Using Arias Intensity to Constrain Design Ground Motions for Earth Dams

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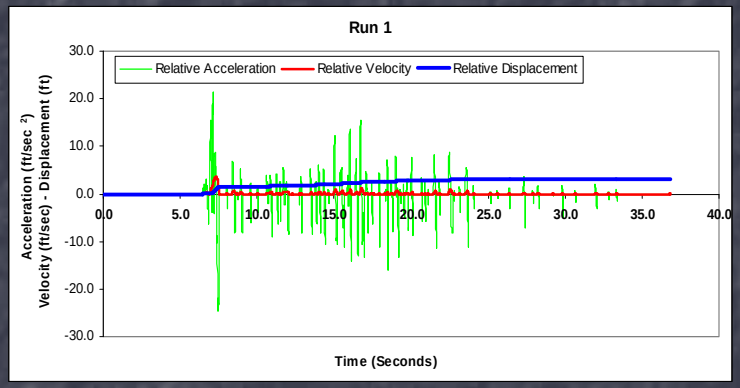
DEPARTMENT OF
WATER RESOURCES
SAFETY OF DAMS

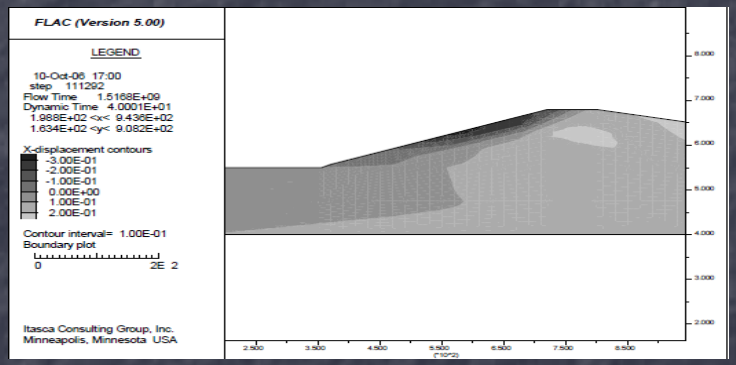
California Division of Safety of Dams (DSOD) Perspectives

- 37 million people,
- 100+ active faults
- 1200+ dams under DSOD jurisdiction
  - ~1050 embankments
- Analysis sophistication vs. practicality
  - Progressive approach: start w/ simple-conservative, refine as needed

DSOD Progressive Approach for Dynamic Embankment Analysis

- Newmark displacement - index of inertial stability
  - More sophisticated (eg. FLAC) if displacement ambiguous
- Increasingly using time series to represent seismic loading





Guidance on Design Ground Motions for Dams

- USCOLD/USSD (1999)
- DSOD (2002)
- USACE (1995/2003)
- FEMA 65 (2005)
- FERC (in progress)

1) Site-specific analysis
2) No code-prescribed methodology
3) GM duration important
4) Safety evaluation should consider no less than M_{max} loading (DSHA)...

...but consider PSHA perspectives

FEMA-ERDC (2004): Important research needs include

GM prediction, characterizing directivity, duration/intensity

DSOD's Deterministic Seismic Hazard Approach

- Characterize active sources
- Characterize site
- Develop 50th to 84th PGA, PGV ,SA, Arias intensity

  [AI replaced duration after 2004]
- Identify parameters best correlating w/ performance
- Identify candidate controlling M_{max} event(s)

(...need probabilistic feedback)

Load Selection Using Consequence Hazard Matrix (2002)

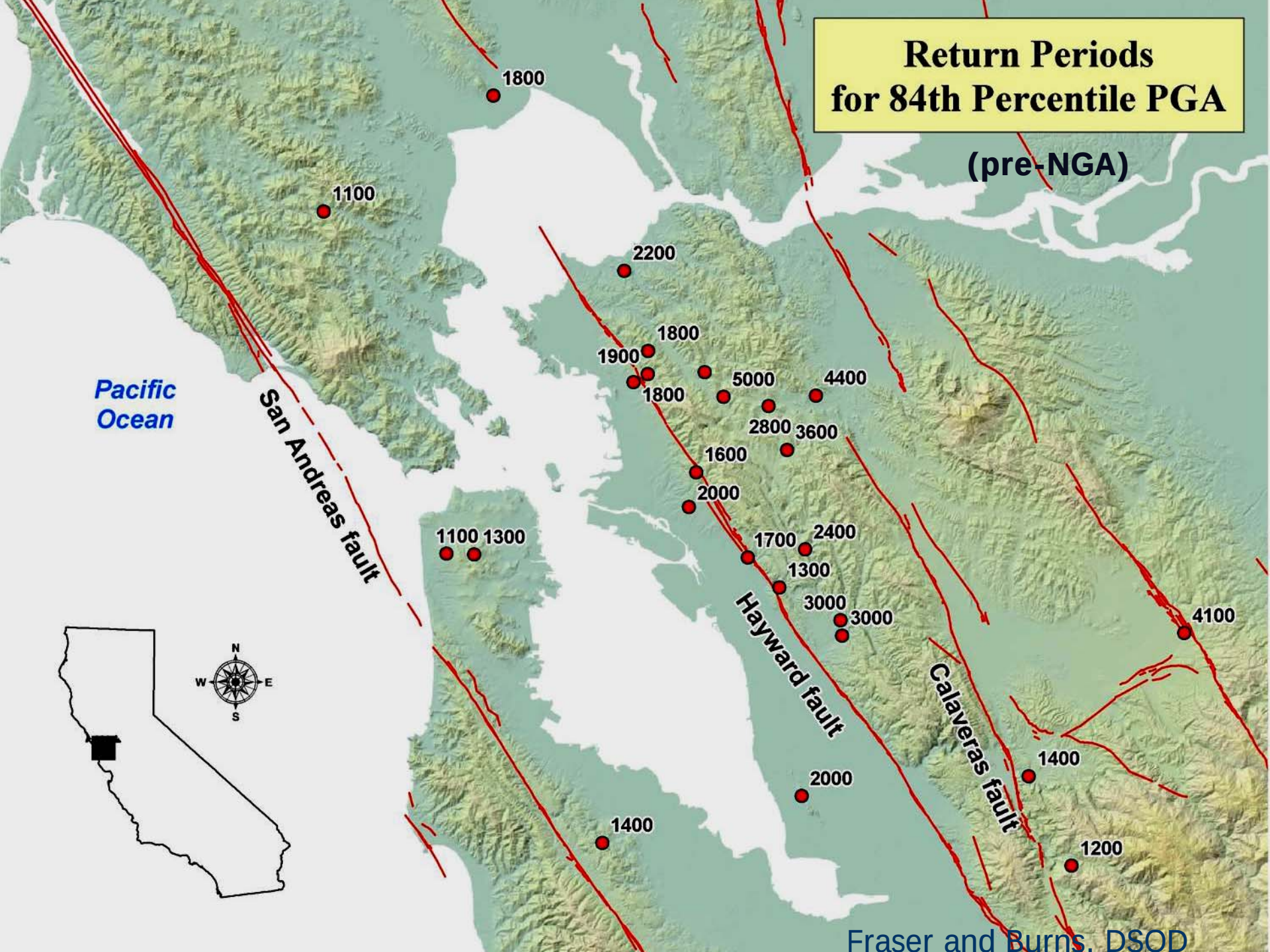
- M_{max} loading range: 50th to 84th % motion
- Use event likelihood & d/s consequence

When "50th to 84th" ...

- PSHA/pga
- Goal: minimum RP "several thousand" years
- (USSD/ICOLD: 3 to 10k yr)

	Very High Slip Rate 9 or greater mm/yr	High Slip Rate 8.9 to1.1 mm/yr	Moderate Slip Rate 1.0 to 0.1 mm/yr	Low Slip Rate less than 0.1 mm/yr
Extreme Consequence Total Class Weight 31-38	84th	84th	84th	50th to 84th
High Consequence Total Class Weight 19-30	84th	84th	50th to 84th	50th to 84th
Moderate Consequence Total Class Weight 7-18	84th	50th to 84th	50th to 84th	50th
Low Consequence Total Class Weight 0-6	50th	50th	50th	50th

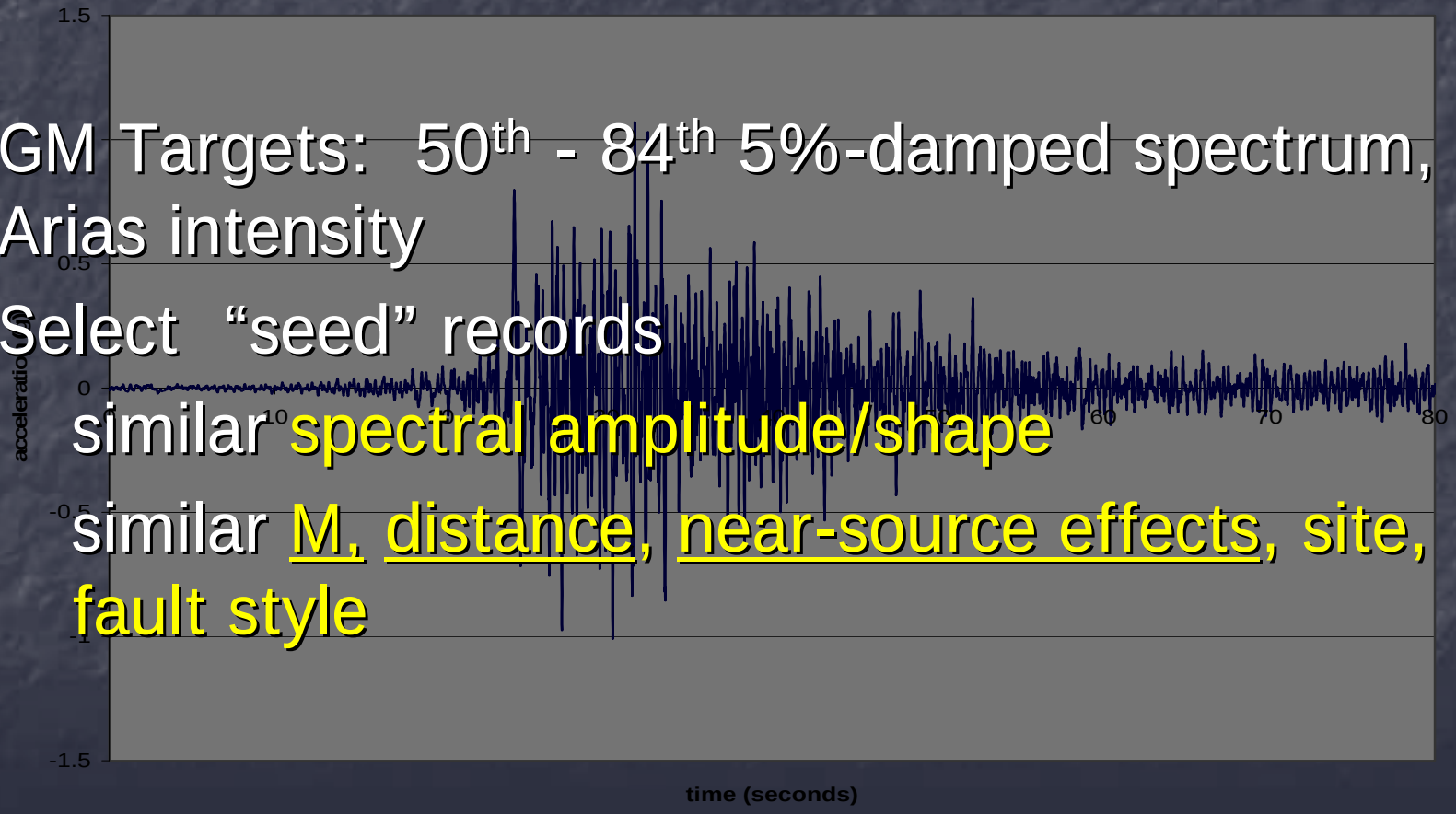
DSOD Consequence-Hazard Matrix
October 4, 2002



Fraser and Burns, DSOD

Design Ground Motion Development

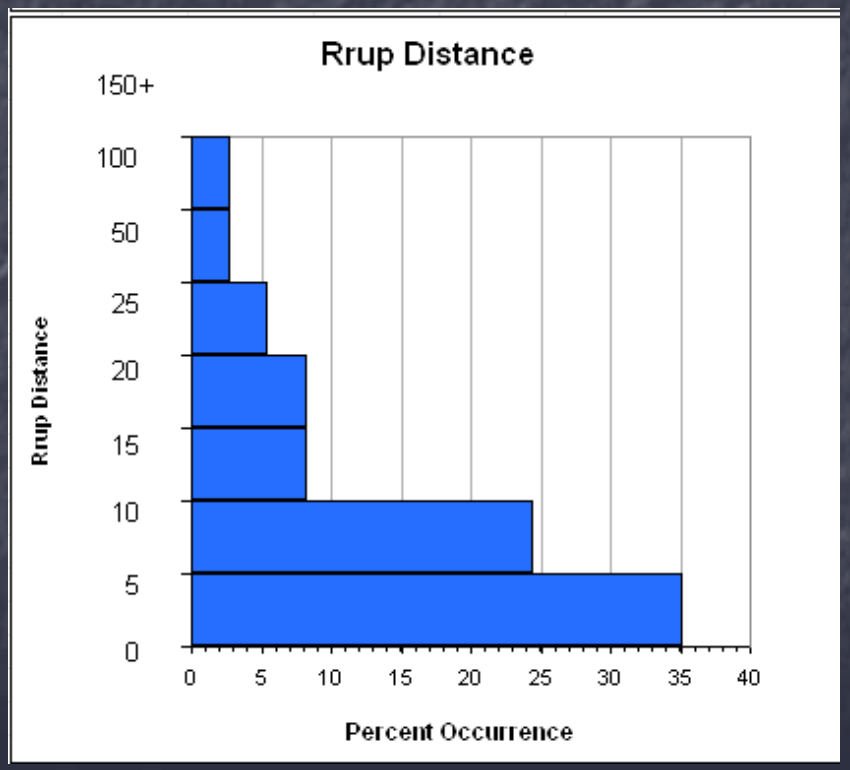
Objective: Minimum of 3 time histories for controlling earthquake scenario

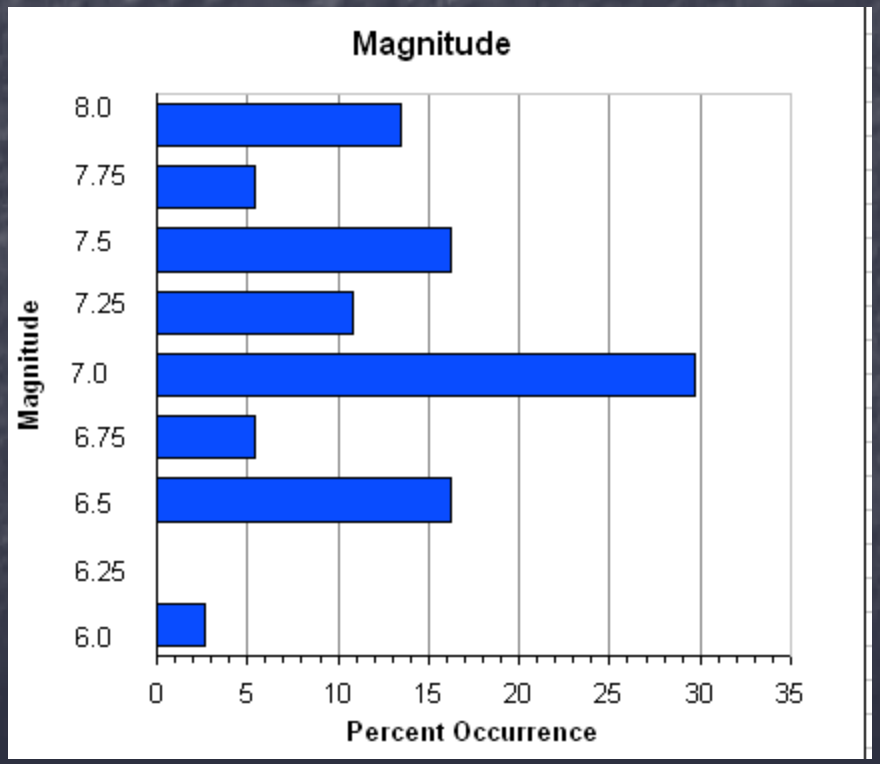


- GM Targets: 50th - 84th 5%-damped spectrum, Arias intensity
- Select "seed" records
  - similar spectral amplitude/shape
  - similar M, distance, near-source effects, site, fault style

Seed Record Issues

Design EQs commonly M $\geq$ 6.5, R $\leq$ 10 km...





Seed Record issues (cont.)

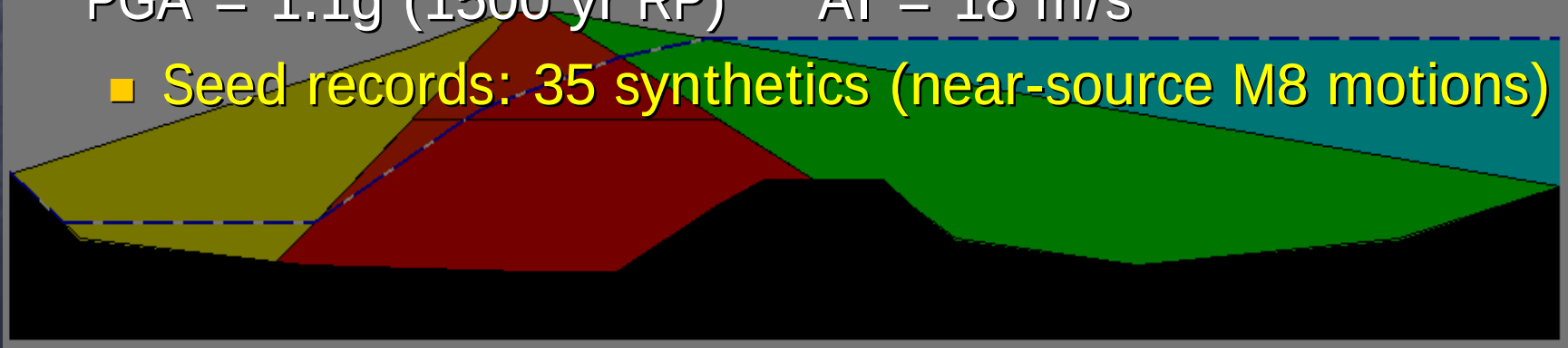
- Directivity expected …
  - Strike-slip: ~50/50 chance
  - Dip-slip: up-dip rupture for larger events
- Fewer seed record candidates…
- Potential scenario inconsistencies…

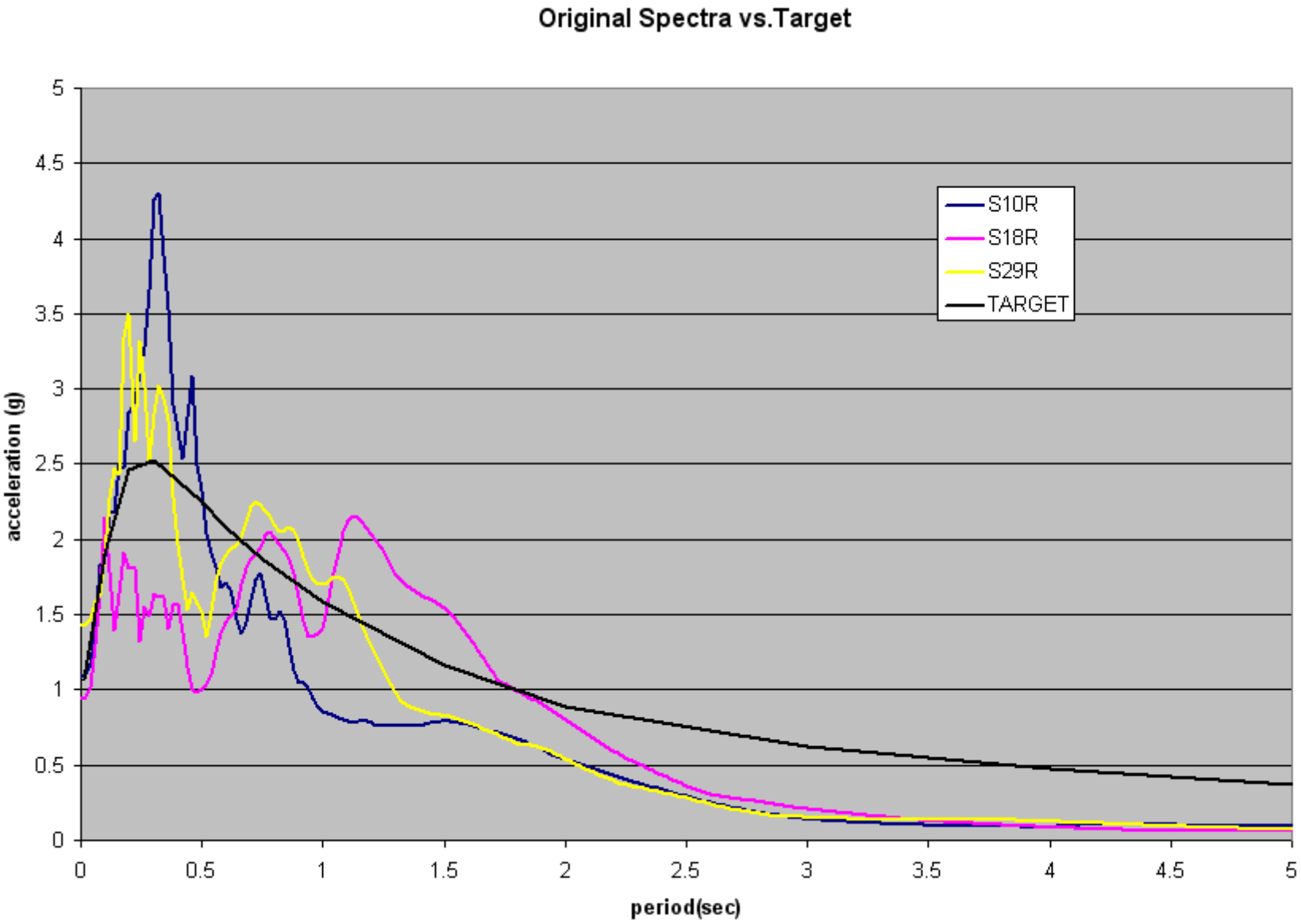
… Can use AI to check durational aspects

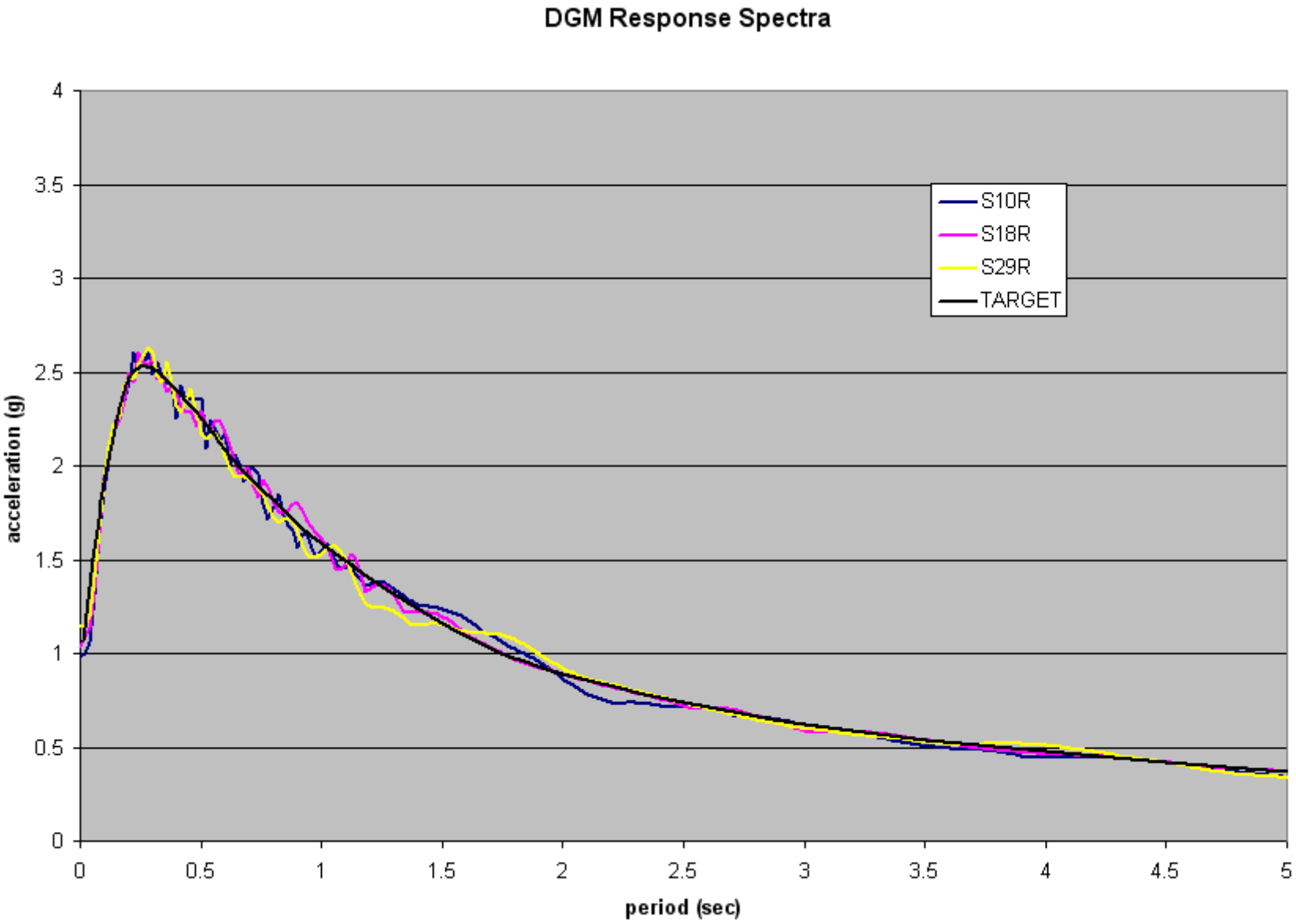
Example: Design EQ/GM Development

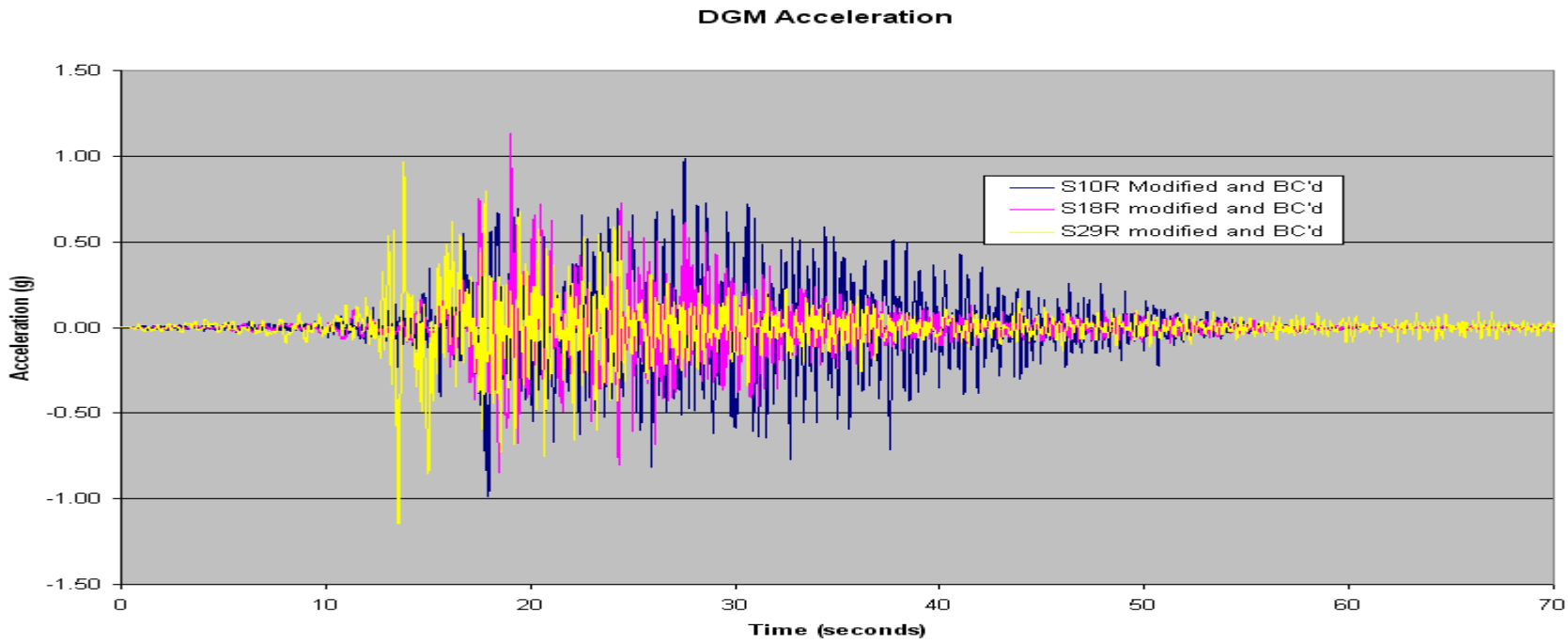
- 250 ft high, water supply to 60,000 people downstream
- 3 km from San Andreas fault (M_{max} = M8)
- Analysis section nearly FN
- K_y = 0.15
- Design GM: 84th percentile loading w/ directivity

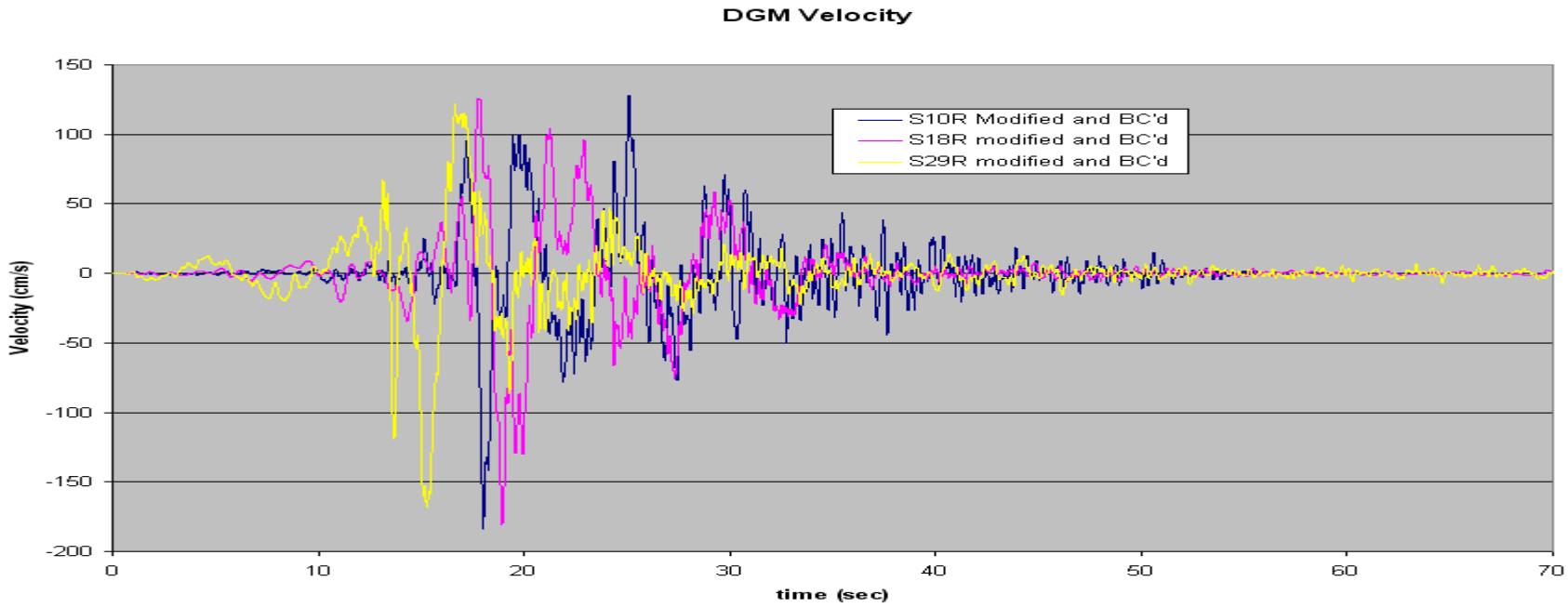
  PGA = 1.1g (1500 yr RP) AI = 18 m/s
  - Seed records: 35 synthetics (near-source M8 motions)




Original Spectra vs.Target
acceleration (g)
period(sec)
S10R
S18R
S29R
TARGET
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


DGM Response Spectra
acceleration (g)
period (sec)
S10R
S18R
S29R
TARGET
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


DGM Acceleration
Acceleration (g)
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
0
10
20
30
40
50
60
70
Time (seconds)
S10R Modified and BC'd
S18R modified and BC'd
S29R modified and BC'd


DGM Velocity
Velocity (cm/s)
150
100
50
0
-50
-100
-150
-200
0
10
20
30
40
50
60
70
time (sec)
S10R Modified and BC'd
S18R modified and BC'd
S29R modified and BC'd

Record	Newmark displacement $K_y = 0.15$	PGV	$SA_{1.0}$	Arias intensity (target ~18m/s)
S18R	**4.8 ft**	180 cm/s	1.54g	18.7 m/s
S29R	**4.7 ft**	190 cm/s	1.53g	19.1 m/s
S10R	**8.3 ft**	183 cm/s	1.54g	36.1 m/s

Conclusions:

- 84th targets yield $4^1/_2$ to 5 ft (blue is "too conservative")
- Probably not "1500-yr" motions (PGA poor indicator)
- How conservative?

Assessing GM Conservatism

- Need different parameter for PSHA
- PBEE - ideal parameter is...
  - Efficient – correlates well w/ performance
  - Sufficient – predicts performance by itself
- PGA, PGV, SA aren't....
- Note: DSOD concerned with large motions and large deformations (e.g., feet)

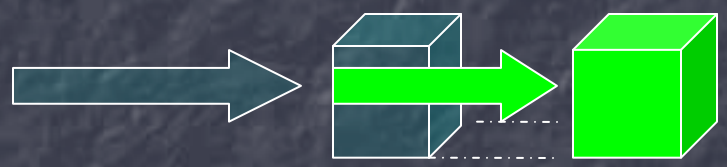
Force vs. Work/Energy

- Force: potential to move an object (F = m × a)

stress, pressure

- Work: object's displacement from application of force over time (W = F × d)

displacement, settlement, strain



  - Work: transfer of energy to object
    (Energy = potential to do work)

Analysis for potential displacement, deformation, strain (**work**), should consider GM **energy**

- Most Dynamic Geotechnical Analyses Implicitly Address Work/Energy

…when GM amplitude & duration used:

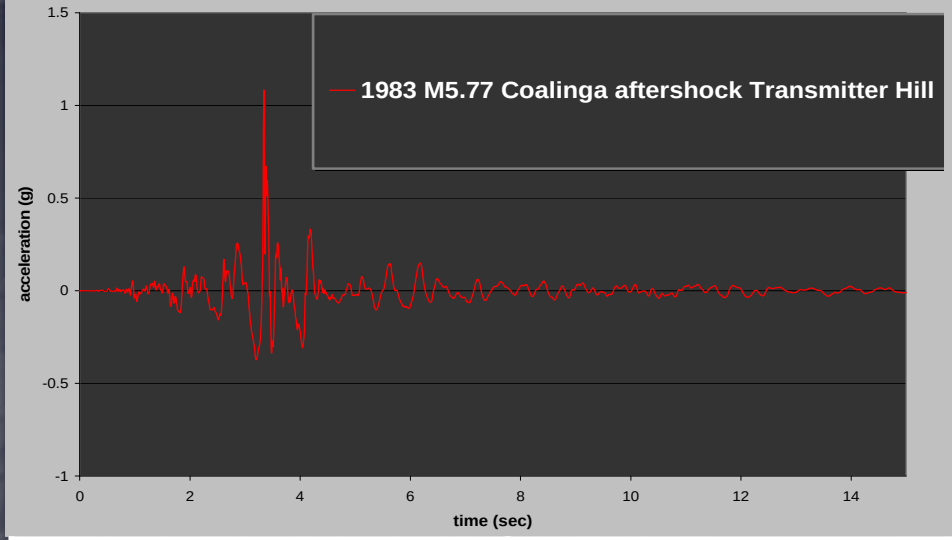
- Simplified: when using peak value and Magnitude (as proxy for duration)
- Detailed: when using acceleration time history

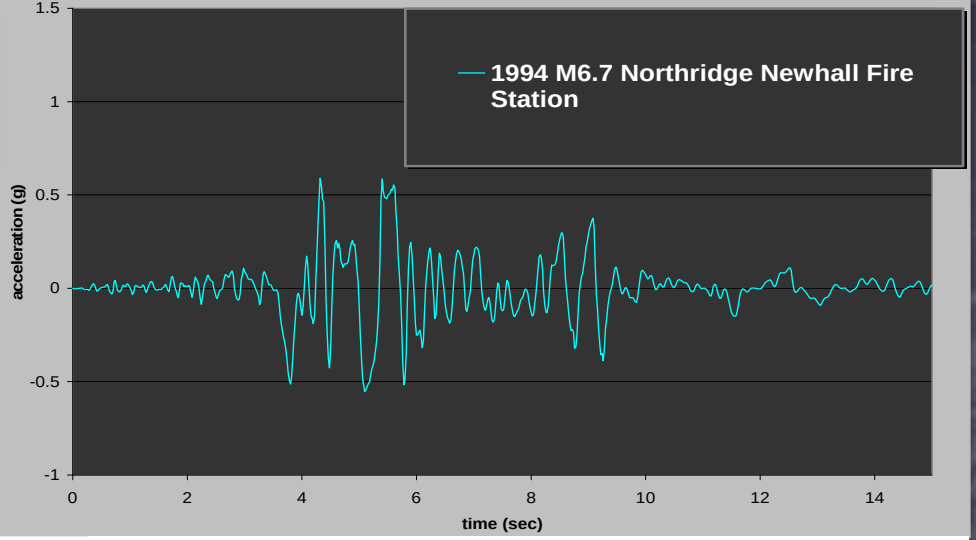
Arias Intensity:

$$I_a = \frac{\pi}{2g}\int_0^{\infty}[a(t)]^2\,dt$$

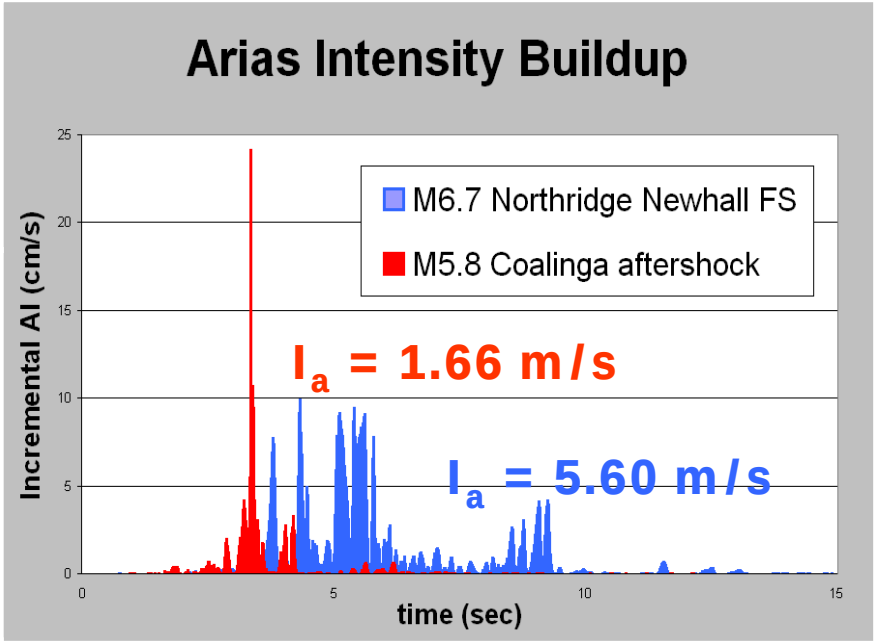
Wave Energy: "sum of the squares of the amplitudes of elements in a wavelet times a proportionality constant that is often omitted"

(Encyclopedic Dictionary of Geophysics, 3rd edition, 1991)





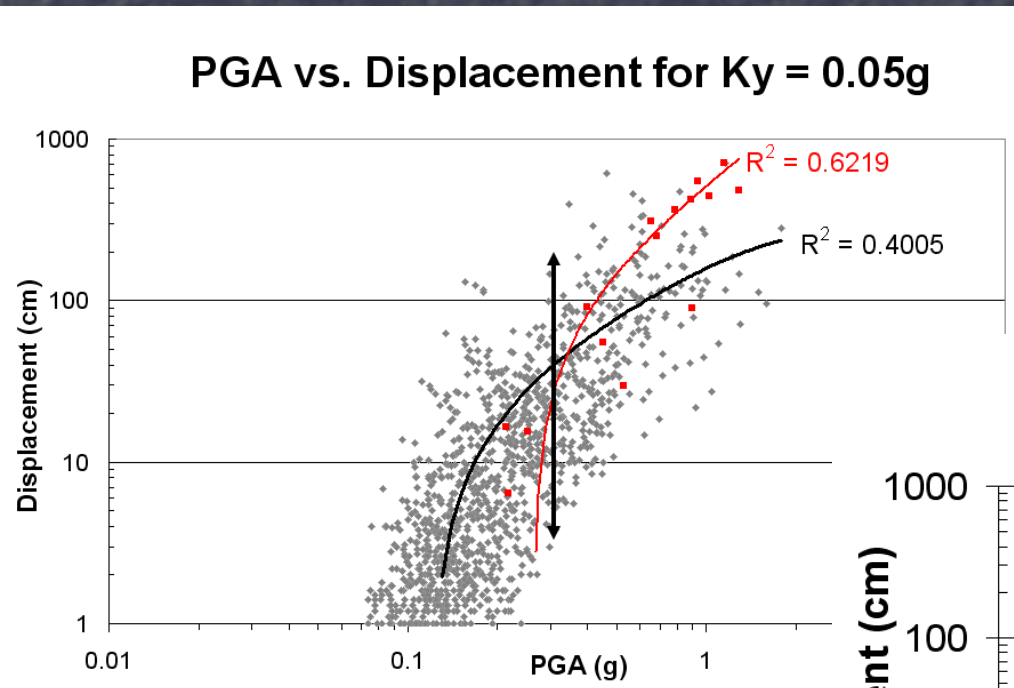
Ground motion record	Coalinga M5.8 aftershock	Northridge M6.7 Newhall FS
Peak acceleration	1.08g	0.59g
Peak velocity	40 cm/s	97 cm/s
Arias Intensity	**1.7 m/s**	**5.6 m/s**
Newmark Displacement k_y0.15	**0.24 ft**	**1.69 ft**



Arias Intensity addresses amplitude & durational aspects (energy)

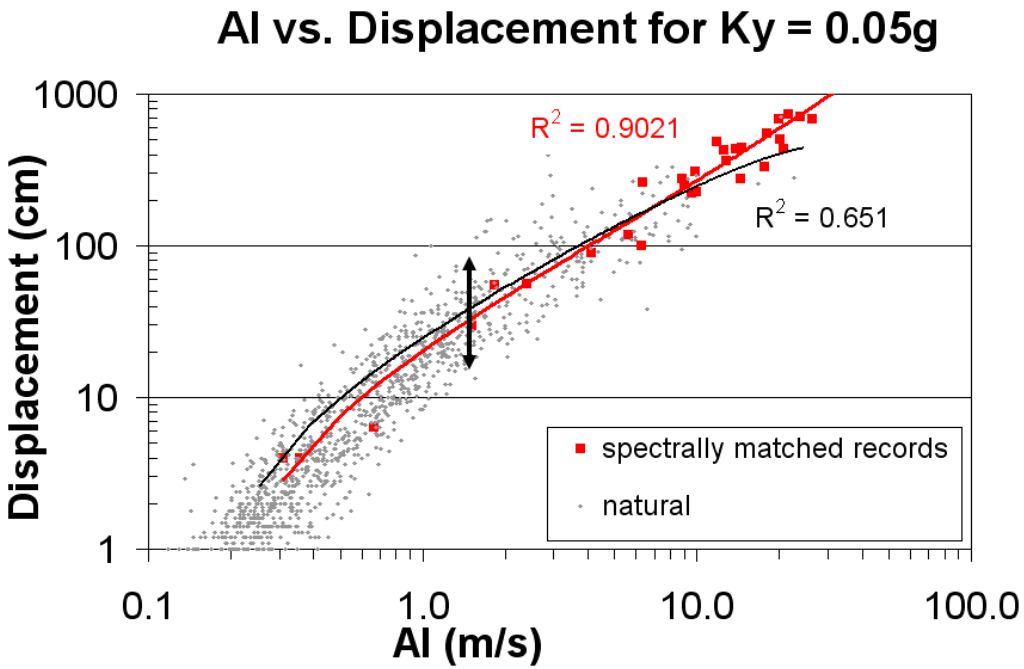
Efficiency & Sufficiency:

Arias Intensity & PGA vs. Newmark Displacement natural & spectrally matched motions



Arias intensity

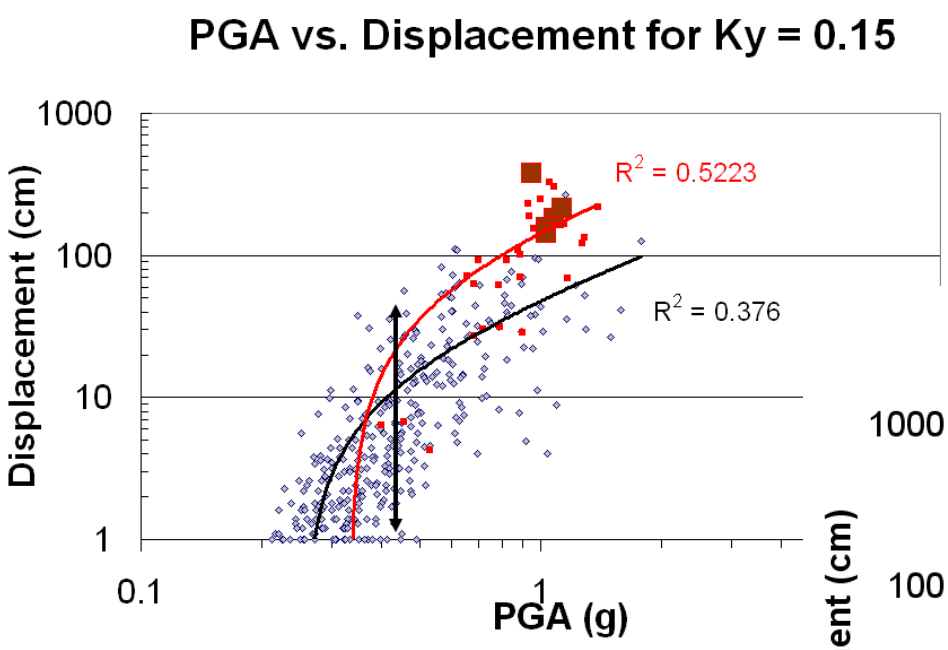
PGA



after Jibson &Jibson (2003)

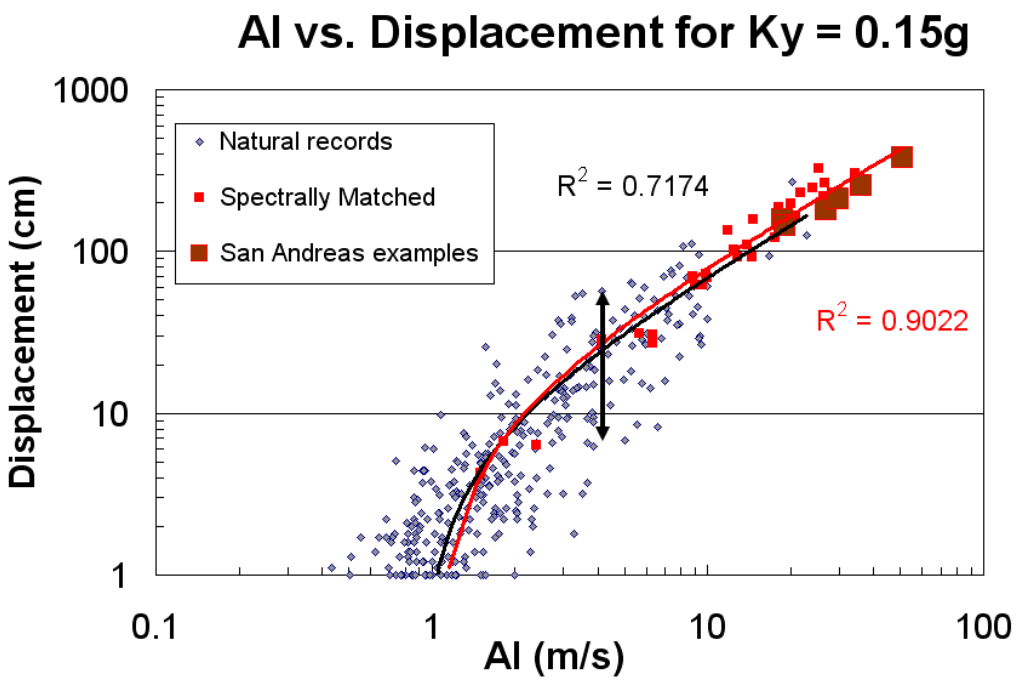
Efficiency/Sufficiency (cont).

Arias Intensity & PGA vs. Newmark Displacement natural & spectrally matched motions

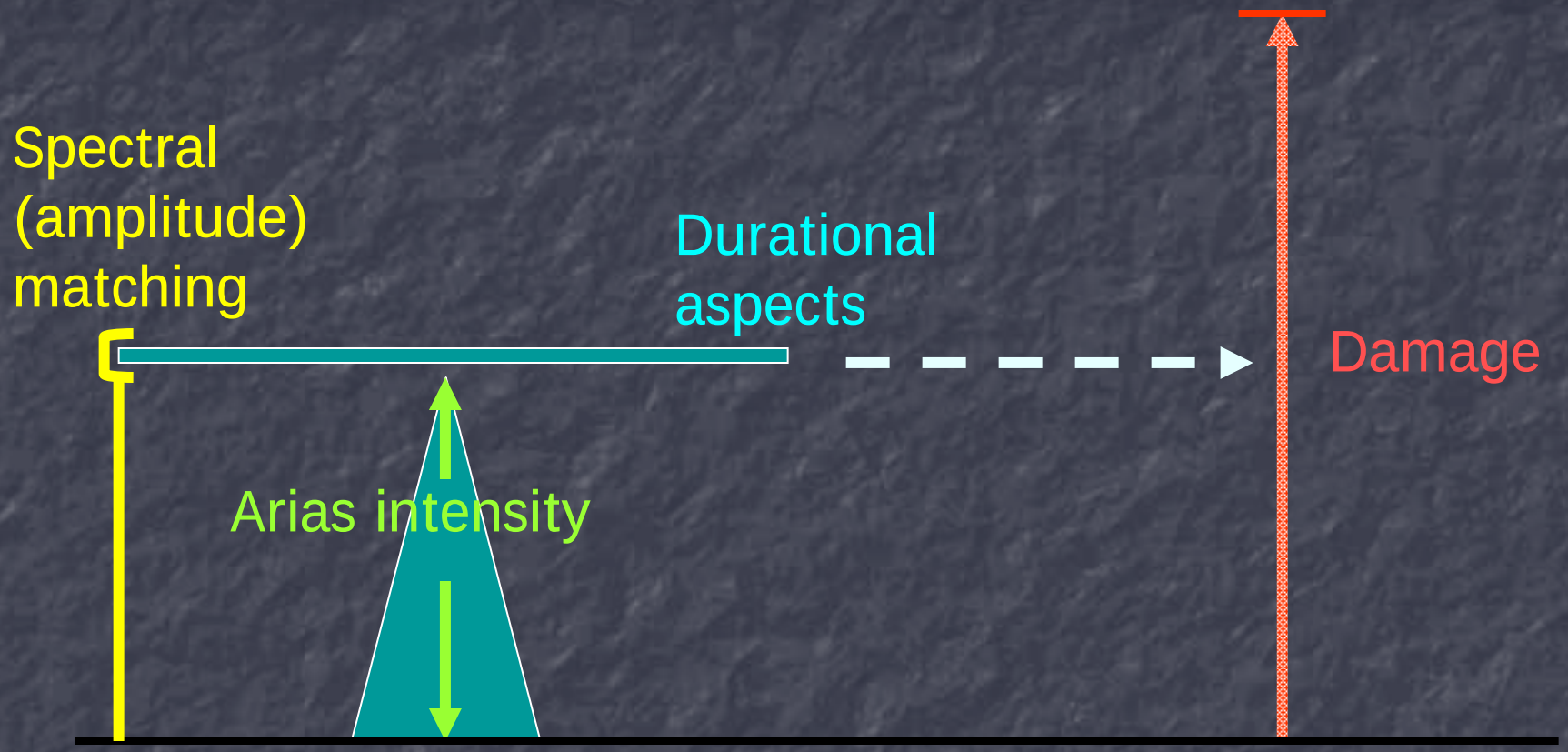


Arias intensity

PGA



after Jibson &Jibson (2003)


Spectral
(amplitude)
matching
Durational
aspects
Damage
Arias intensity

Prediction Capability and PSHA:
Empirical AI Attenuation Formulas

- Travasarou, Bray, and Abrahamson (2003)

  $\ln(AI) = f(M_w, R_{rup}, \text{site condition, fault style})$

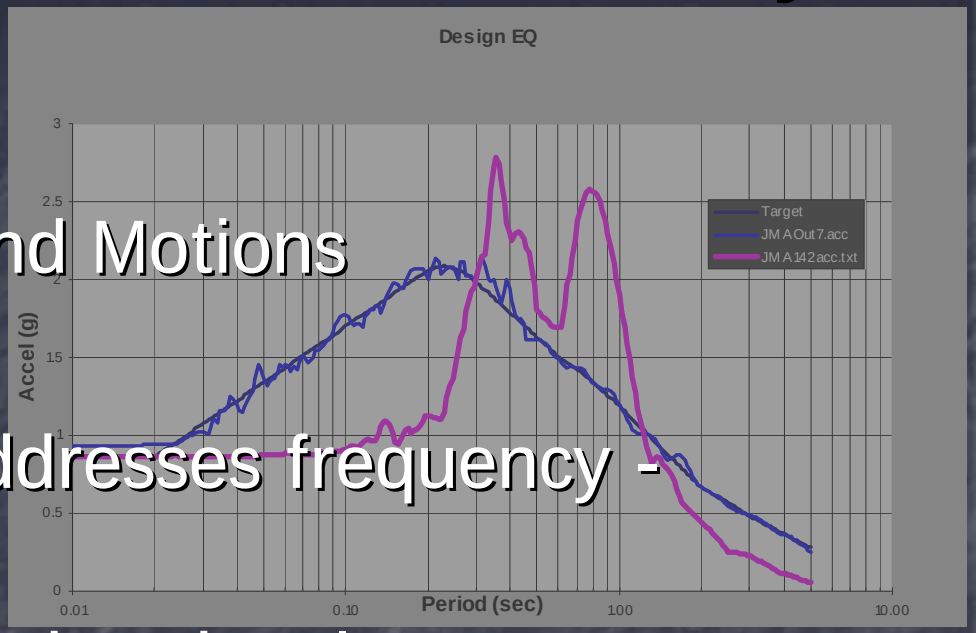
- Watson-Lamprey and Abrahamson (2006)

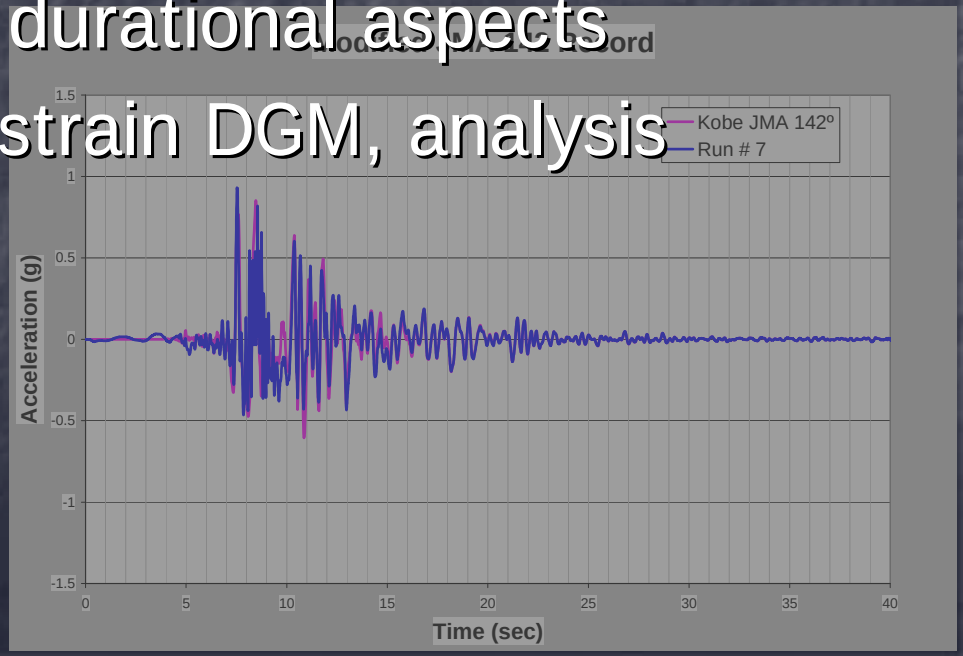
  $\ln(AI) = f(M_w, R_{rup}, V_{s30}, PGA, SA_{T@1s})$

Potential Uses for Arias Intensity Predictions

1) Targets for Design Ground Motions

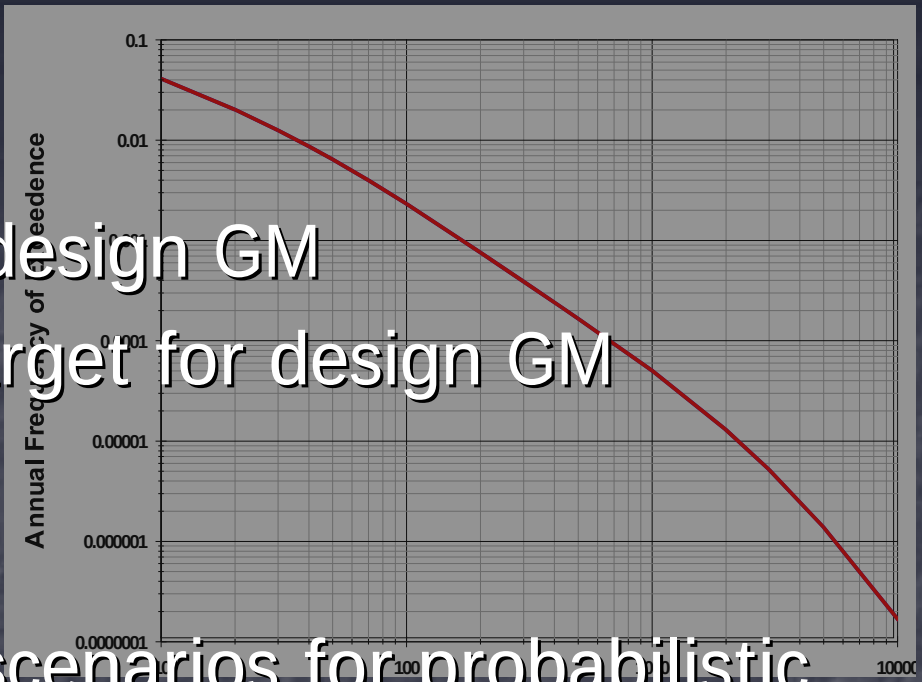
- Response spectrum addresses frequency - amplitude
- AI (energy) addresses durational aspects
- Use both to better constrain DGM, analysis





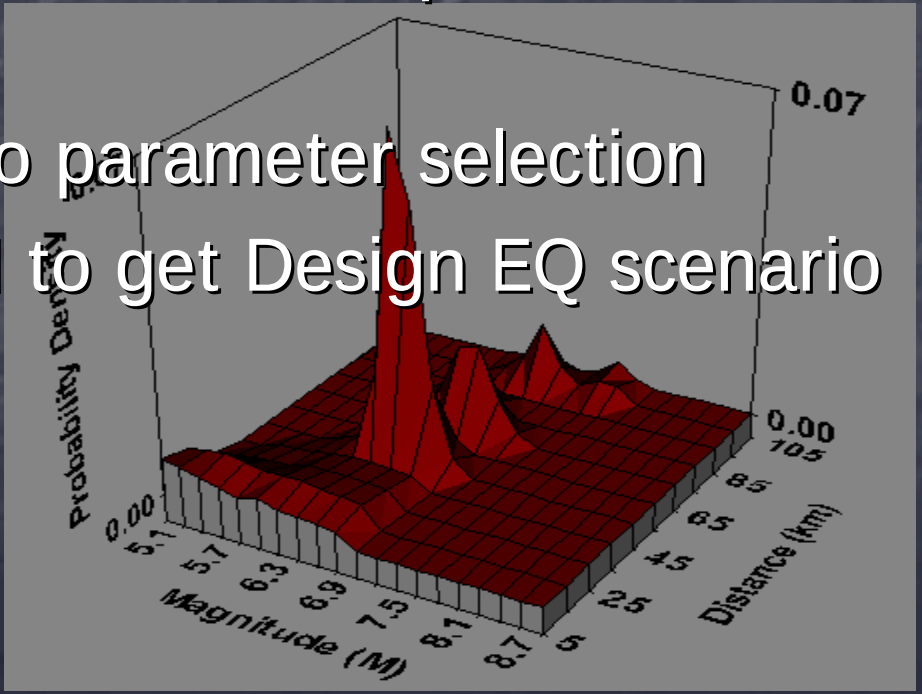
2) PSHA Hazard Curves

- Conservatism of design GM
- Probabilistic AI target for design GM

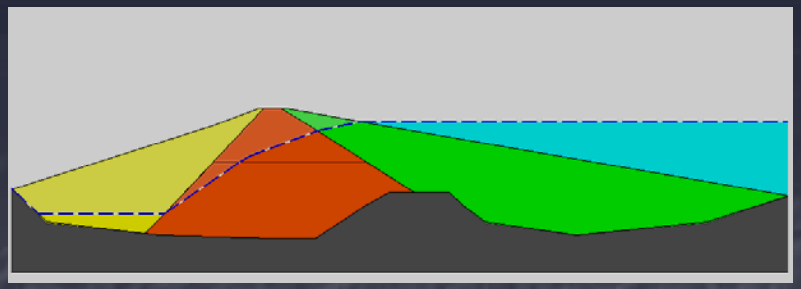


3) PSHA Deaggregation

- Gives most likely scenarios for probabilistic load
- Results sensitive to parameter selection
- Consider AI-based to get Design EQ scenario

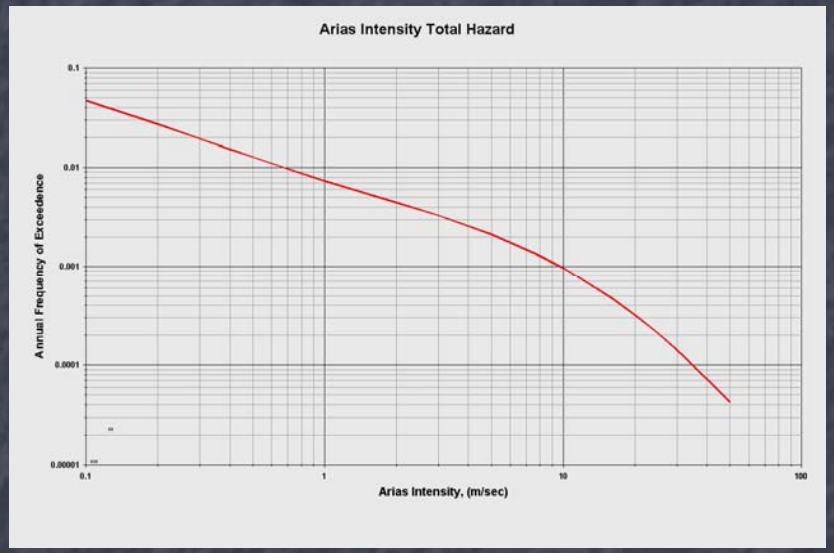


Example: Dam near San Andreas fault:



Design GM conservatism based on AI

- 84th target AI = 18 m/s
  2000-yr return period



Revisiting design GM results:

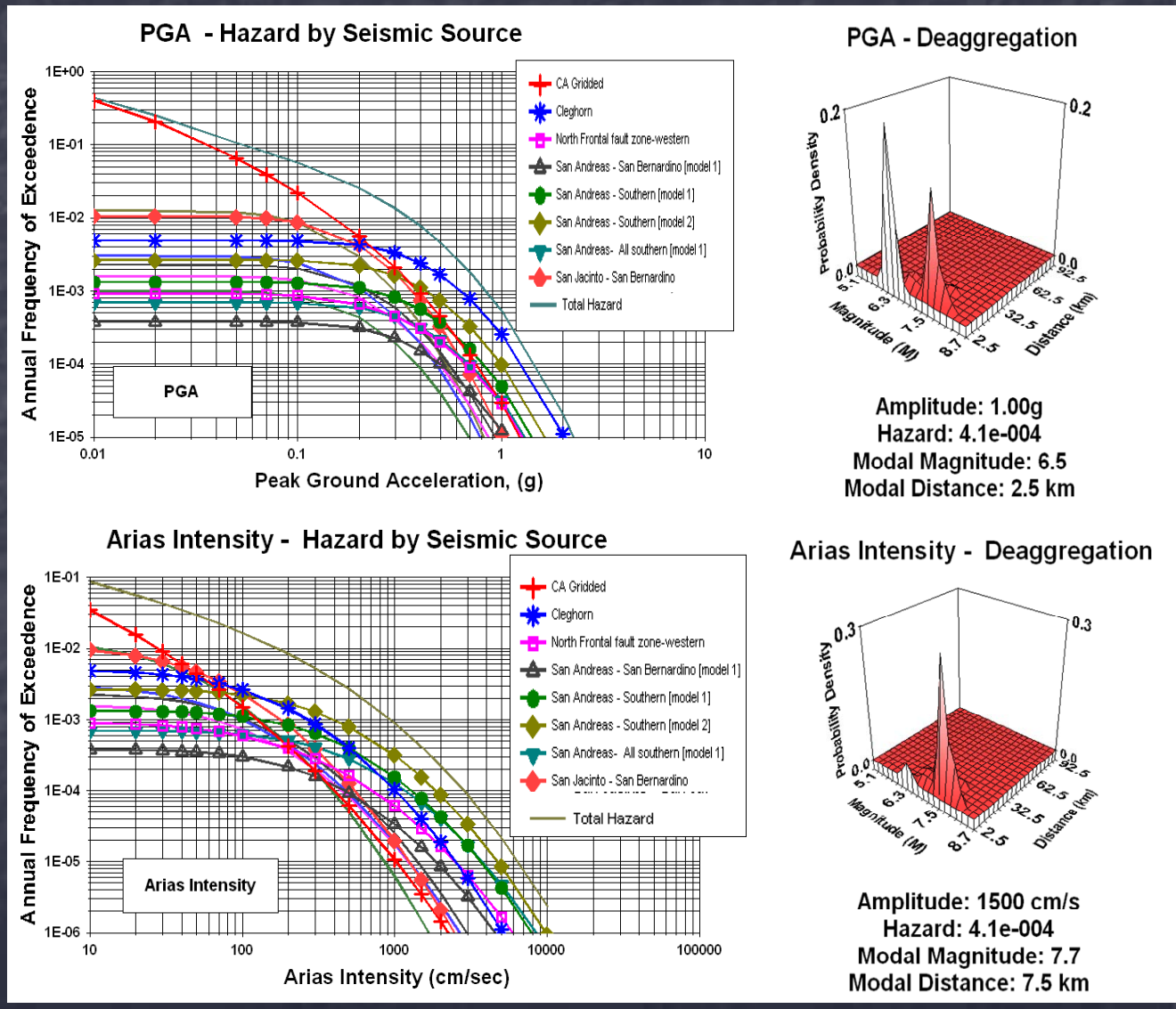
- S18R - 4.8 ft AI = 18.7 (2100-yr)
- S29R - 4.7 ft AI = 19.1 (2200-yr)
- S10R - 8.3 ft AI = 36.1 (7500-yr)

- S23R - 6.0 ft AI = 27.0 (3700-yr)
- S16R - 7.0 ft AI = 29.6 (5000-yr)
- CT3N - 7.4 ft AI = 36.7 (7500-yr)
- S37-090 - 12.5 ft AI = 50.8 (16,500-yr)

Design Earthquakes from PSHA

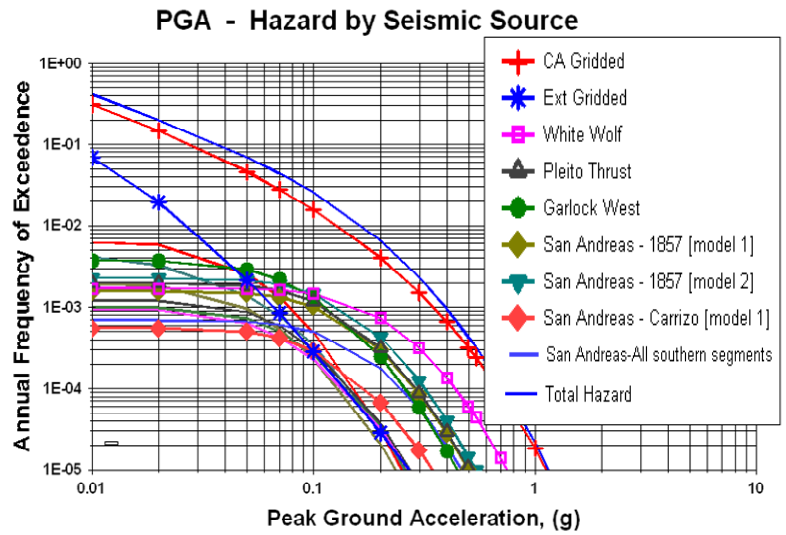
San Bernardino Mountains – weathered rock site

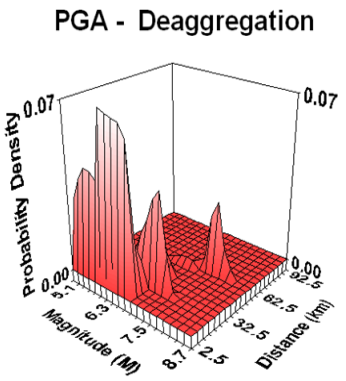
- 2500-yr ERP
- PGA (1.0g): M6.5 @ 3 km
- AI (15 m/s): M7.7 @ 8 km



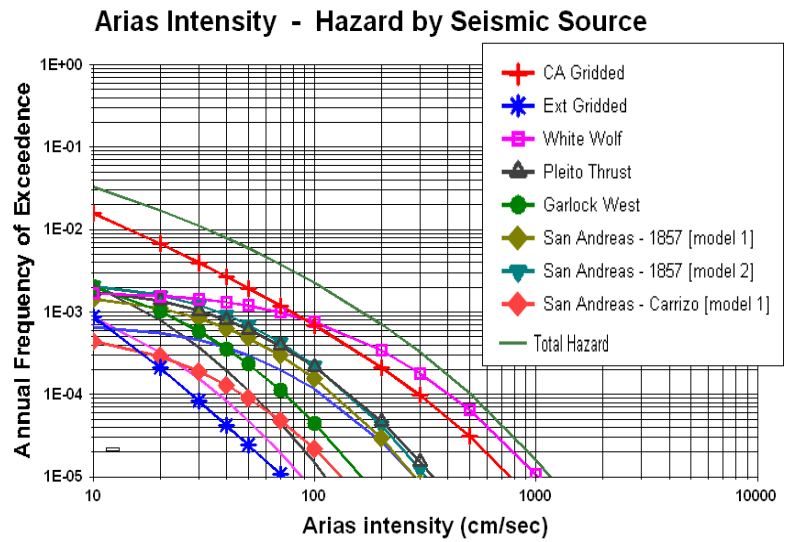
SE of Bakersfield – soil site

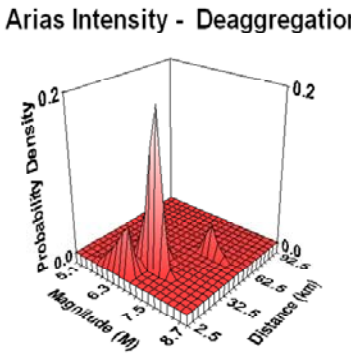
- 3000-yr ERP
- PGA (0.54g): M6 @ 8 km
- AI (3 m/s): M7.3 @ 23 km





Amplitude: 0.54g
Hazard: 3.3e-004
Modal Magnitude: 6.1
Modal Distance: 7.5 km

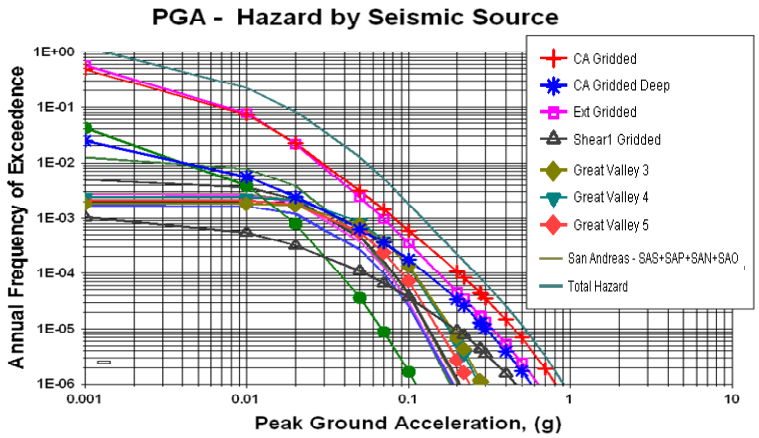


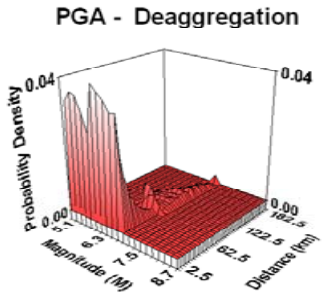


Amplitude: 300 cm/s
Hazard: 3.3e-004
Modal Magnitude: 7.3
Modal Distance: 22.5 km

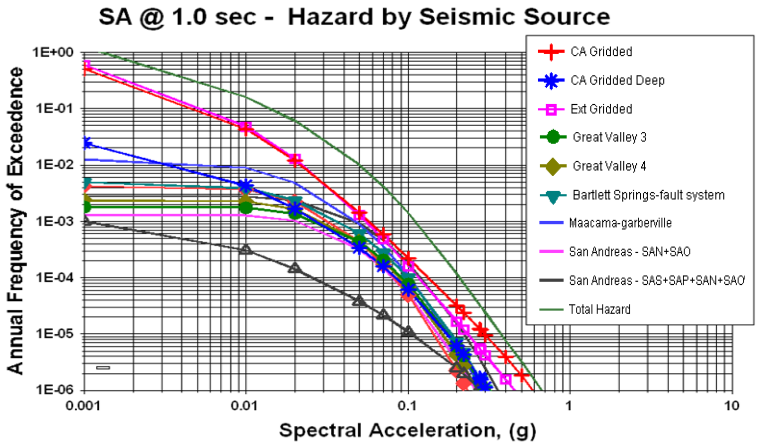
Eastern Sacramento Valley – unweathered rock site

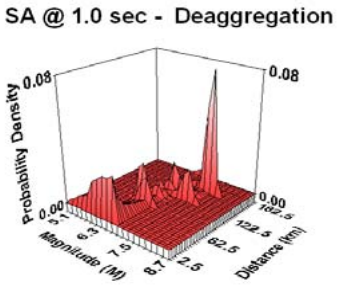
- 10,000-yr ERP
- PGA (0.28g): M6 @ 8 km
- SA_{1s} (0.22g): M7.9 @ 160 km
- AI (1.0m/s) M6.5 @ 77km



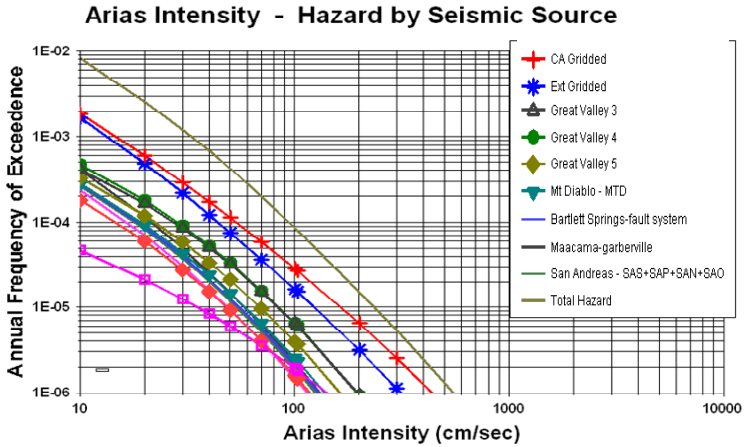


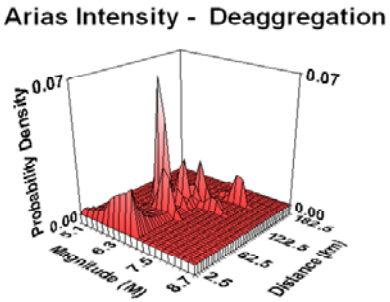
Amplitude: 0.28g
Hazard: 8.0e-005
Modal Magnitude: 6.1
Modal Distance: 7.6 km





Amplitude: 0.22g
Hazard: 8.0e-005
Modal Magnitude: 7.9
Modal Distance: 157.5 km





Amplitude: 103.00 cm/s
Hazard: 8.0e-005
Modal Magnitude 6.5
Modal Distance: 77.5 km

Summary

- Embankment dynamic analysis is concerned with ground motion amplitude & durational aspects - (energy)
- AI represents GM energy
- AI correlates with inertial displacement (esp. for spectrally matched GM) – efficient/sufficient
- Robust AI prediction capability exists (DSHA & PSHA)
- AI + spectral targets better constrain design analysis
- PSHA using AI
  - Hazard curves – GM conservatism or probabilistic target
  - Deaggregation - design EQ scenarios for probabilistic load

end