Ground-Motion Lessons from the Northridge Earthquake

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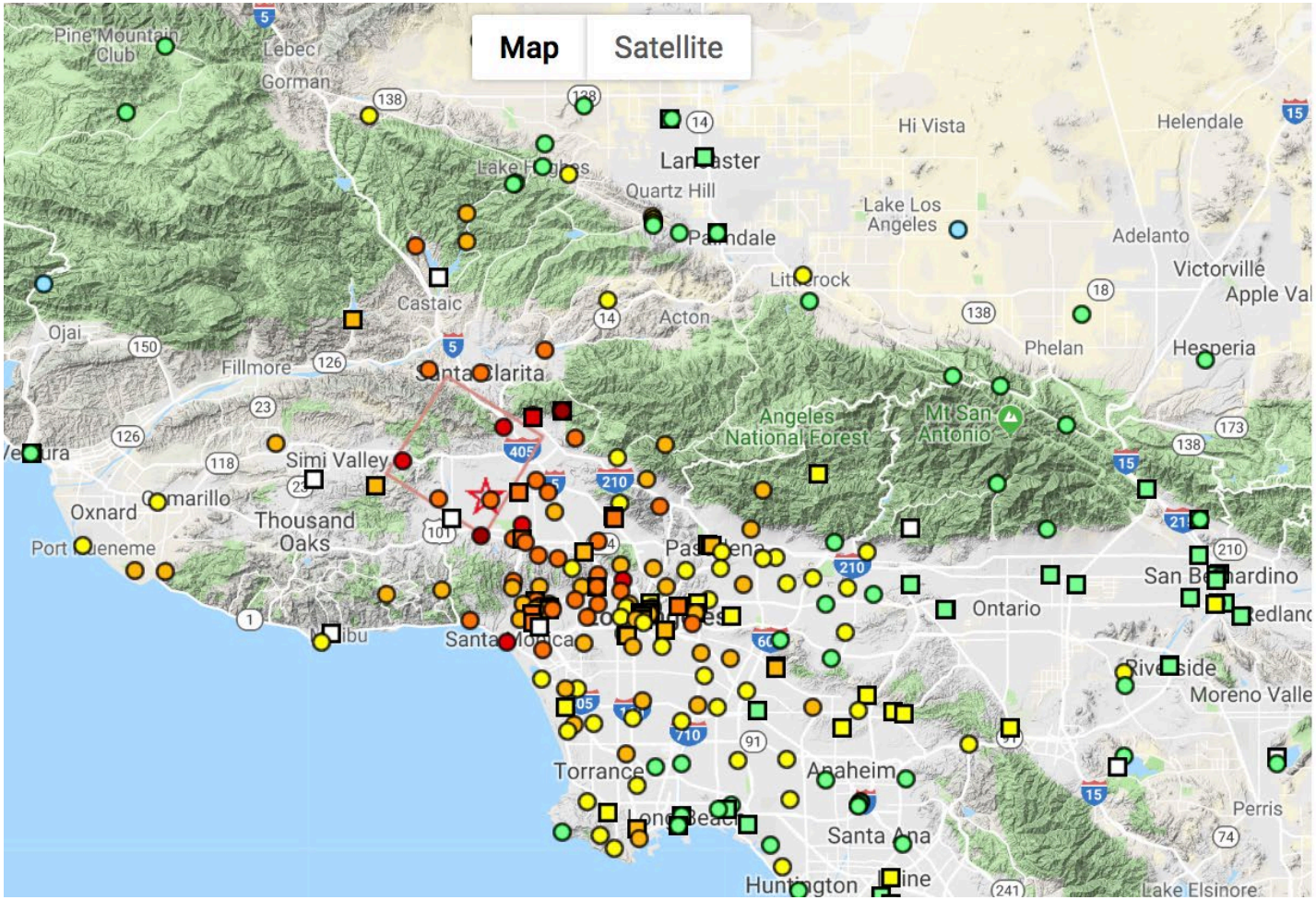
1994 Northridge Earthquake



PGA (%g)
- >124
- 65-124
- 34-65
- 18-34
- 9.2-18
- 3.9-9.2
- 1.4-3.9
- <1.4

Ground Station
Structure Station

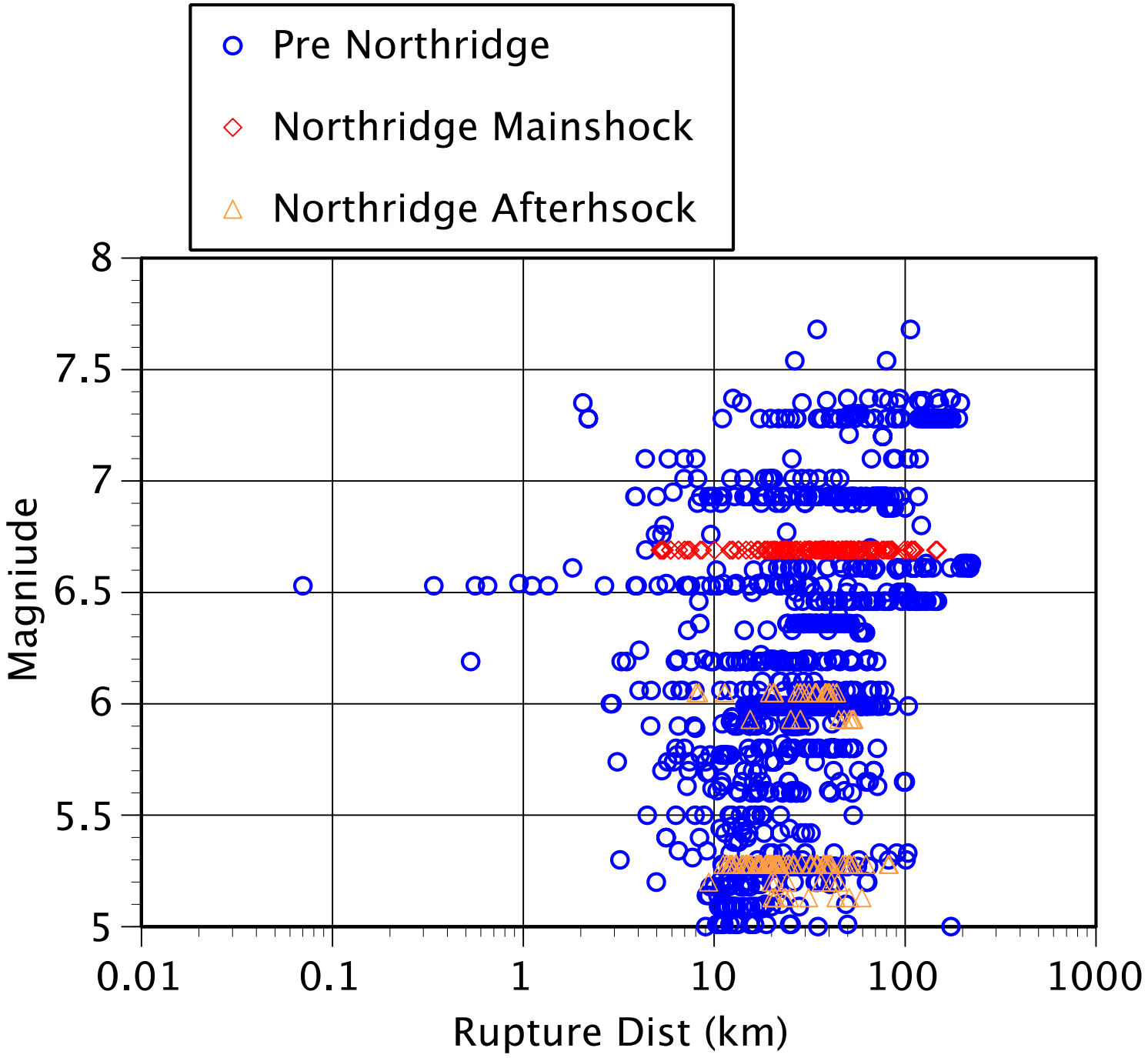
Hover over station to reveal station number and photo.

Note: Station locations are approximate when viewed at high zoom levels.

Record

M6.7, Rev, Dip=42, ZTOR=6 km

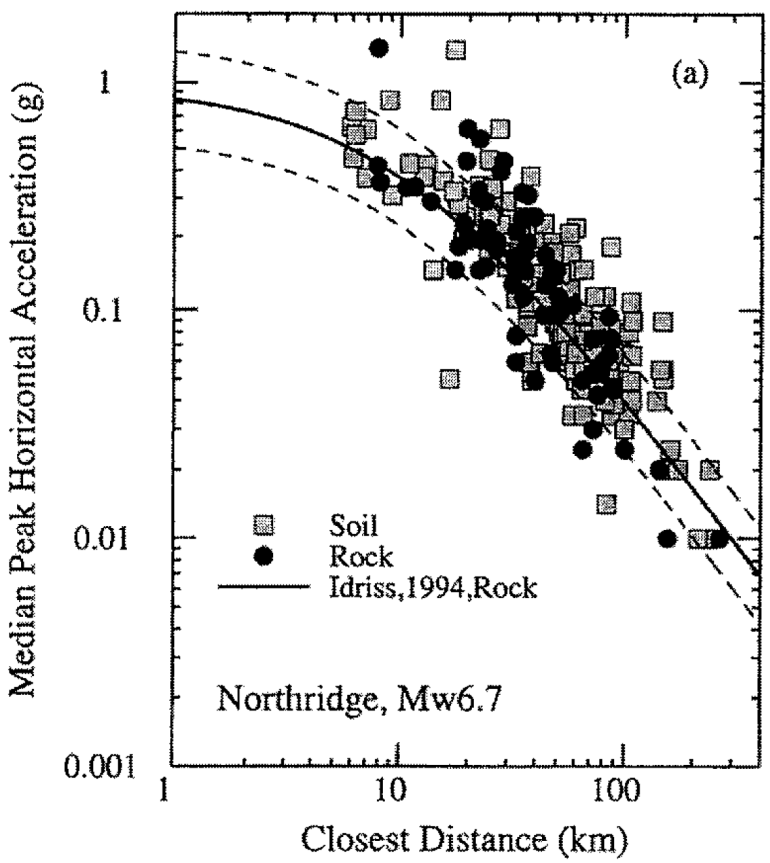
From CESMD


Pre Northridge
Northridge Mainshock
Northridge Afterhsock
8
7.5
7
6.5
6
5.5
5
Magniude
0.01
0.1
1
10
100
1000
Rupture Dist (km)

Key Issues for Ground Motion Models

- Blind Faults / Buried Ruptures
- Hanging-Wall Effects
- Large Variation over Short Distances
- Non-Linear Site Factors
- Velocity Pulse
- Basin effects
- Vertical Ground-Motions

Horizontal PGA from Northridge



From Somerville et al (BSSA, 1996)

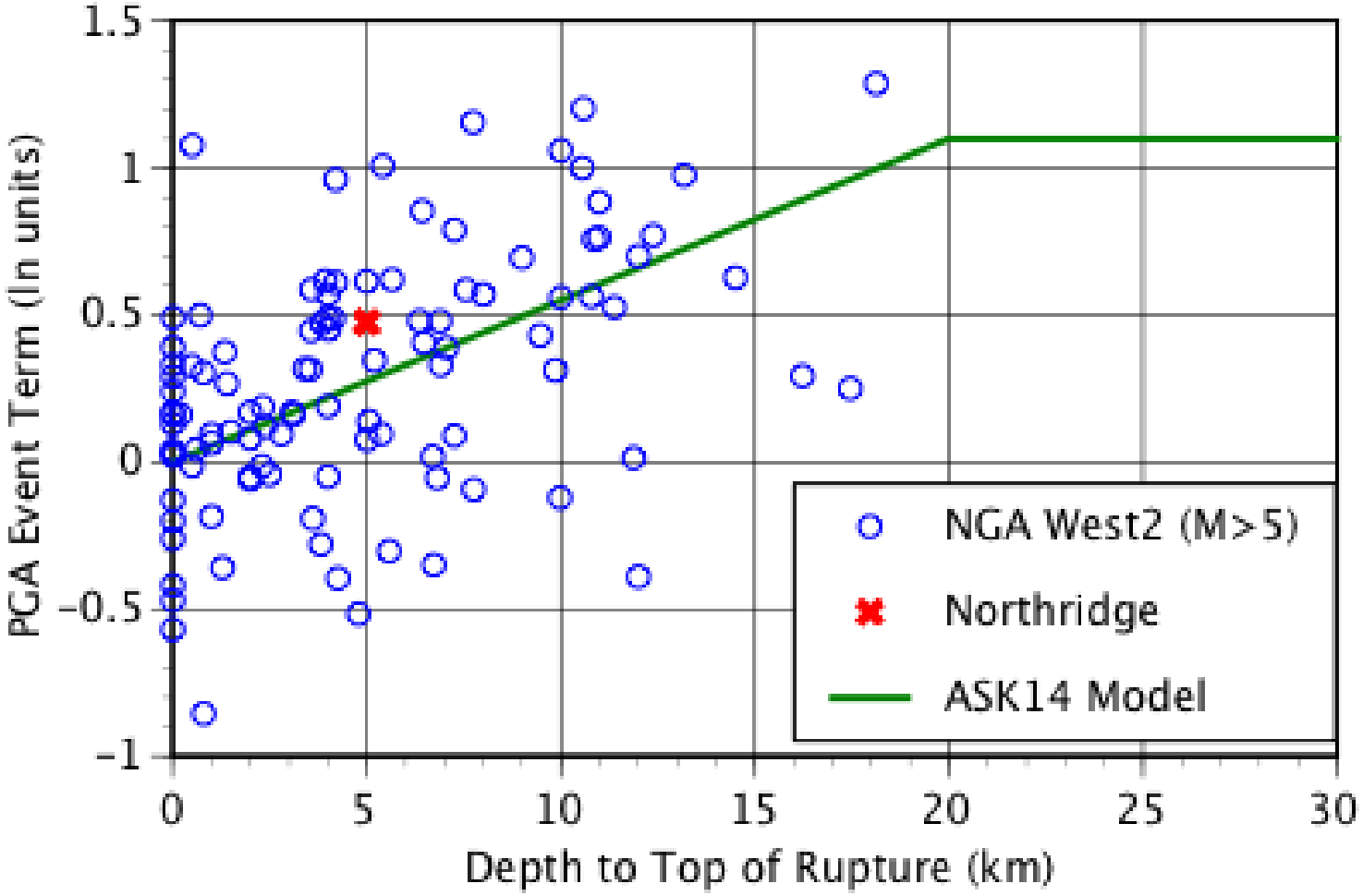
- On average, PGA values were 50% larger than the Idriss94 GMPE
  - Due to blind fault
    - Higher stress drops for blind faults
  - Due to the buried rupture?
    - Higher stress drops for earthquakes at depth?
  - Due to style-of-faulting?
    - Larger factor than 20%?

NGA-West 2 GMPEs

- Some models include depth scaling
  - 3 Models include depth scaling
    - ZTOR (depth to top of rupture)
    - Zhypo (hypocentral depth)
  - 2 Models have no depth scaling

- There is a trade-off between RV/SS factor and depth scaling
  - Models with depth scaling show weaker RV/SS factors

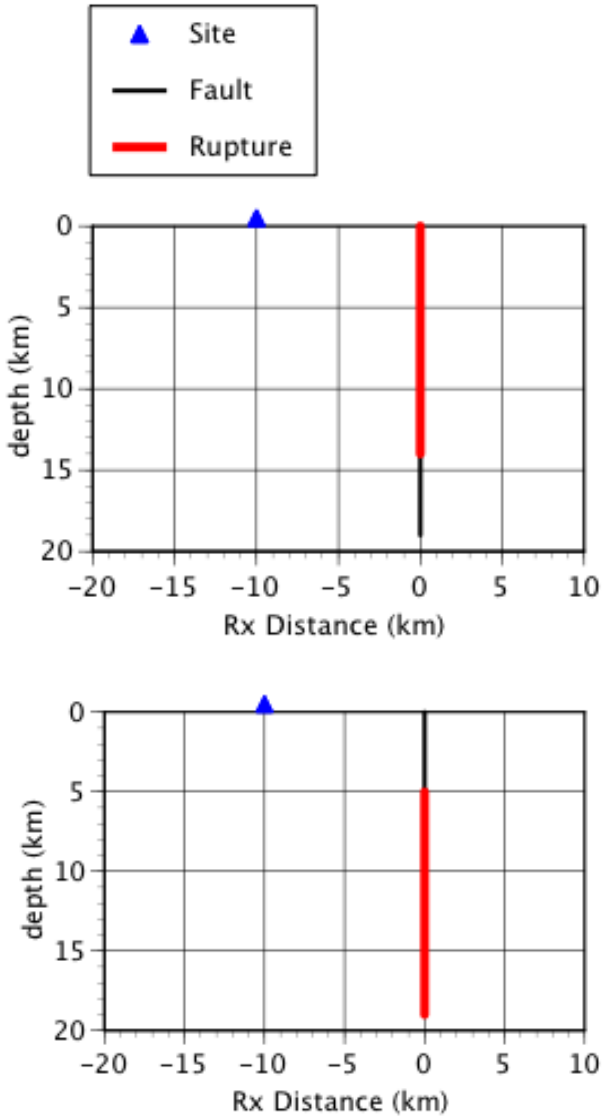
Depth Scaling for PGA in ASK14 GMPE

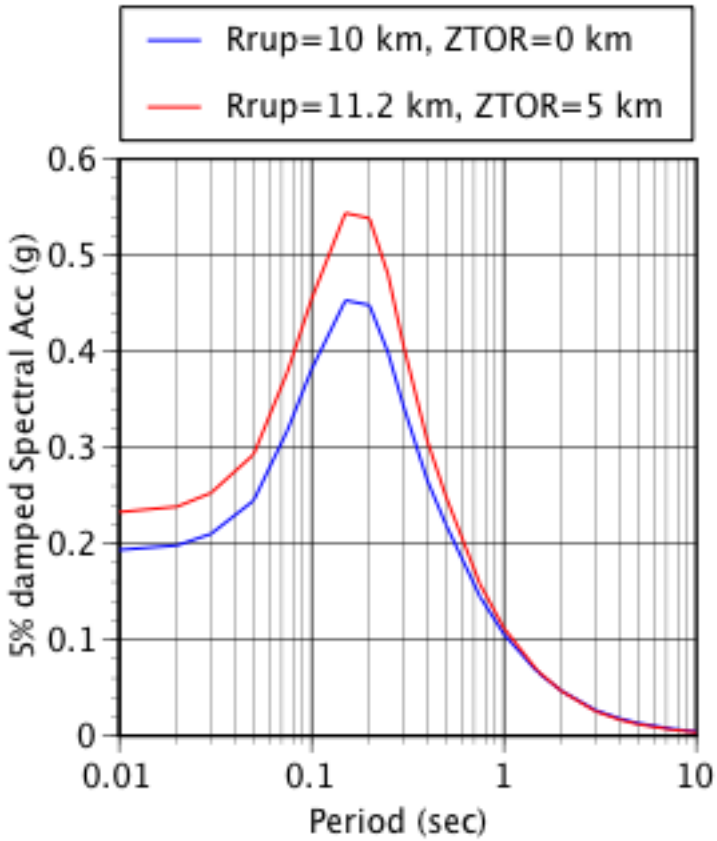


Putting Rupture at Closest Point Does Not Always Lead to Largest GM

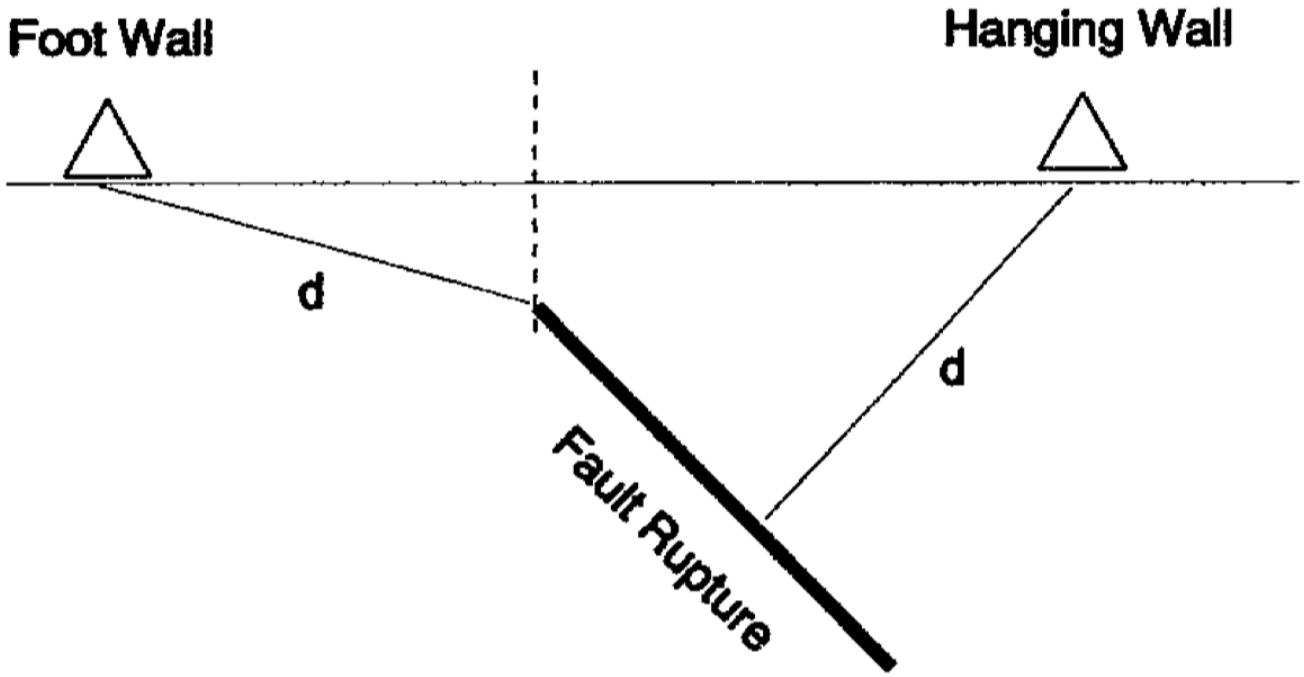
M6.5, rupture at closest distance
Rrup=10 km

M6.5, rupture at depth
Rrup=11.2 km

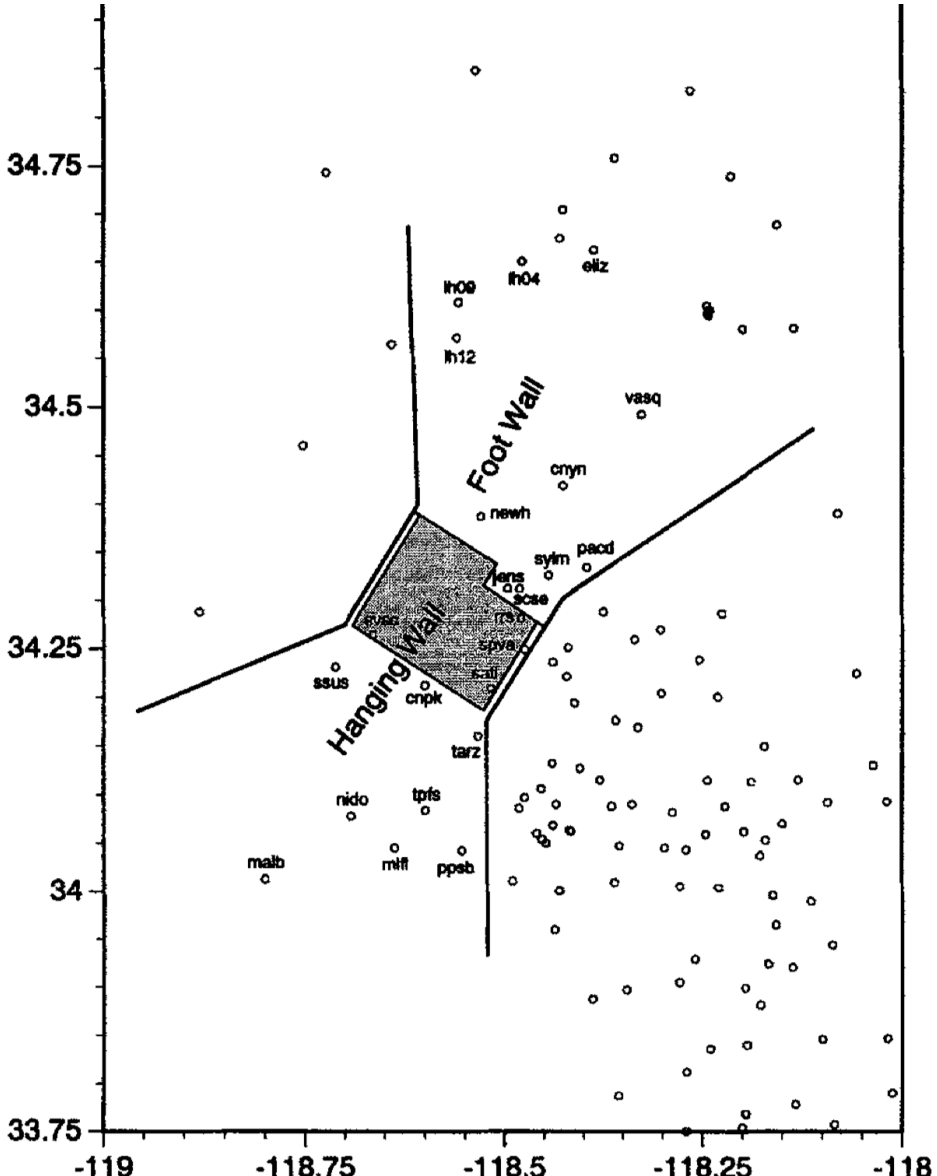




Hanging-Wall Effects

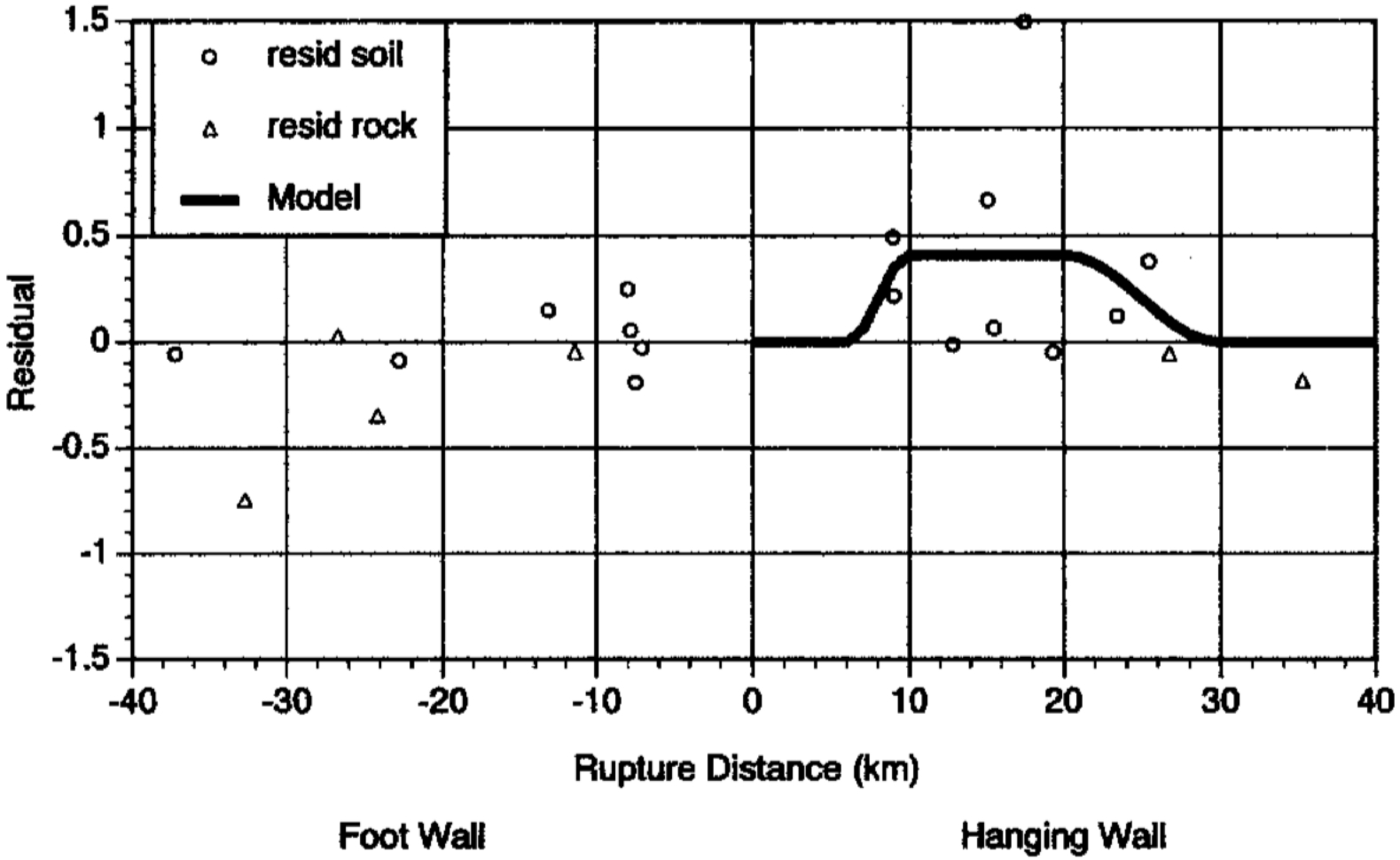


Data for HW effects

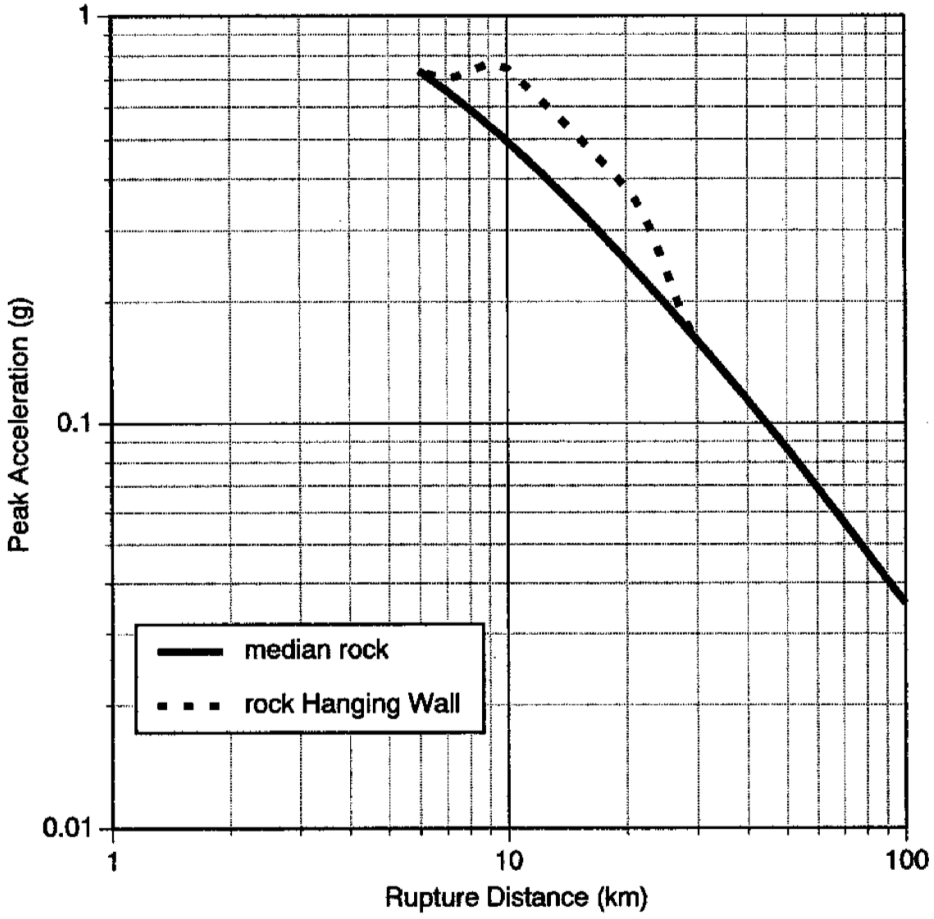


- First earthquake with multiple recordings on both HW and FW sides of the rupture
- Still few eqk with good data on both HW and FW sides of rupture.
  - Chi-chi

PGA Residuals from Northridge-Specific GMPE



Northridge PGA Scaling with HW Effects

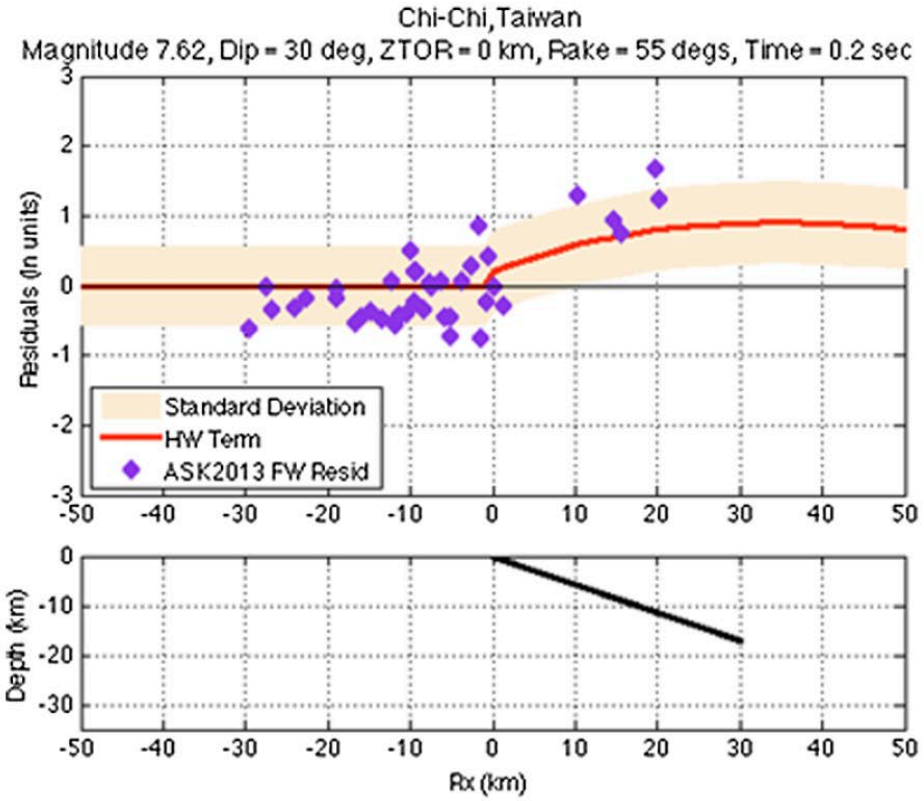


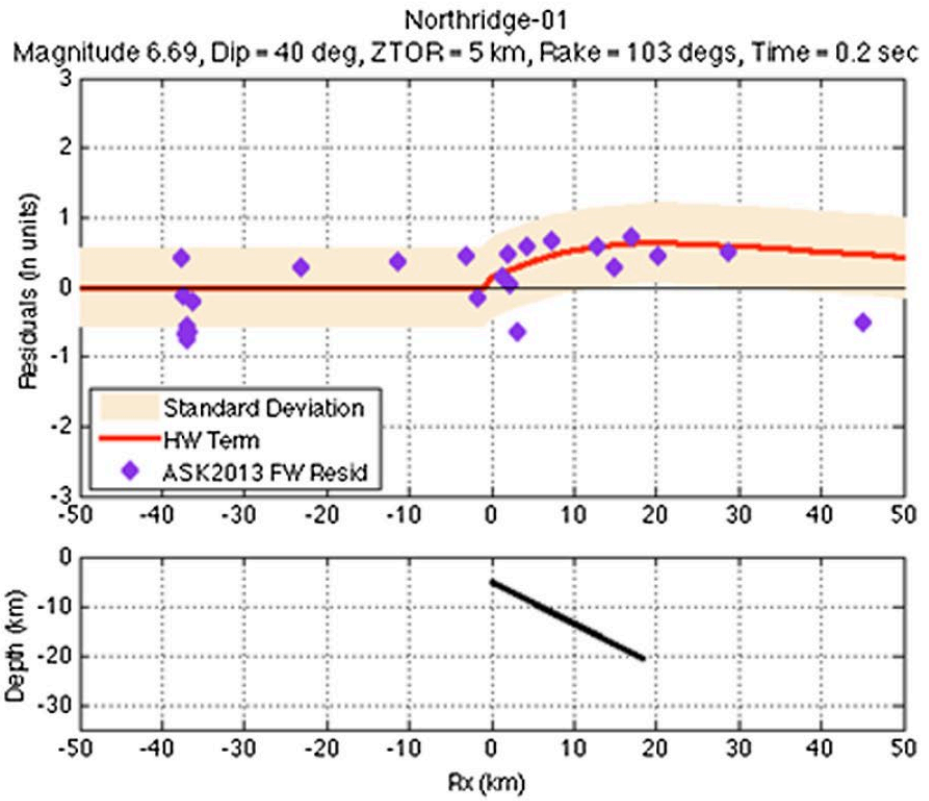
Still Sparse Empirical Data for HW

Database	Event	Year	Mag	Dip	Rake	# of recs	# of recs $R_{JB} = 0$	# of recs <15 km on FW	# of recs <15 km on HW
NGA (2008)	Irpinia, Italy-01	1980	6.9	60	−90	5	0	1	1
NGA (2008)	Whittier Narrows-01	1987	5.99	30	150	13	1	5	6
NGA (2008)	Loma Prieta, CA	1989	6.93	70	140	14	1	3	6
NGA (2008)	Northridge-01	1994	6.69	40	103	26	10	3	12
NGA (2008)	Chi-Chi, Taiwan	1999	7.62	33	55	53	7	24	7
NGA (2008)	Chi-Chi, Taiwan-06	1999	6.3	30	100	34	1	2	1
NGA-W2	Niigata, Japan	2004	6.63	47	93	23	0	2	2
NGA-W2	L'Aquila, Italy	2009	6.3	48	−98	7	4	2	4
NGA-W2	Wenchuan, China	2008	7.9	50	138	34	3	1	5
NGA-W2	Iwate	2008	6.9	40	104	37	1	2	3
NGA-W2	El Mayor-Cucapah	2010	7.2	63	−164	9	0	1	1
NGA-W2	Christchurch, New Zealand	2011	6.2	67	135	6	1	4	2

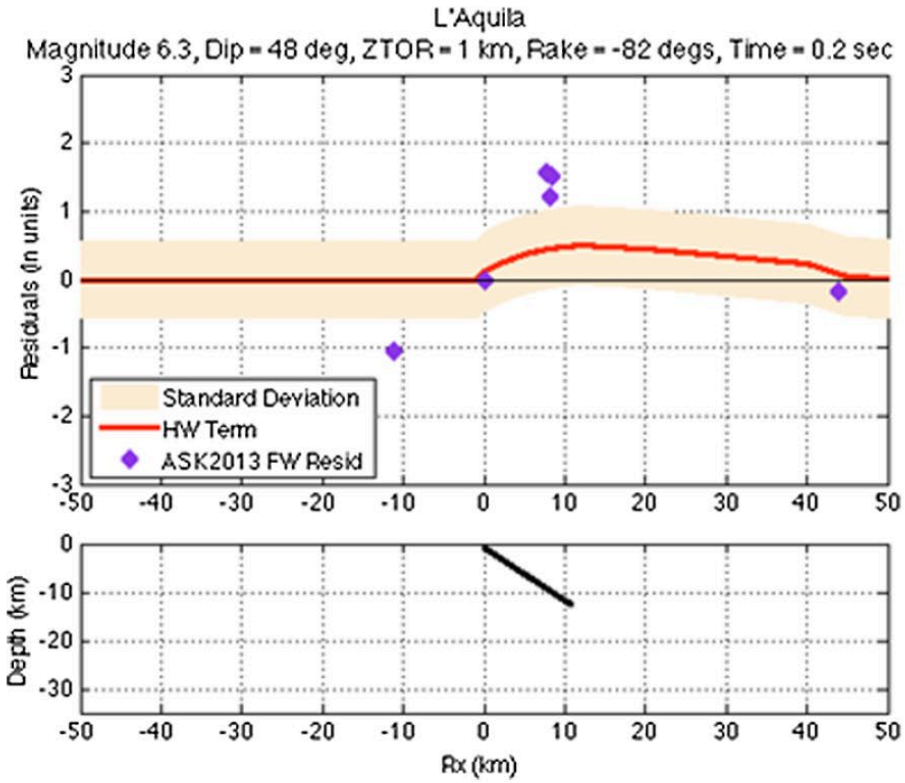
(From Donahue and Abrahamson, 2014)

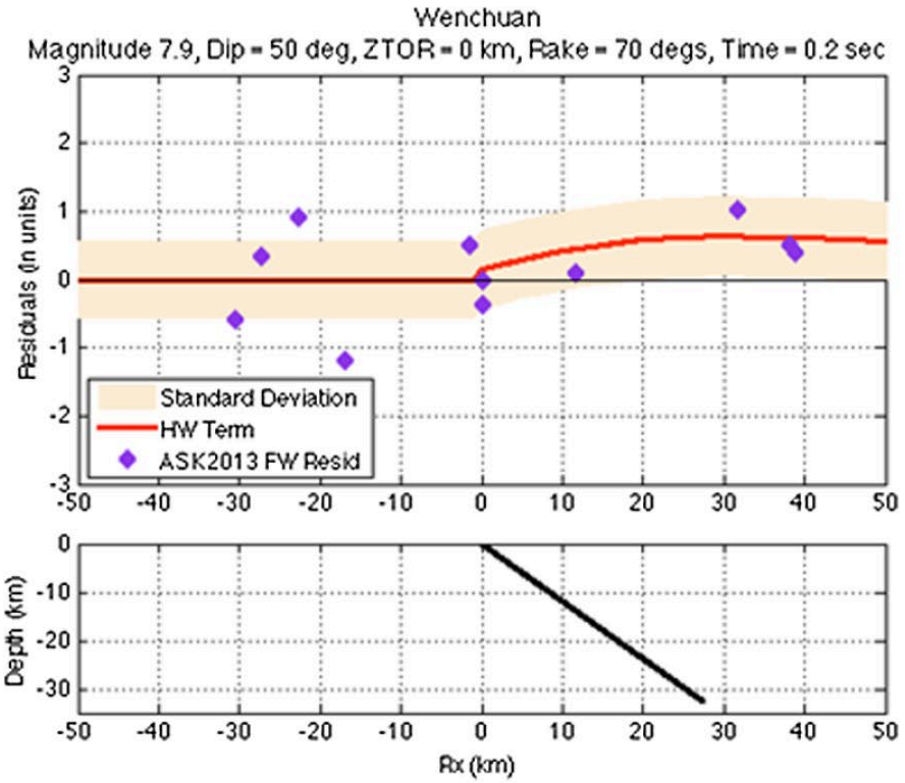
Earthquakes with HW & FW data



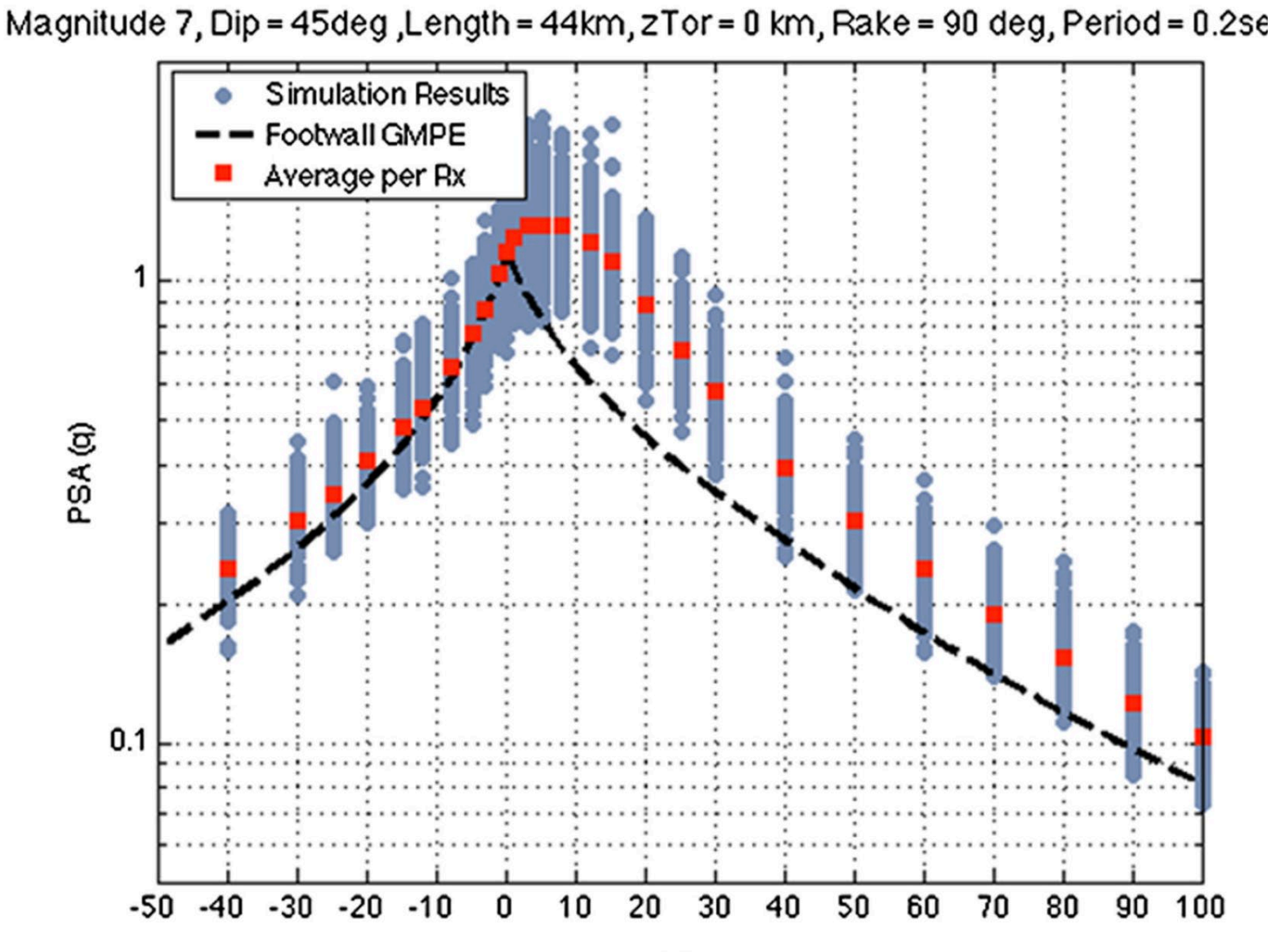


Earthquakes with HW & FW data





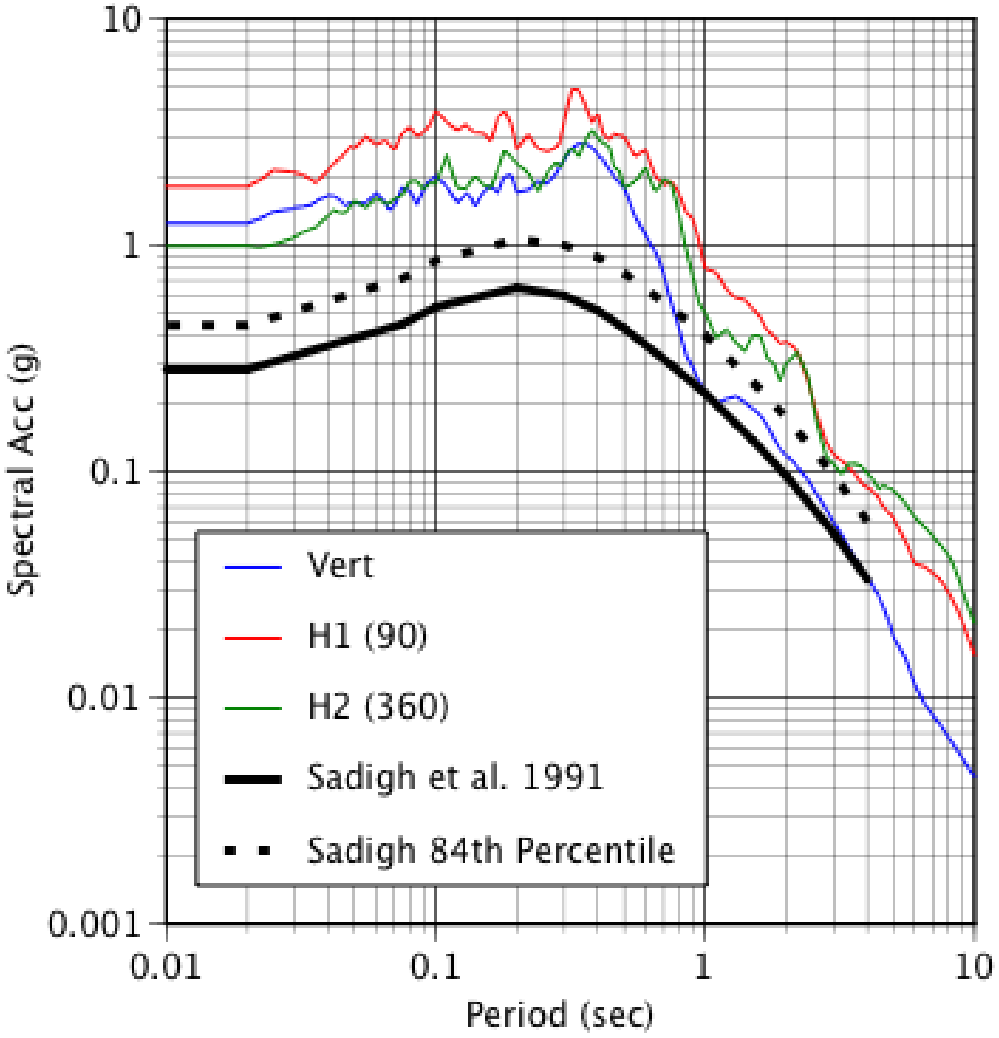
Scatter in Simulations



Post Northridge

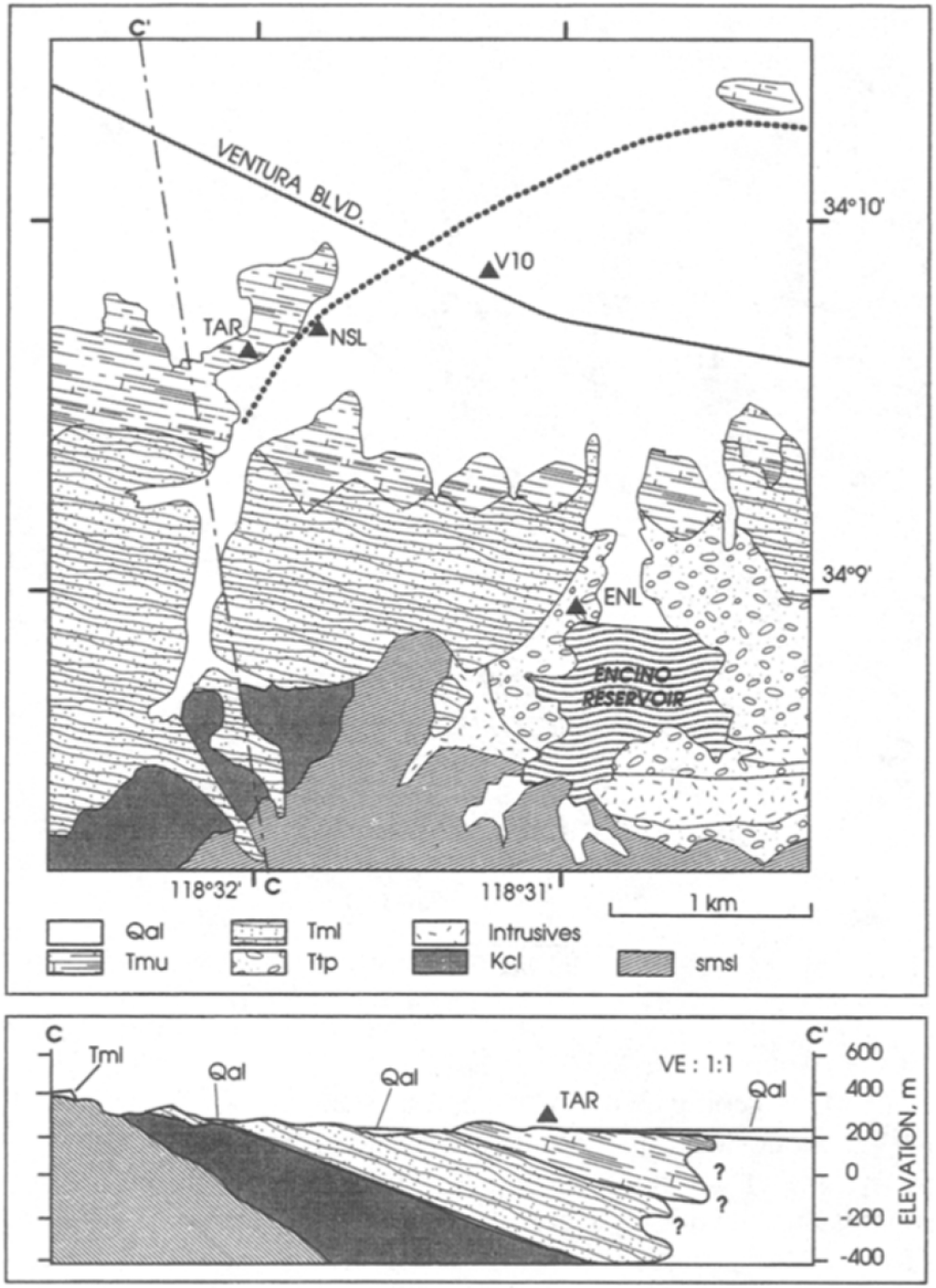
- Use seismological simulations to constrain dependence of HW factors
  - Magnitude
  - Dip
  - Depth to Top
  - Rx

Tarzana Recording



- PSA at Tarzana
  - Greater than 2 sigma based on pre-Northridge GMPEs

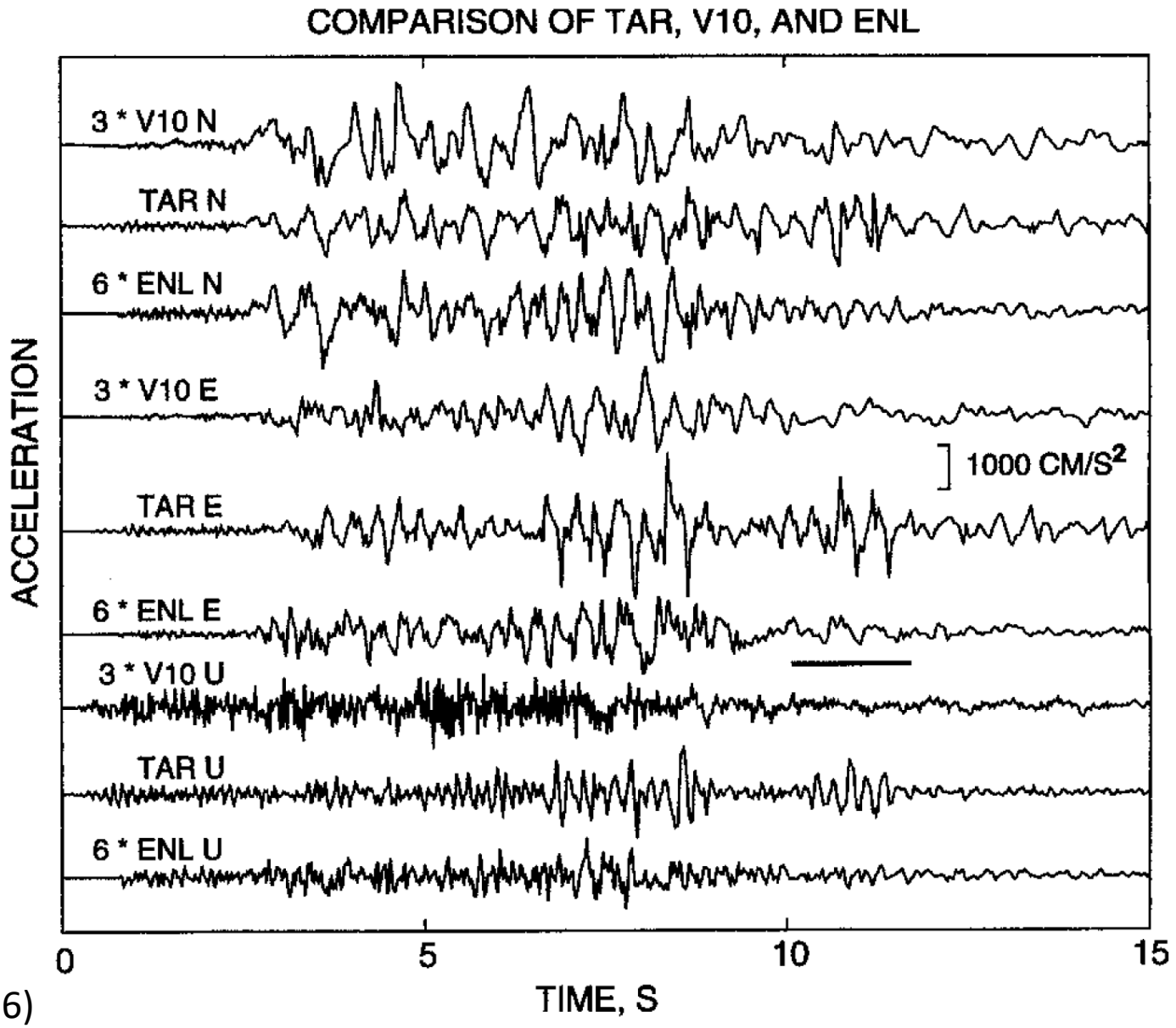
- Large Variability in ground motions over short distances



From Spudich et (1996)

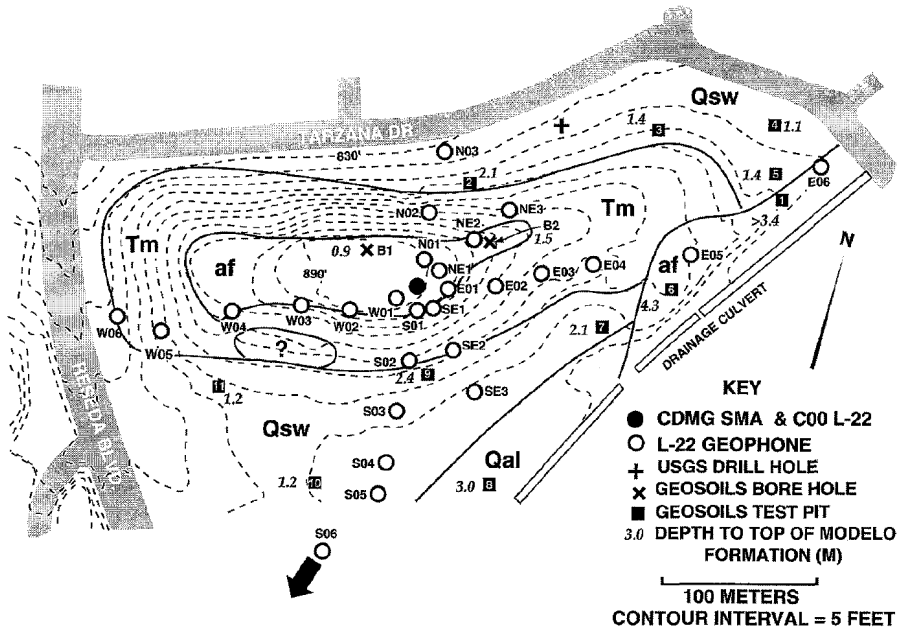
V10 scaled by 3

ENL scaled by 6



From Spudich et (1996)

Studies of Spatial Variation Over Short Distances from Aftershocks



- Detailed seismological modeling can explain variability
- But this information is not usually available
- Our ground-motion data sets are severly under sampled spatially

From Spudich et (1996)

Basin Effects

- 2-D and 3-D modeling of basin response from Northridge earthquake
  - Large basin effects by depends on specific ray paths
- Empirical Models
  - Simplified basin effects to scale with soil depth (Z1.0 and Z2.5)
  - Scaling varies by region
    - Basin scaling from Northridge may not be applicable to other regions

Post Northridge

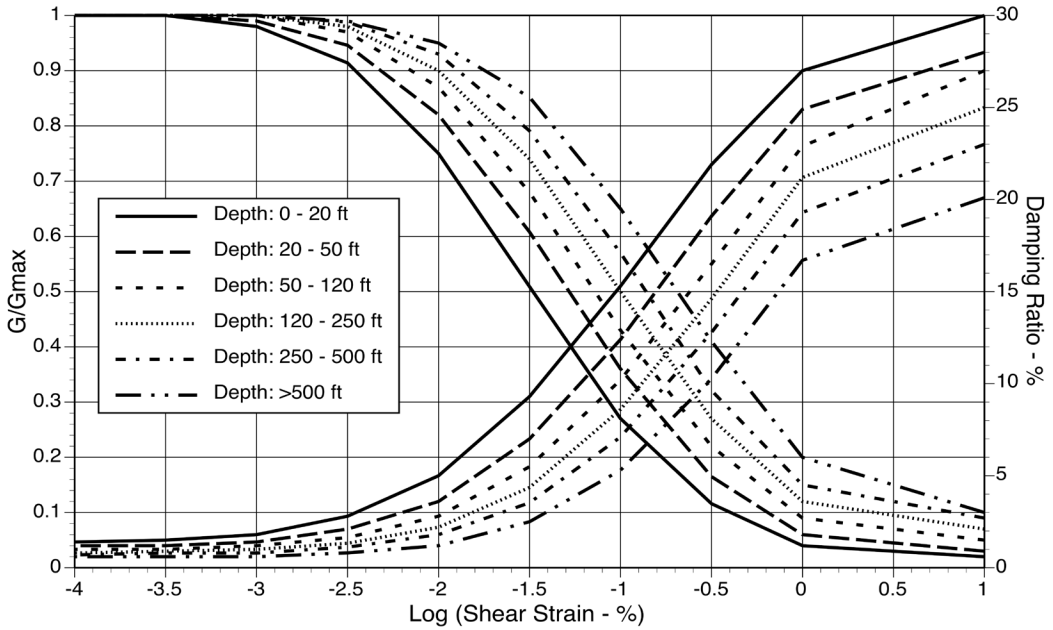
- Use of 3-D simulations for basin scaling
- Issue: How to apply the 3-D results to GMPEs
  - GMPEs include average 3-D basin effects in the VS30 scaling
    - VS30 is correlated with basin depth
    - To avoid double counting, use an average depth for a given VS30

Nonlinear Site Response

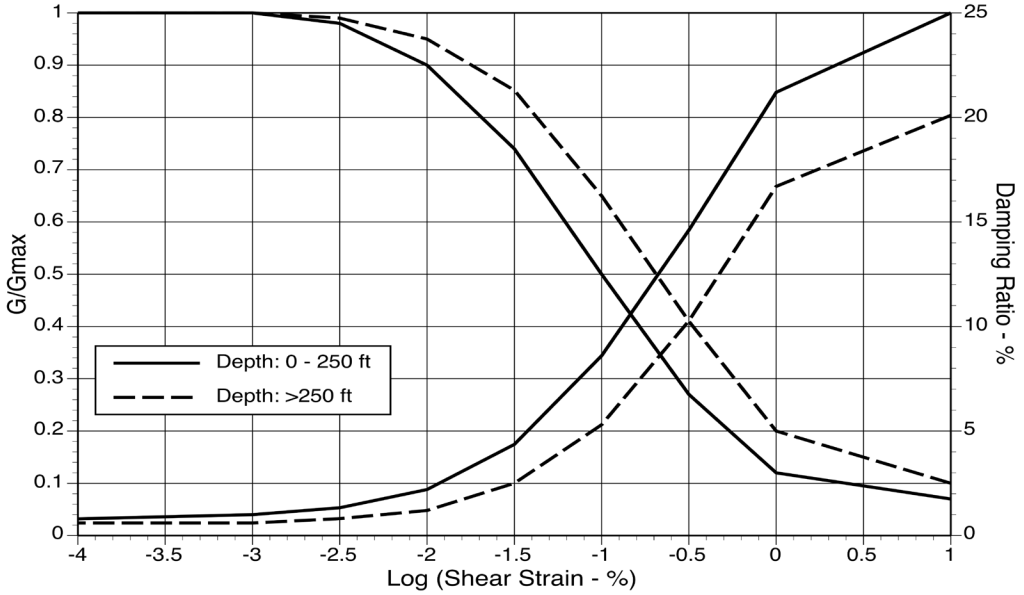
- 1989 Loma Prieta earthquake
  - Provided empirical data for evaluating nonlinear site response
- 1994 Northridge earthquake
  - Site response was not consistent with models based on Loma Prieta
  - Resolution of Site Response Issues in the Northridge Earthquake (ROSRINE)
    - Soils in the Northridge eqk region are more linear than soils in the Loma Prieta eqk region

Example NL Curves

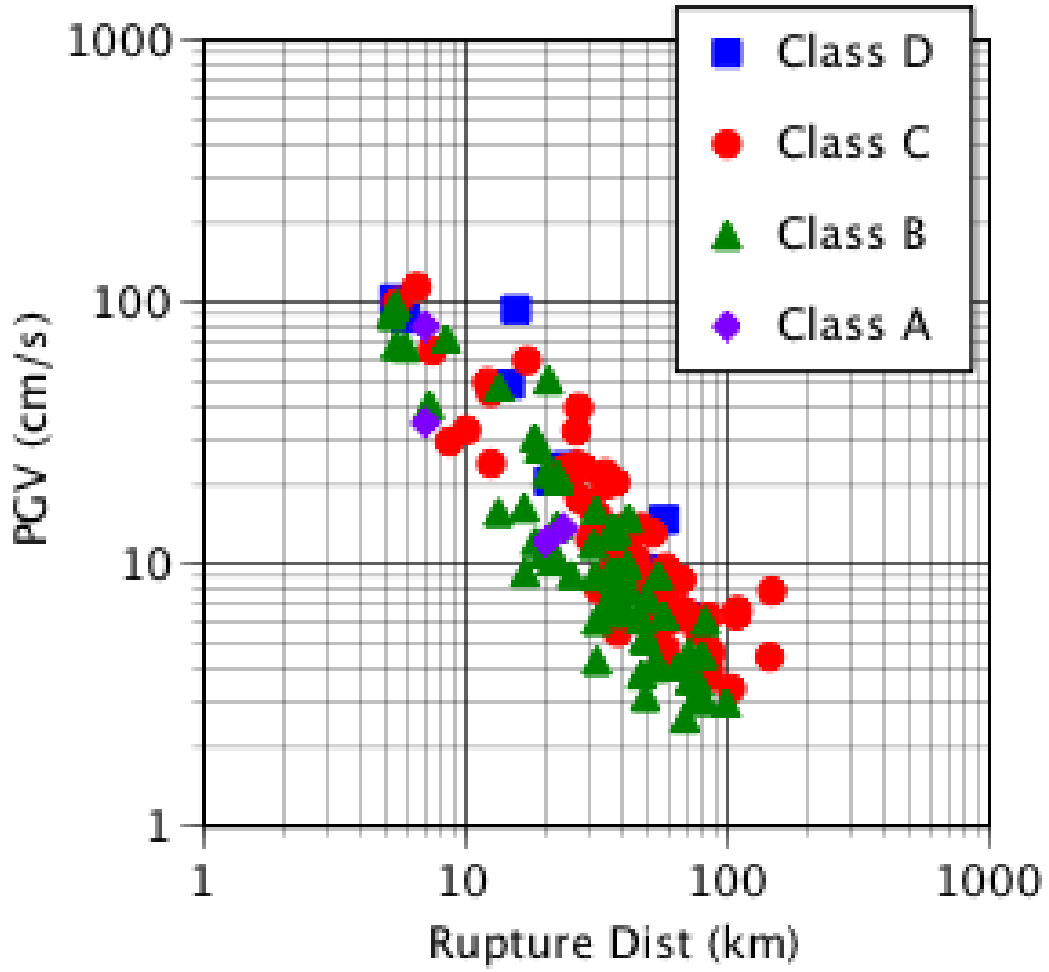
Based on Loma Prieta Cohesionless Soils (EPRI)



Based on Northridge Cohesionless Soils (Peninsular Range From ROSRINE)



Large Peak Velocities

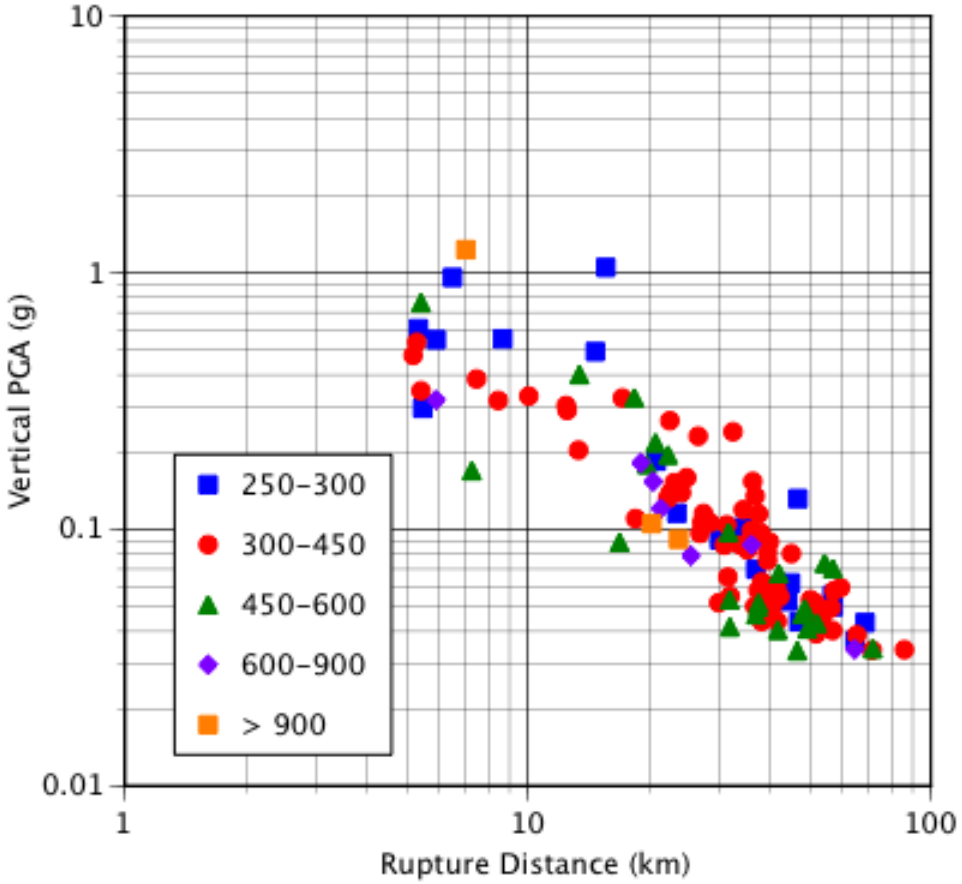


RotD50 PGV

Velocity Pulse - Renaldi

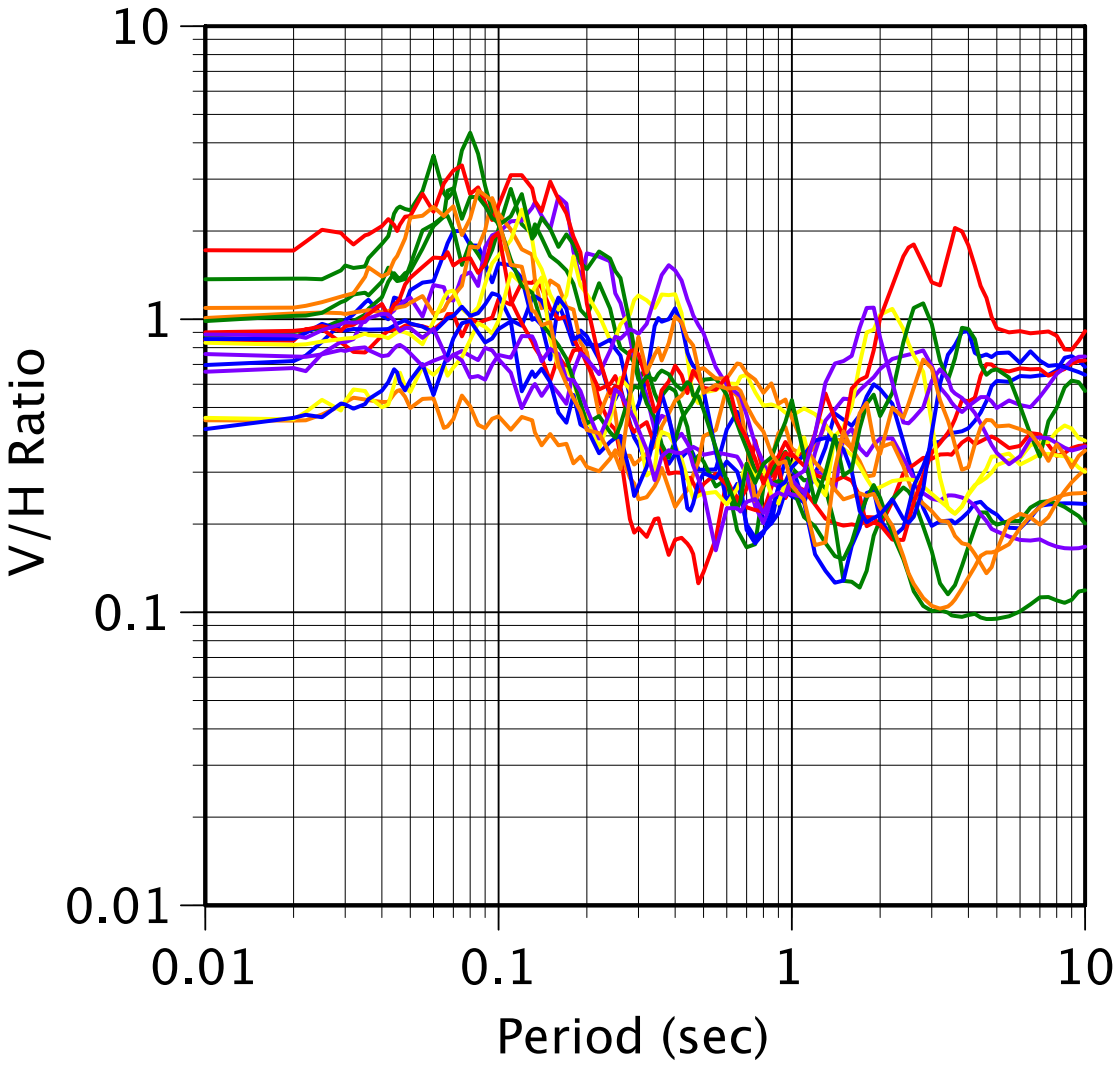
From PEER GM data base

Verticals



- Two recordings with > 1 g vertical PGE
- Verticals are large, but horizontals are also large
- V/H is not unusual

V/H Ratios for Rrup < 15 km



Key Changes to Ground-Motion Models due to the Northridge Earthquake Lessons

- Depth scaling
  - Stronger shaking from ruptures at depth is now common in GMPEs
- HW scaling
  - HW factors are now common (scaling is constrained by simulations)
  - Increase short-period PSA by up to factor of 2
- Basin Factors
  - Basin Depth factors are now common
  - Use of 3-D simulations for more resolution (beyond depth factors)
- Nonlinear site factors in GMPE
  - For CA-wide GMPEs, NL terms are constrained by Northridge NL models, not the Loma Prieta NL models
    - So they don't work as well for Bay Area region
  - Region average empirical factors are closer to Northridge