The Northridge Earthquake - 30 Years Later

A Catalyst for Engineering Resilient Communities

2024 Webinar Series

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Series Partners:

- American Society of Civil Engineers (ASCE) Infrastructure Resilience Division
- ASCE Los Angeles Section
- Earthquake Engineering Research Institute (EERI) Southern California Chapter
- Structural Engineers Association of Southern California (SEOASC)
- Earthquake Country Alliance (ECA), led by the Statewide California Earthquake Center

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Episode 1: The January 17, 1994 Northridge Earthquake – Science & Engineering Aspects
K. Hudnut, J. Stewart, C. Davis, D. Cocke
EarthquakeCountry.org/northridge30-webinar1/

Episode 2: Insurance Issues and Impacts Following the Northridge Earthquake
C. Scawthorn, J. Maffei
EarthquakeCountry.org/northridge30-webinar2/

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Episode 3: 30 Years of Progress in Quantification of Seismic Hazards

Yousef Bozorgnia
Professor, Department of Civil and Environmental Engineering, &
Director, Natural Hazards Risk and Resiliency Research Center (NHR3), UCLA

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Episode 3: 30 Years of Progress in Quantification of Seismic Hazards

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Outline

- Progress in **ground motion** databases, models, hazard: From 1994 to 2024
- Advancement in **fault displacement** hazard quantification
- Summary

- Before we begin, I would like to apologize for not mentioning all important contributions in the last 30 years

Progress in ground motion models (GMMs)

- "Ground motion models" (GMMs)…also known as GMPEs
- They are scaling models of ground motions with respect to magnitude, distance, site conditions, …
- For active tectonic regions, the models are mainly based on observations or empirical data, i.e., recorded ground motions

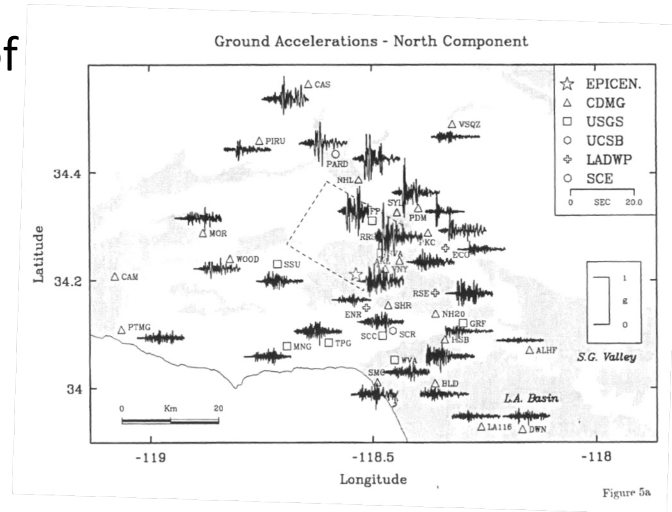
Some historical milestones in developments of GMMs

- 1964 Esteva & Rosenblueth: $a = c\exp(\alpha M)R^{-\beta}$
- 1970 Esteva: $a = c_1\exp(c_2 M)(R + c_3)^{-c_4}$
- 1978 Sadigh, et al.: $\ln(y) = \ln A + BM_S + E\ln[R + d\exp(fM_S)]$
- 1981 Campbell: $PGA = a\exp(bM)[R + c_1\exp[(c_2 M)]^{-d}$
- 1981 Joyner & Boore: $\log y = \alpha + \beta M - \log r + br \; ; r = (d^2 + h^2)^{1/2}$

For sure there more important contributions

1994 Northridge earthquake

- ❖ Provided a well-recorded set of ground motions
- ❖ An important Reverse faulting EQ that provided a contrast between hanging wall and footwall ground motions

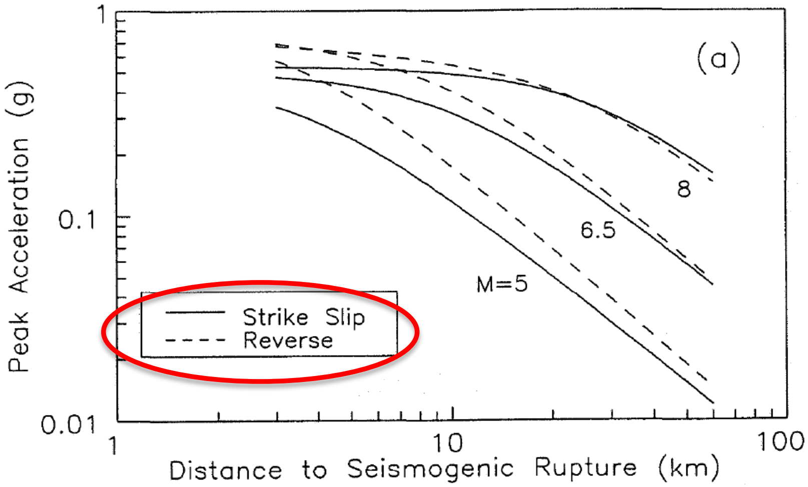


Source: **Wald and Heaton** (1994). Open-File Report 94-278

What we had in 1994

- ❖ Distance measures: Joyner & Boore distance, seismogenic distance,…
- ❖ Soil condition was considered important
  - – It was mainly classified as “hard rock”, “soft rock”, “stiff soil”, “soil”
  - – Boore et al. started using scaling with V_{S30}
- ❖ Concept of “magnitude saturation” was acceptable by some researchers

In 1994: Style of faulting was recognized as important



NEAR-SOURCE ATTENUATION OF PEAK HORIZONTAL ACCELERATION FROM WORLDWIDE ACCELEROGRAMS RECORDED FROM 1957 TO 1993

K. W. Campbell[1] and Y. Bozorgnia[2]

Abstract

We have used 645 near-source accelerograms from 47 worldwide earthquakes of magnitude 4.7 and greater recorded from 1957 to 1993 to develop an updated strong-motion attenuation relationship for peak horizontal ground acceleration. Based on this analysis, we have found that: (1) reverse and thrust earthquakes generate peak accelerations that are higher than those from strike-slip earthquakes at short distances, with this effect becoming less important at longer distances and larger magnitudes, (2) peak accelerations on rock are higher than those on alluvium at short distances and less than those on alluvium at longer

1994 vs 2024

- In 1994 era, the traditional seismic hazard research projects were mainly individual or a small group of researchers
- Interactions among GMM developers were relatively minor
- We now have major expansion of **community-based** research projects
- Community-based programs broke the "walls" between research teams
- Research teams learn from each other

1994 vs 2024

- In 2024: There are great constructive interactions among:
  - Most modelers
  - Junior and senior researchers
  - Practitioners
  - End users
- ➔These interactions result in higher quality of data and models
- There are also "some" interactions among ground motion experts and Engineers!...we need much more

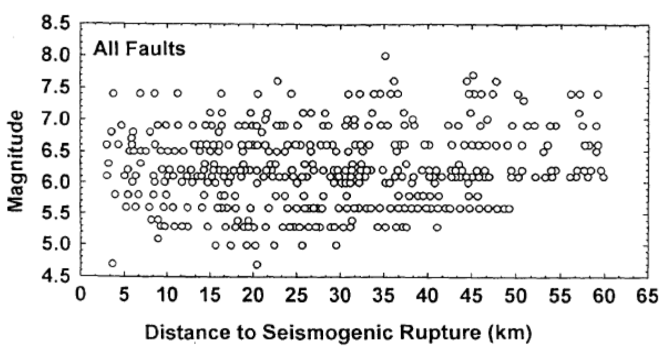
Examples of major technical progress on ground motion modeling

For shallow crustal EQs: NGA-West1 & NGA-West2

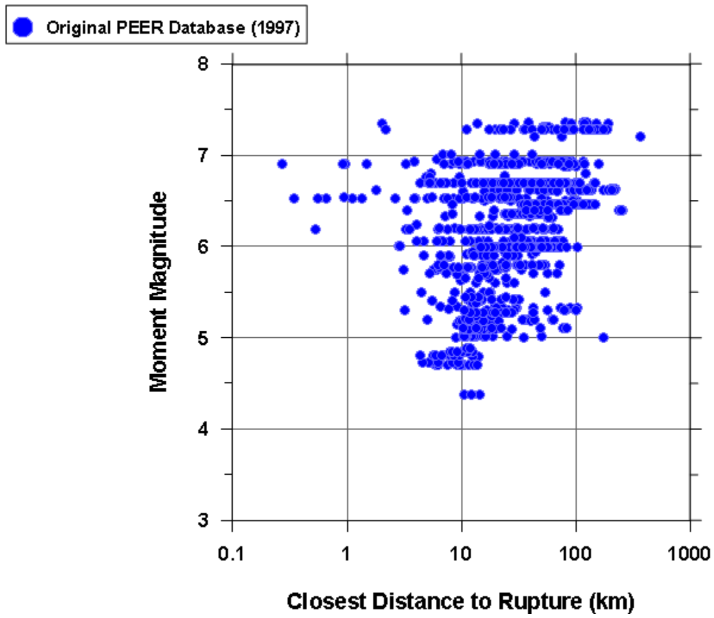
- ❖ NGA-West(1) Initiated in October 2003
- ❖ In 2008, NGA-West GMMs were finalized
- ❖ In 2008 USGS adopted the NGA-West GMMs for the US National Seismic Hazard Maps
- ❖ NGA-West2 was a follow-up of NGA-West
  - – Completed in 2014

In 1994, a typical database was…

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



Evolution of ground motion database: 1997



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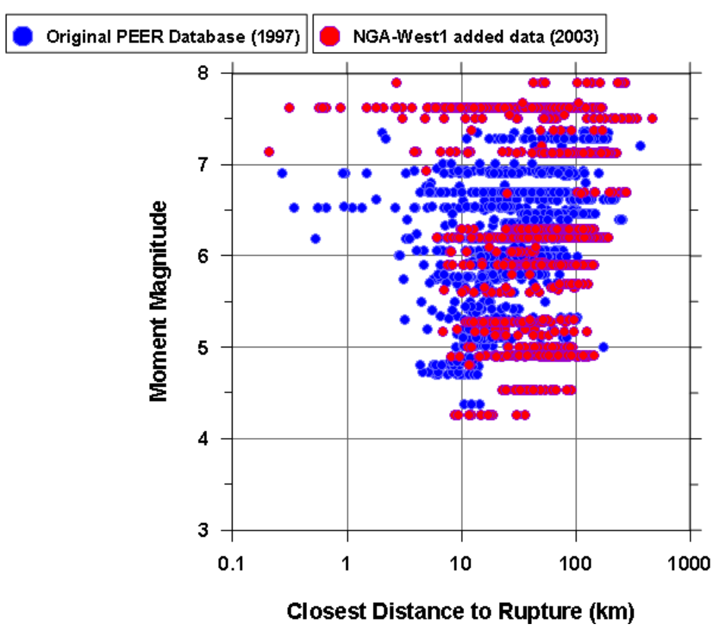
Evolution of ground motion database: NGA-West



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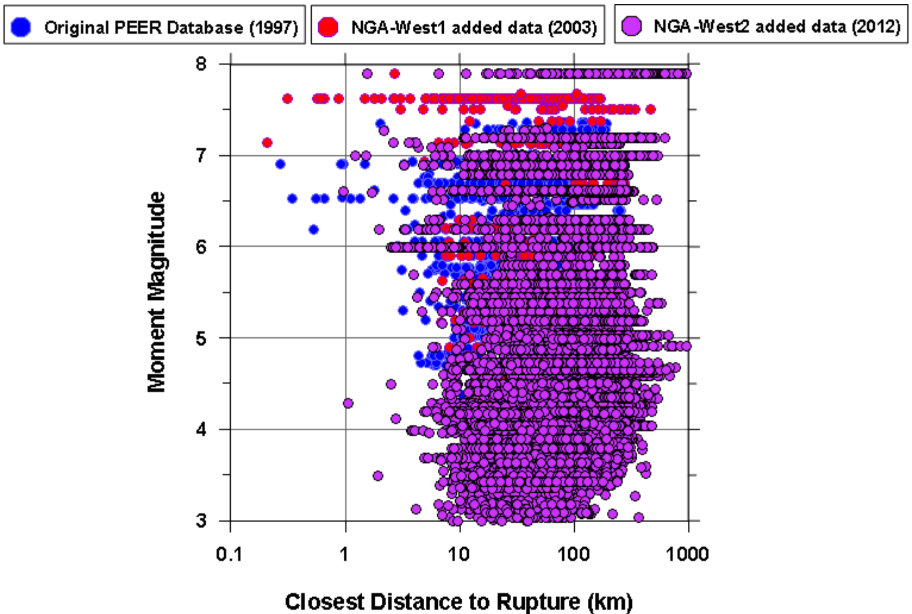
Evolution of ground motion database: NGA-West



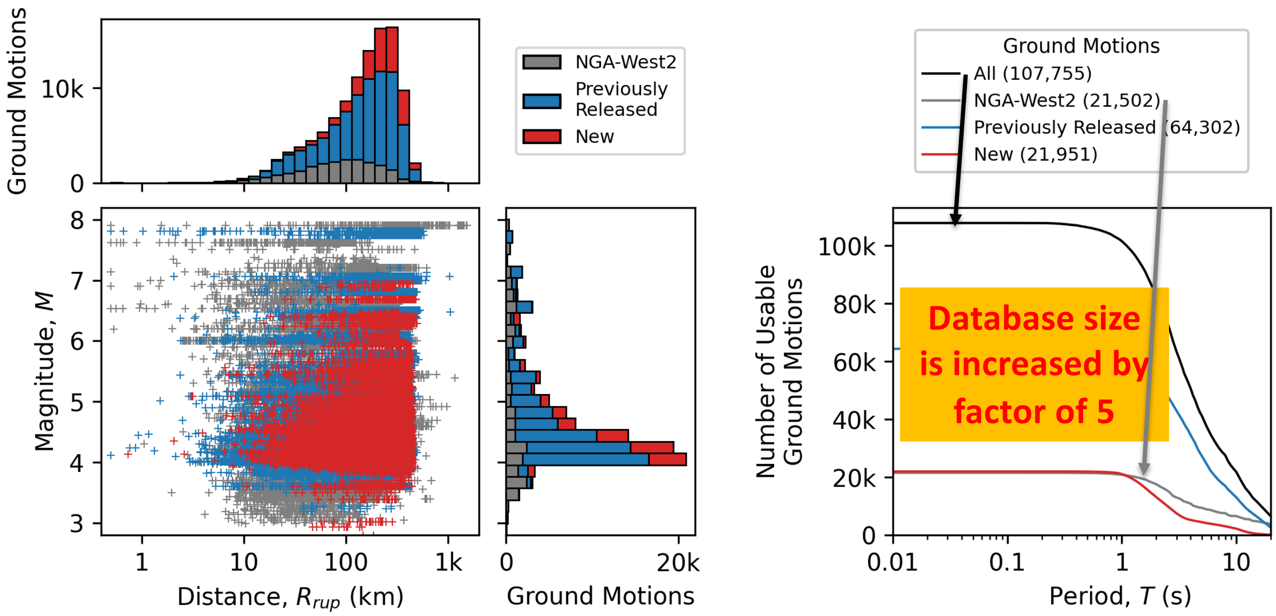
NGA-West2 database includes over 21,000 three-component recordings… (over 63,000 records)

Database evolution

❖ Selected databases for ground motion for modeling:

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

Ongoing community-based NGA-West3 database



Source: **Tristan Buckreis** (NGA-W3)

Availability of databases in 1994 vs 2024

- In 1994: Most of the ground motion databases were not public (with some exceptions)
  - Individual teams had their own databases
- In 2024: Any data used to develop models are made available to the public…PGA, PGV, PSA, FAS, AI,…
- All NGA flatfiles are shared with the public
- Database is checked multiple times by multiple teams

Models…in 1994

❖ A typical ground motion model

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

A current NGA model…

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

Magnitude Term

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

Geometric Attenuation Term

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

Style of Faulting Term

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

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

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

Hanging Wall Term

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

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

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

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

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

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

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

$$f_{hng,M} = \begin{cases} 0; & \mathbf{M} \le 5.5 \\ (\mathbf{M} - 5.5)[1 + a_2(\mathbf{M} - 6.5)]; & 5.5 < \mathbf{M} \le 6.5 \\ 1 + a_2(\mathbf{M} - 6.5); & \mathbf{M} > 6.5 \end{cases}$$

$$f_{hng,Z} = \begin{cases} 1 - 0.06 Z_{TOR}; & Z_{TOR} \le 16.66 \\ 0; & Z_{TOR} > 16.66 \end{cases}$$

$$f_{hng,\delta} = (90 - \delta)/45$$

Shallow Site Response Term

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

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

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

Basin Response Term

$$f_{sed} = \begin{cases} (c_{14} + c_{15} S_J)(Z_{2.5} - 1); & Z_{2.5} \le 1 \\ 0; & 1 < Z_{2.5} \le 3 \\ c_{16} k_3 e^{-0.75}[1 - \exp(-0.25(Z_{2.5} - 3)]; & Z_{2.5} > 3 \end{cases}$$

Hypocentral Depth Term

$$f_{hyp} = f_{hyp,H} f_{hyp,M}$$

$$f_{hyp,H} = \begin{cases} 0; & Z_{HYP} \le 7 \\ Z_{HYP} - 7; & 7 < Z_{HYP} \le 20 \\ 13; & Z_{HYP} > 20 \end{cases}$$

$$f_{hyp,M} = \begin{cases} c_{17}; & \mathbf{M} \le 5.5 \\ [c_{17} + (c_{18} - c_{17})(\mathbf{M} - 5.5)]; & 5.5 < \mathbf{M} \le 6.5 \\ c_{18}; & \mathbf{M} > 6.5 \end{cases}$$

Fault Dip Term

$$f_{dip} = \begin{cases} c_{19}\delta; & \mathbf{M} \le 4.5 \\ c_{19}(5.5 - \mathbf{M})\delta; & 4.5 < \mathbf{M} \le 5.5 \\ 0; & \mathbf{M} > 5.5 \end{cases}$$

Anelastic Attenuation Term

$$f_{atn} = \begin{cases} (c_{20} + \Delta c_{20})(R_{RUP} - 80); & R_{RUP} > 80 \\ 0; & R_{RUP} \le 80 \end{cases}$$

The intention is to capture various features as mush as possible

In 2024…the following features are covered for crustal events

- **Most** GMMs 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 basin effects
  - Style of faulting: Strike-slip, Reverse, Normal
  - **Period: 0-10 seconds**

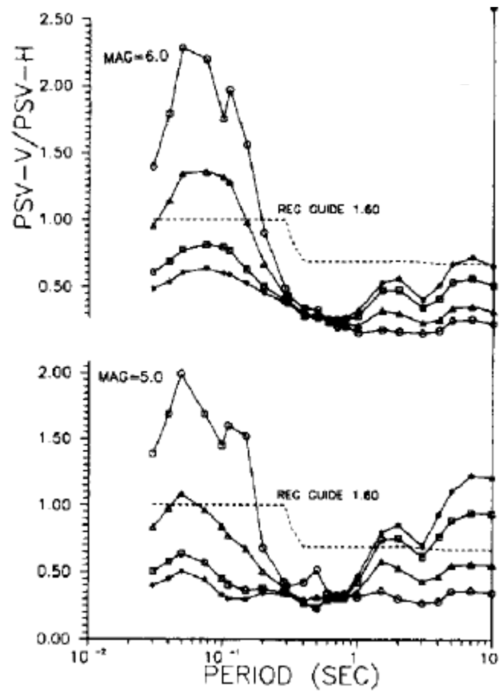
In 1994

- After the Northridge EQ, **vertical** ground motion attracted attention of engineers because of:
  - High vertical accelerations recorded and,
  - Collapses 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

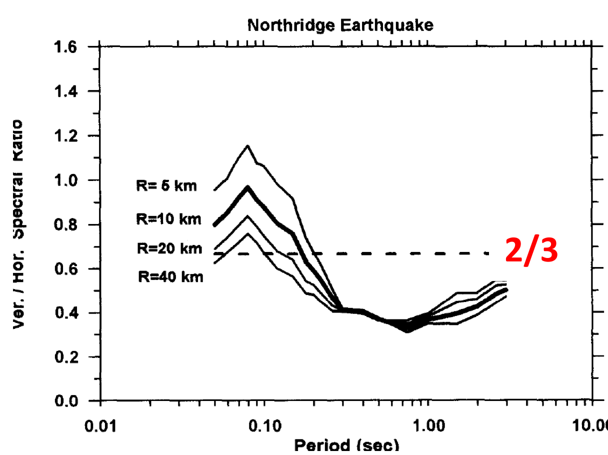


Reference: Niazi & Bozorgnia (1992)

In 1994 we knew…

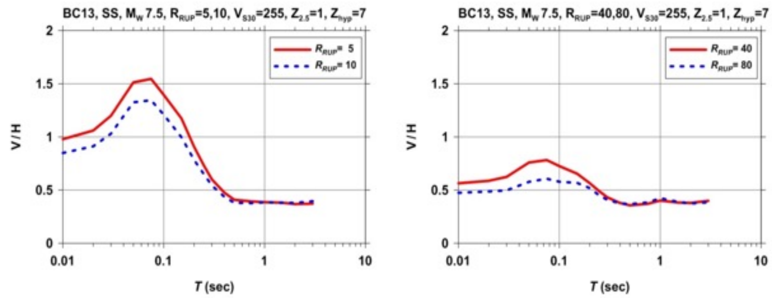
❖ Vertical / Horizontal spectral ratio (V/H)

- Is a strong function of distance and period
- Should not use **2/3** as a scaling factor for V/H
- And, the Northridge confirmed it…



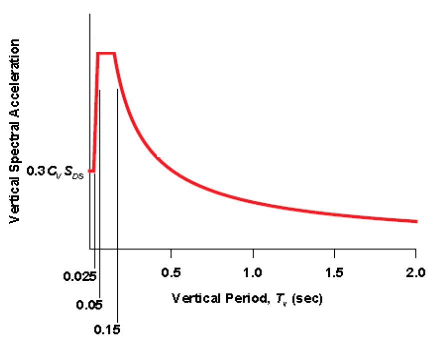
In 2024

- ❖ We now have multiple V and V/H models
- ❖ Qualitatively consistent with previous work
- ❖ Much more robust predictions



In 2024

- ❖ We now have multiple vertical and V/H GMMs
- ❖ Qualitatively consistent with previous work
- ❖ Much more robust predictions



- ❖ Vertical design spectrum has been provided in the building code since 2009