
  - Practitioners
  - End users
  - Earth scientists and Engineers

In 2014: GMPE development is now like putting together pieces of a complicated puzzle through a coordinated multidisciplinary Team Work

Results have much higher quality, and more impacts at the national and international levels

2014 and beyond

- **NGA-West3**
  - Expanding the ranges of applicability of GMPEs
    - Soil with $\boldsymbol{V_{S30}}$<200 m/sec
    - Hard rock with $\boldsymbol{V_{S30}}$>1000 m/sec
  - Refinement of directivity modeling issues
  - Foreshock, mainshock, aftershock issues
  - More advancement in the prediction of vertical ground motion
  - Beyond elastic response spectra
  - Refining estimation of standard deviation ("single-station sigma")

2014 and beyond

- **NGA-East**
  - For stable continental regions
  - 2015
- **NGA-Sub**
  - For subduction regions
  - 2016

Thank You!