Adjusted ASK14 Model for Induced Earthquakes

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Evaluation of Deformation Hazard for Dams from Induced Seismicity[2]

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Modified ASK14 funding from BCHydro,
Dam deformation model funding from PG&E

Seismic Hazard and Risk

- Source Model
- Ground-Motion Model
- Structural Response

<u>Deterministic Approach for Dams</u>

- Choose large rare eqk (M,R)
- Select GM: P(PSA>z|M,R)=0.16

Ground-Motion Hazard

$$Haz(PSA(T) > z) \;=\; \sum Rate(M_i, R_i)\; P(PSA > z|M_i, R_i)$$

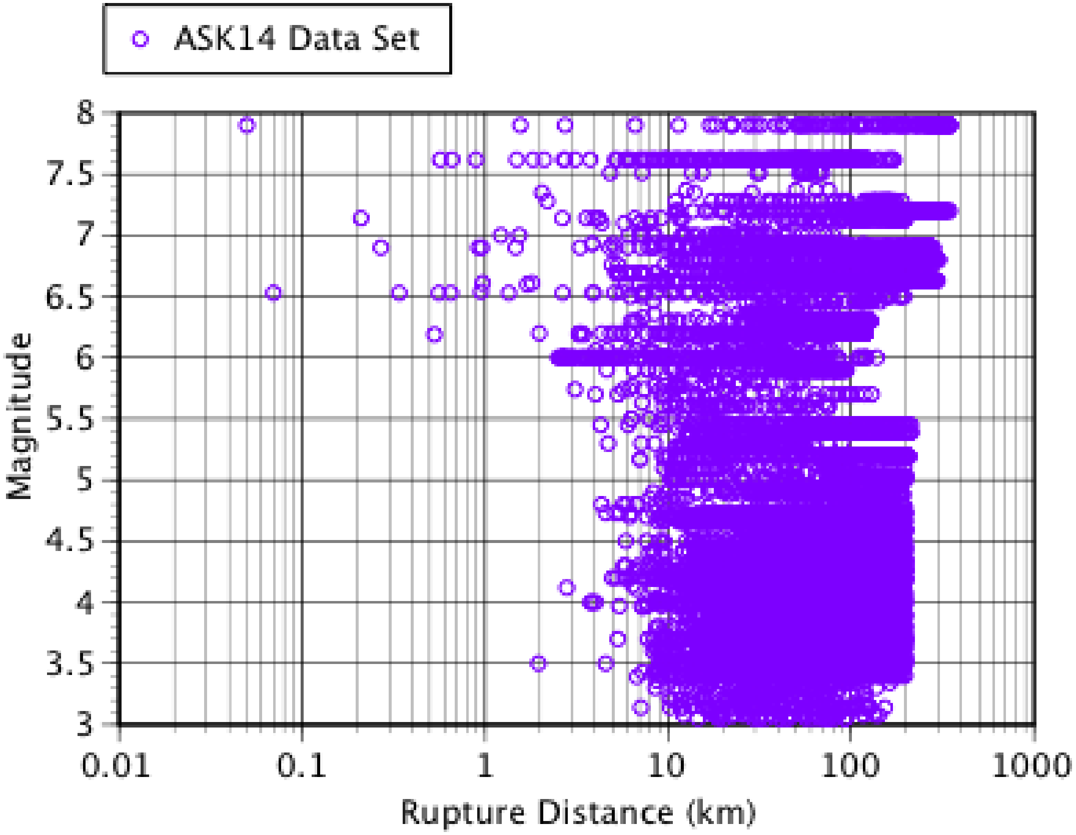
Dam Deformation Hazard

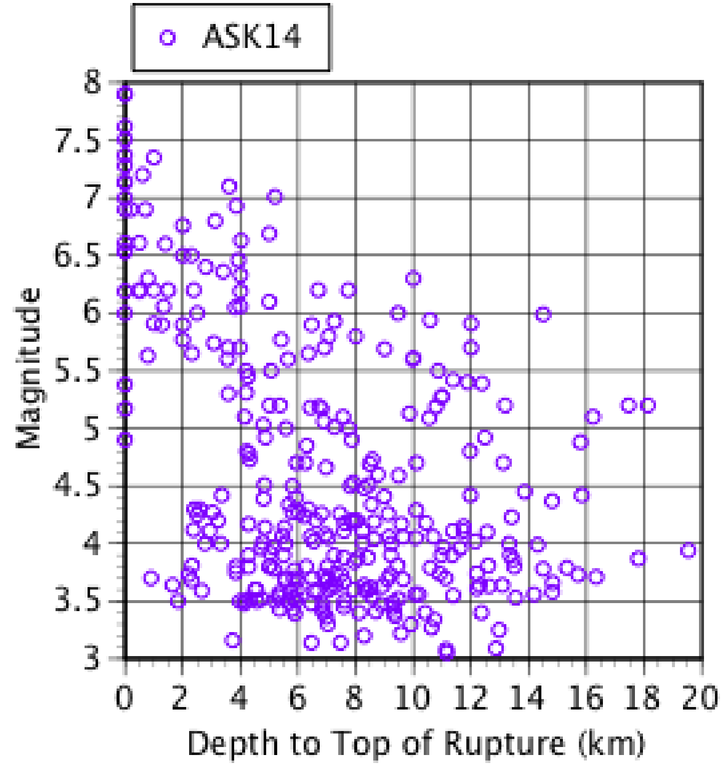
$$Haz(Dam\; Def \;> d) \;=\; \sum Rate(M_i, R_i)\; P(Def \;> d|M_i, R_i)$$

Issues for GMPEs for Induced Eqk

- Most GMPEs focused on extrapolation to short distances for large magnitudes
  - Little attention was paid to small/moderate magnitudes at short distances
  - Few data from small/moderate magnitudes at short distances

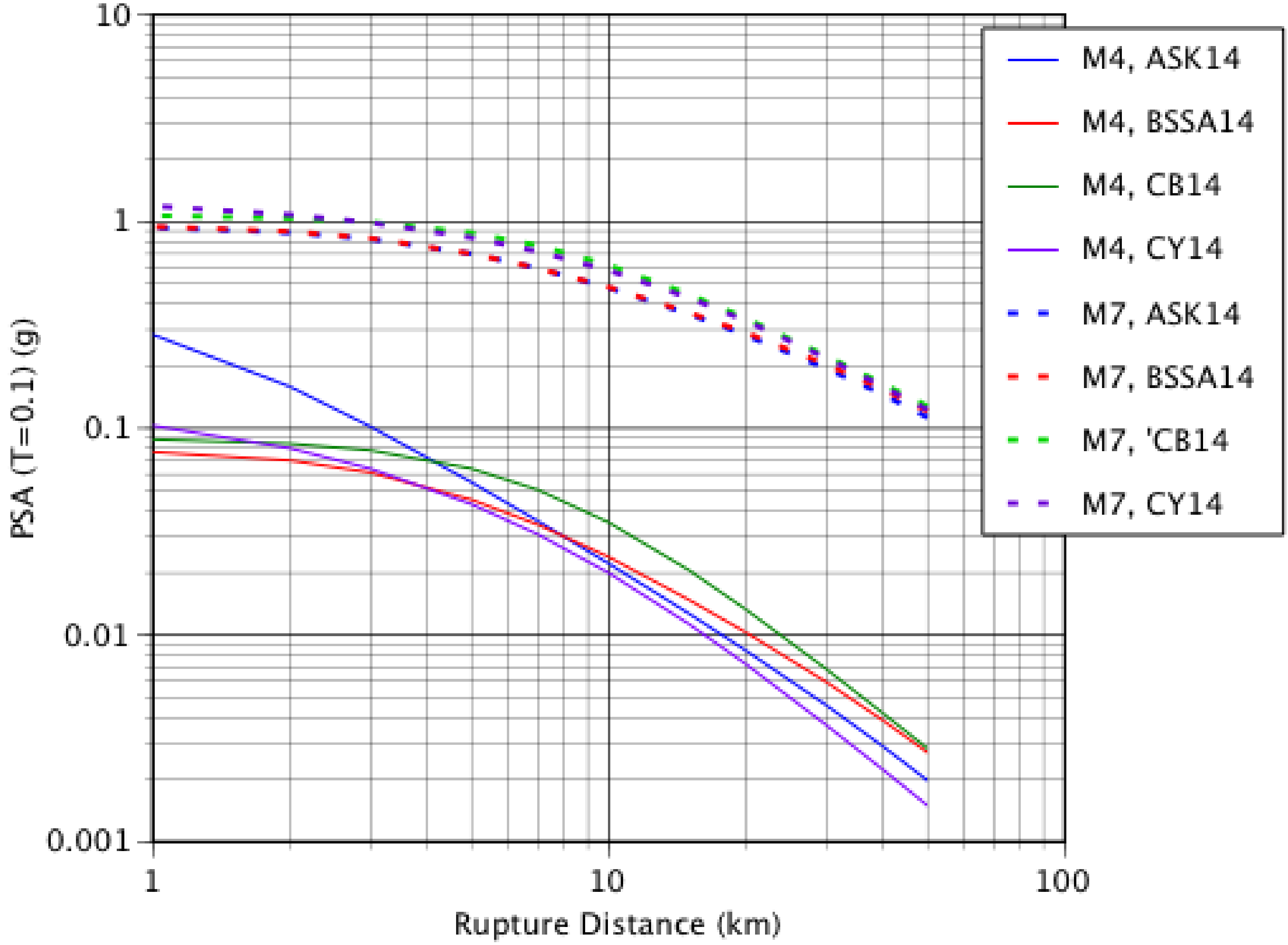
ASK14 Data Set





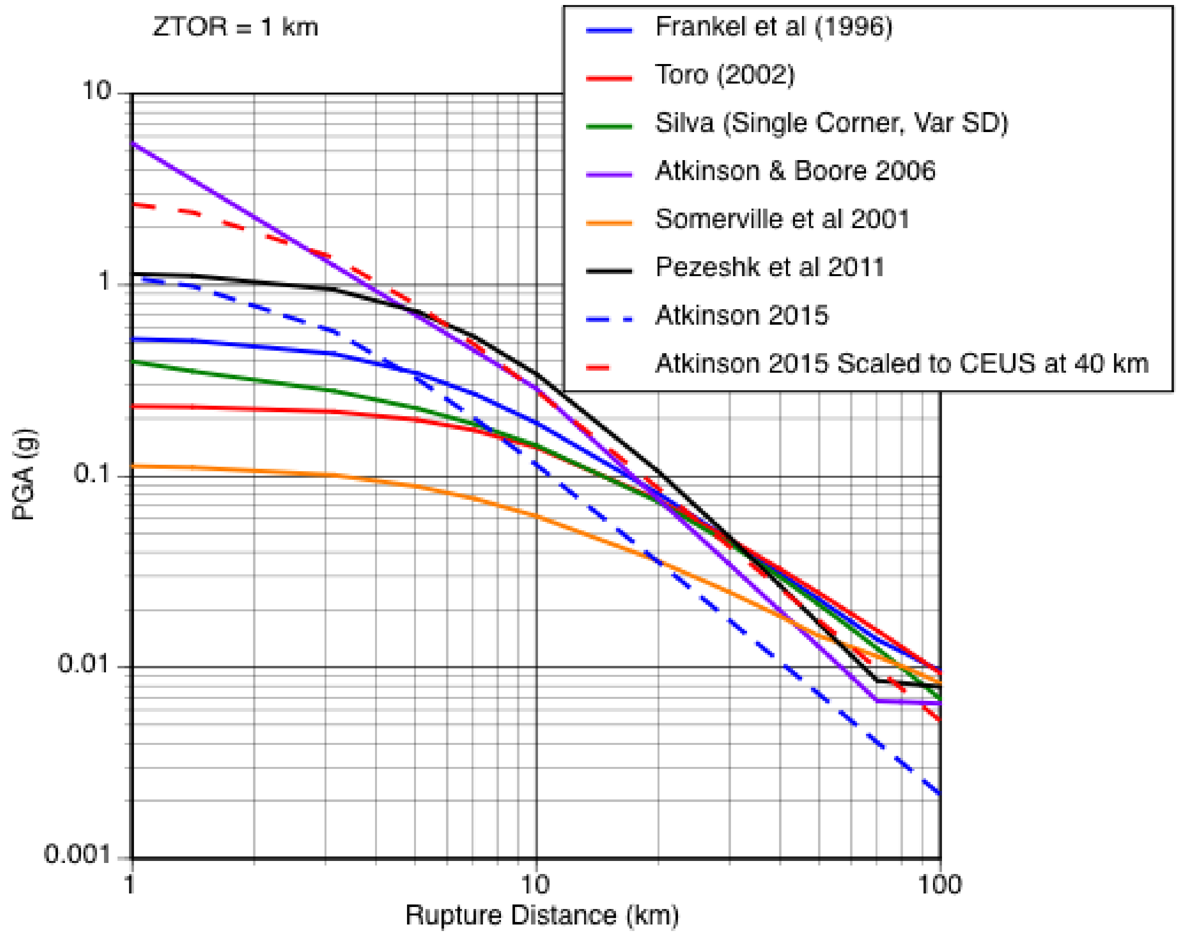
Finite-Fault Term $(c_4 + c_5 M) \, Ln(R + H(M))$

For GMPE Developers, focus has been on larger magnitudes



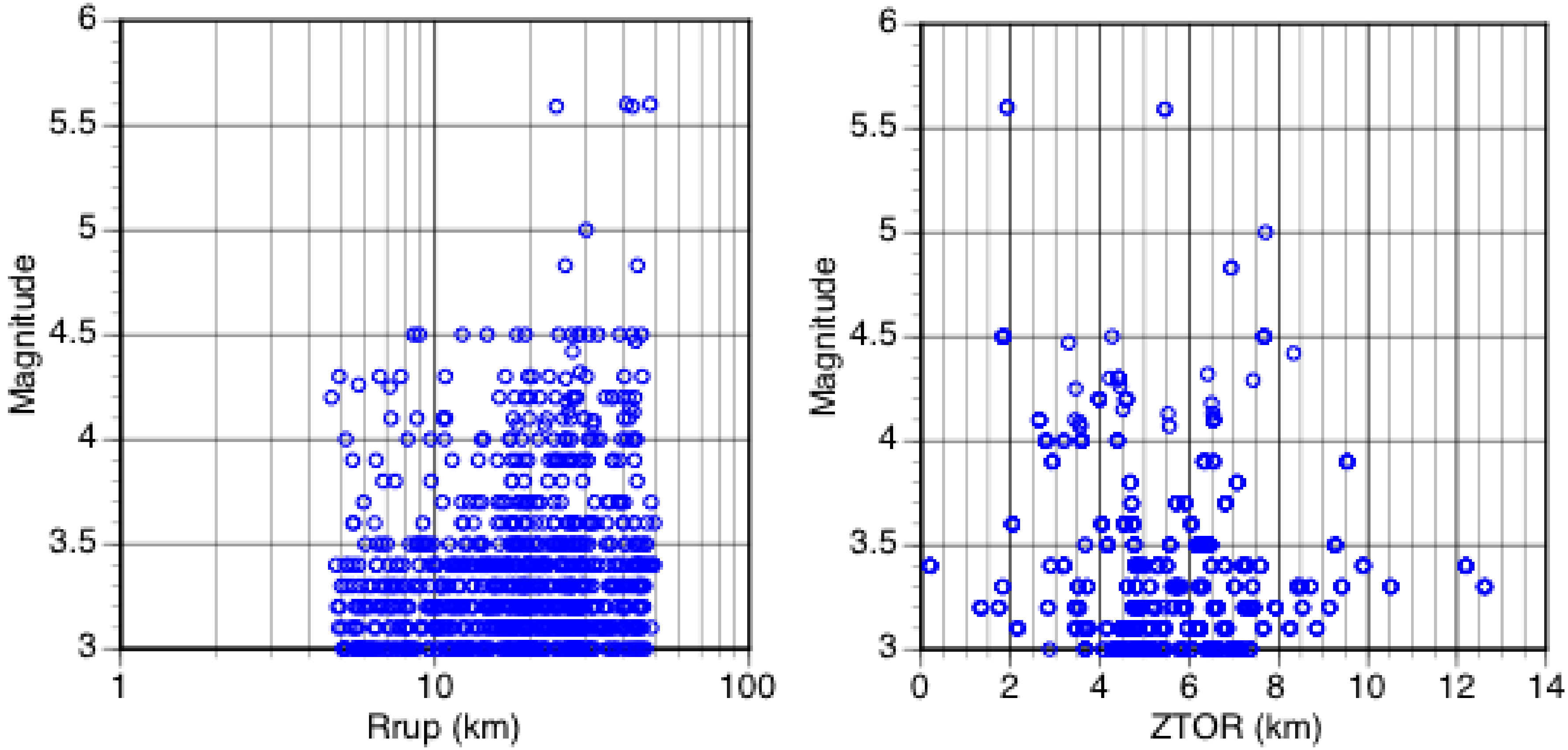
Similar Issue for Many CEUS GMPEs

M=5, Top of Rupture (ZTOR) = 1 km

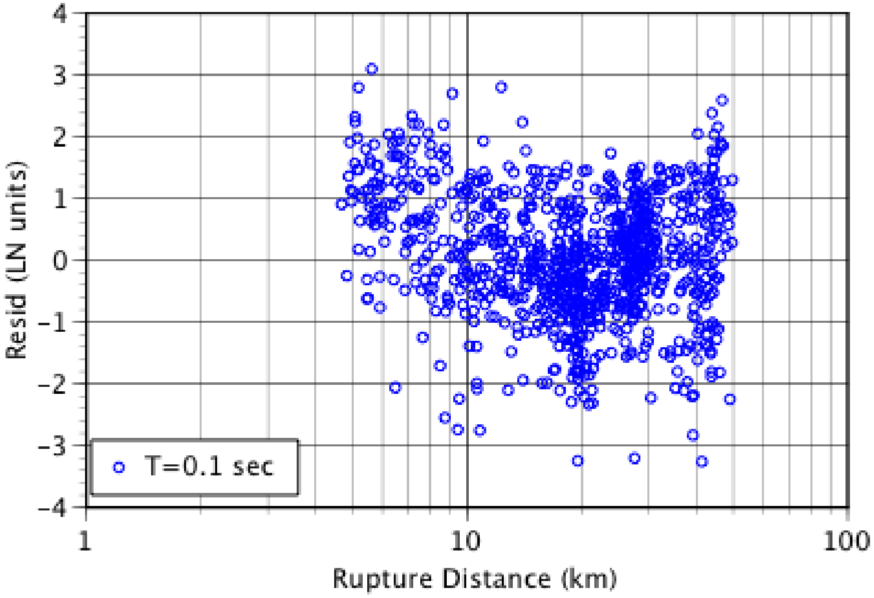


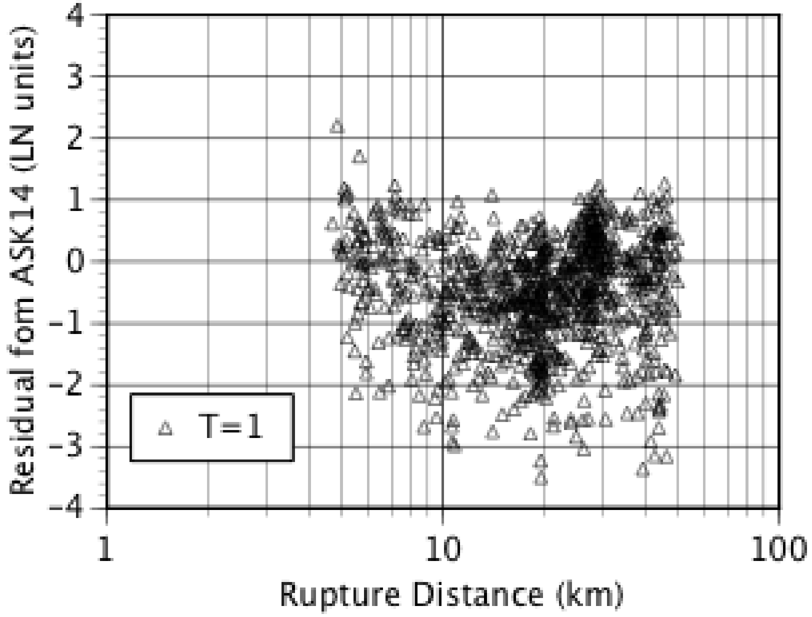
Selected Induced Eqk Data Set

Mainly Oklahoma Region



Residuals Relative to ASK14

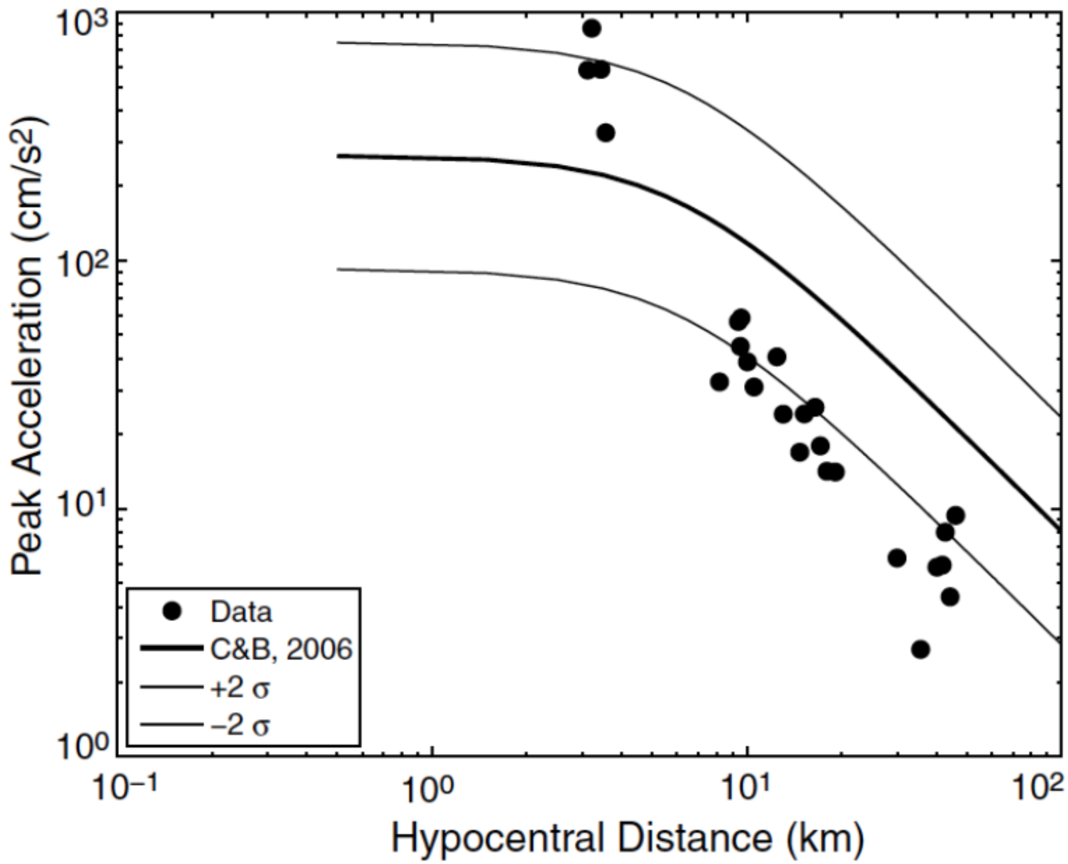




Magnitude range for steeper distance scaling

- What is the magnitude limit for the distance scaling adjustment?
  - Data for M>4.5 are for Rrup > 20 km
- Look at earthquakes from other regions
  - Mogul, Nevada M5, data for Rrup=3-4 km

2009 Mogul, Nevada Earthquake (M=5.0, Depth=3.1 km)



From Anderson et al, BSSA 2009

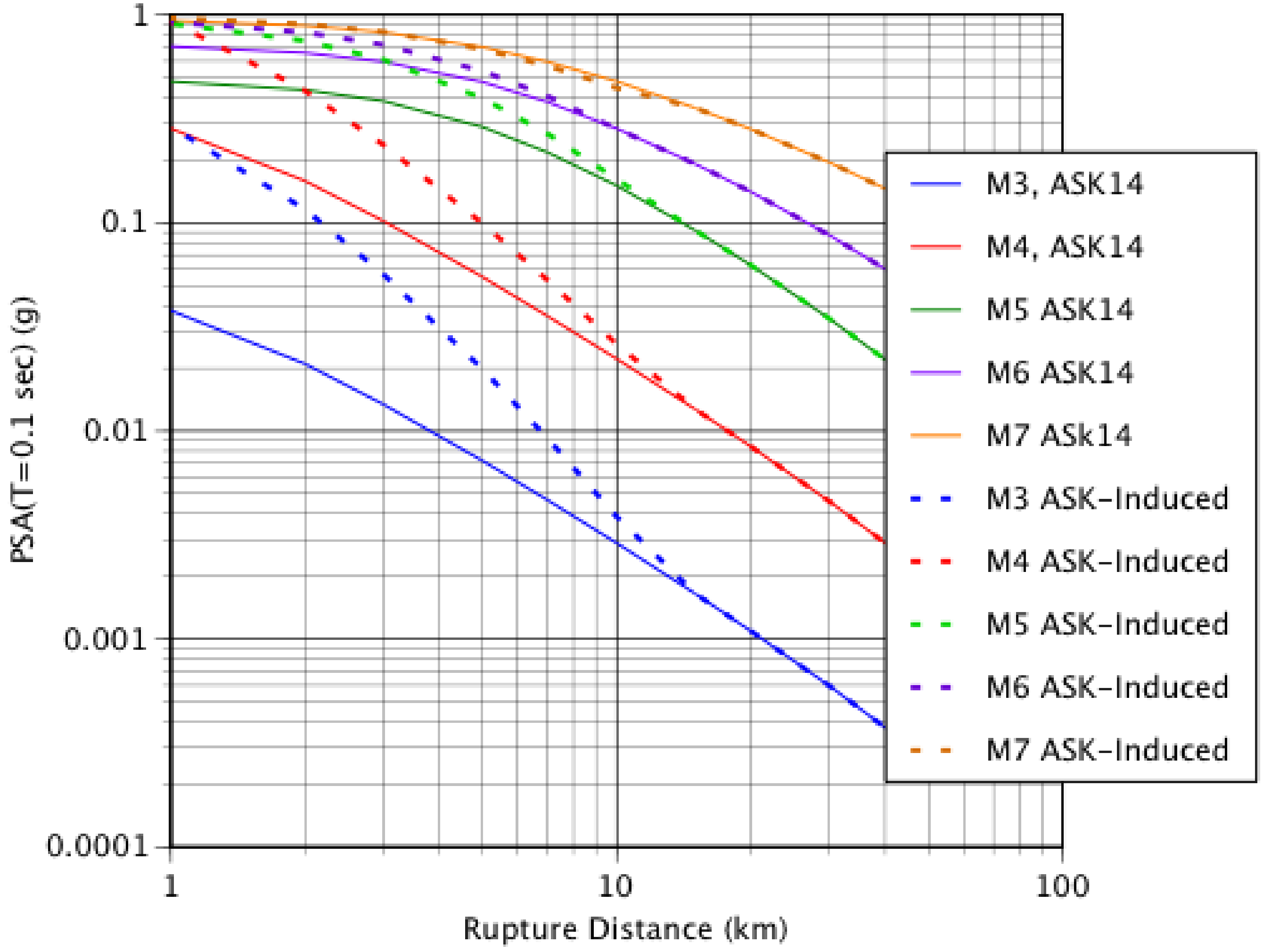
Functional Form of Adjustment to ASK14

$$f_{adjust}(M, R_{RUP}) = (c_0 + f_R(R_{RUP}, L)) * f_m(M)$$

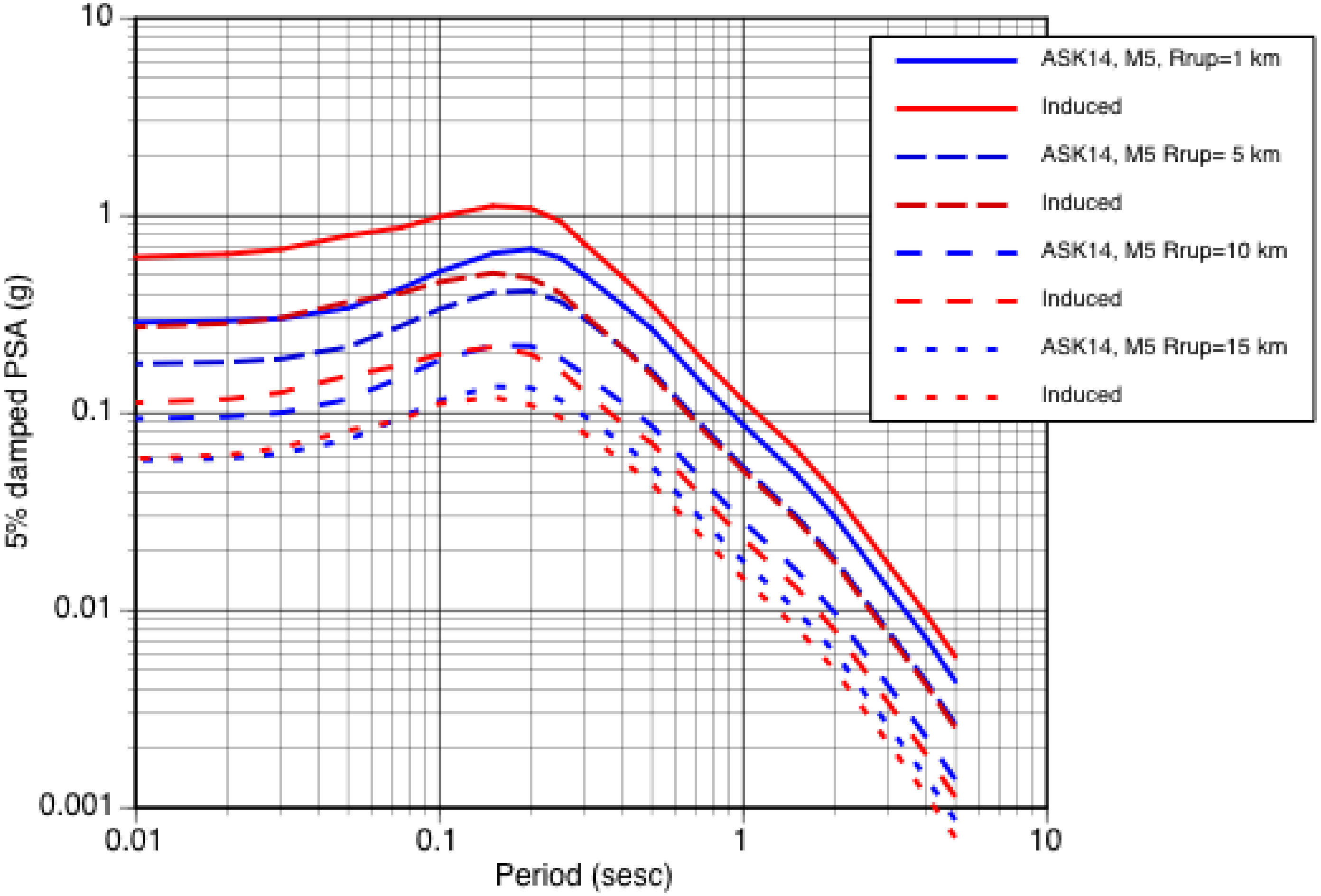
Avoid oversaturation

$$f_R(R_{RUP}, L) = \begin{cases} c_1 ln\left(\frac{R_1+2}{R_c+2}\right) & \text{for } R_{RUP} < R_c \\ 0 & \text{for } R_{RUP} \geq R_c \end{cases}$$

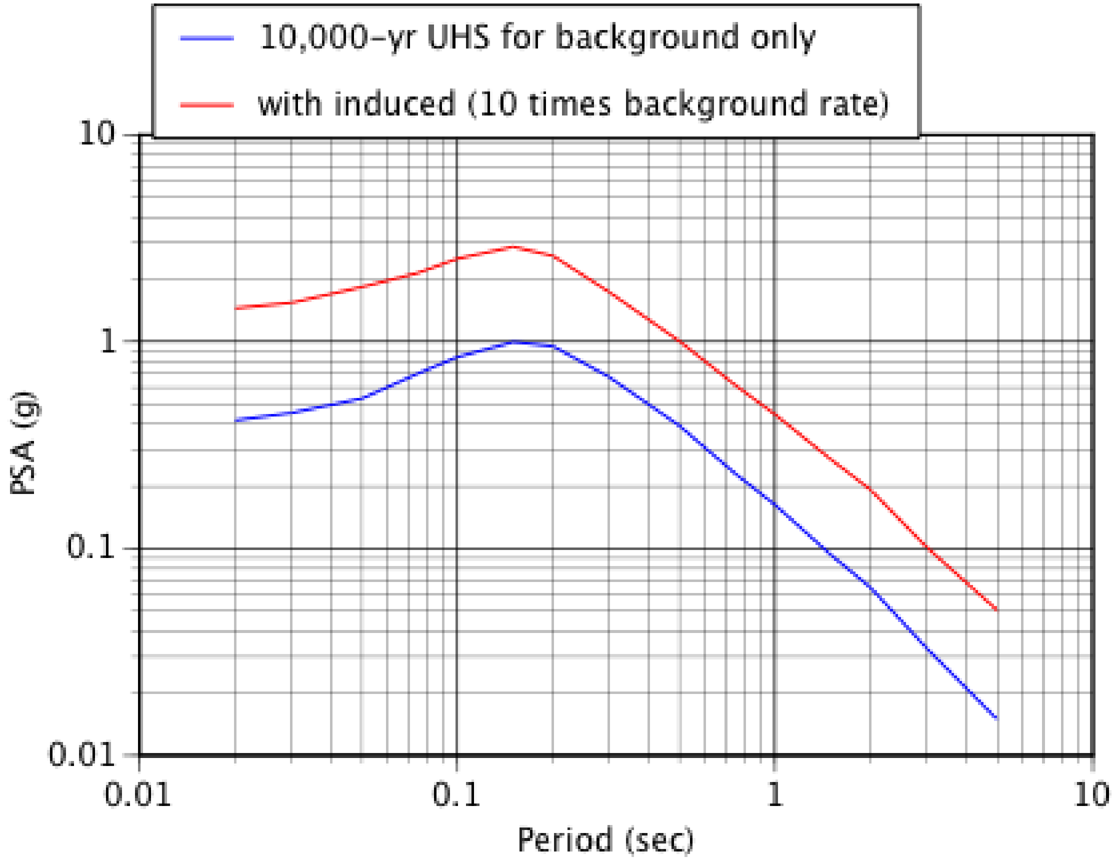
Distance Scaling of ASK14 and Modified ASK14



Comparison of Response Spectra for M=5, Rrup=1, 5, 10, 15 km



Hazard Example

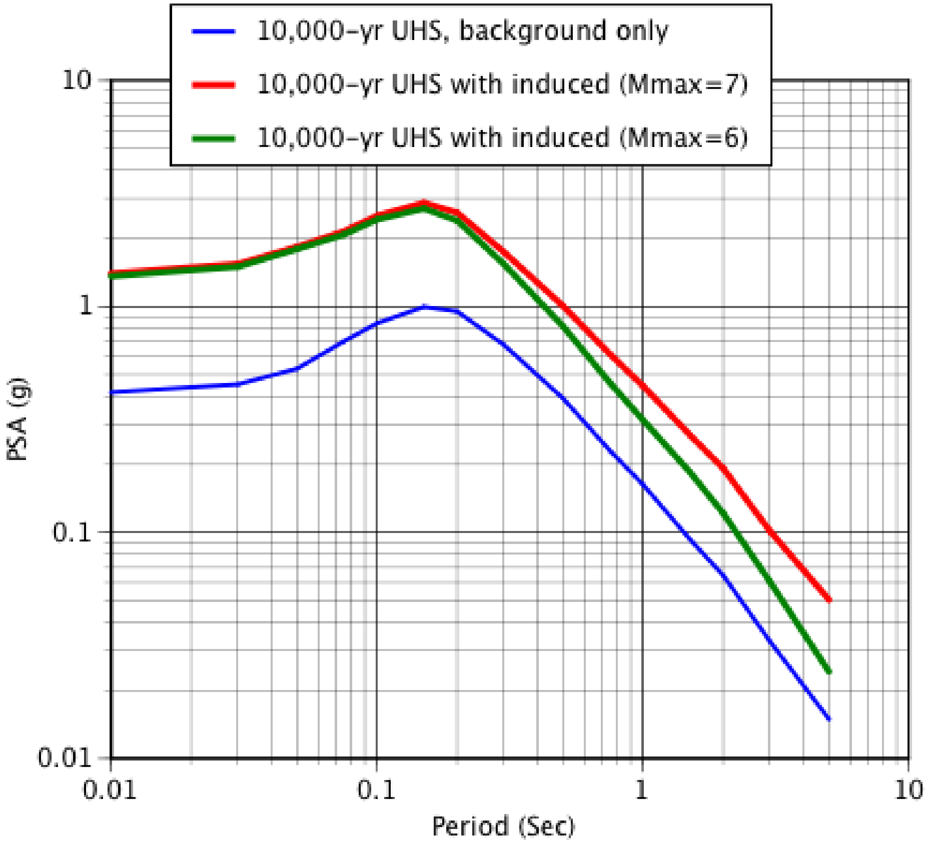


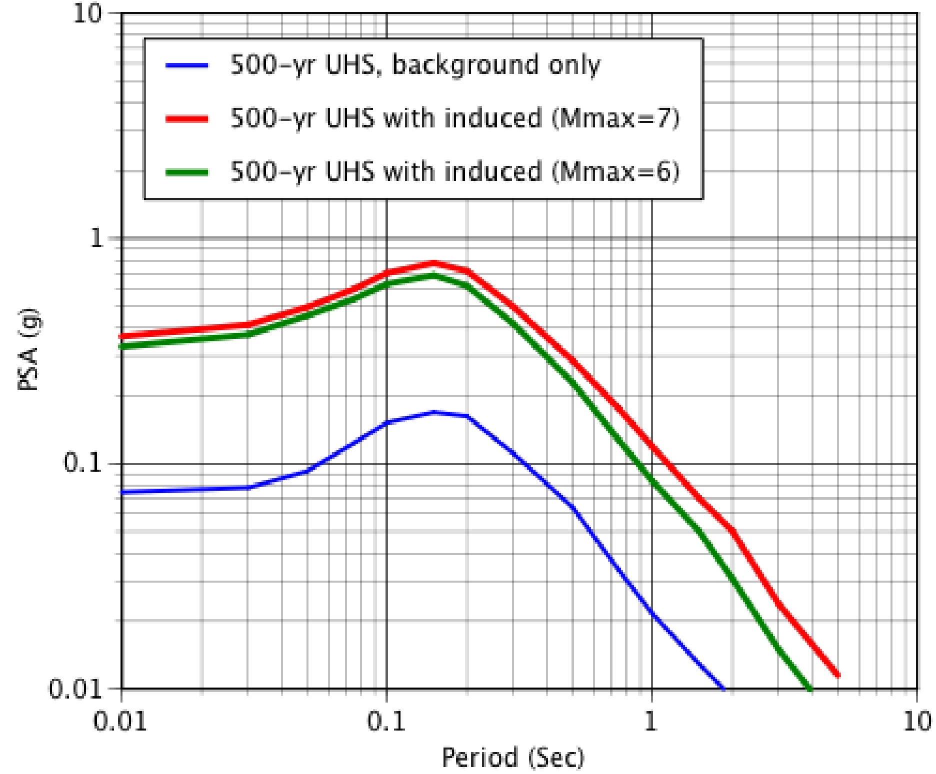
<u>Background zone</u>
Truncated exp mag pdf
b-value = 1.0
Rate of M>5 within 50 km = 0.01/yr
Mmax = 7.0
Depth range: 0-15 km

<u>Induced zone</u>
Truncated exp mag pdf
b-value = 1.0
Rate of M>5 within 50 km = 0.1/yr
Mmax = 7.0
Depth range: 1-8 km

Hazard Example – smaller Mmax

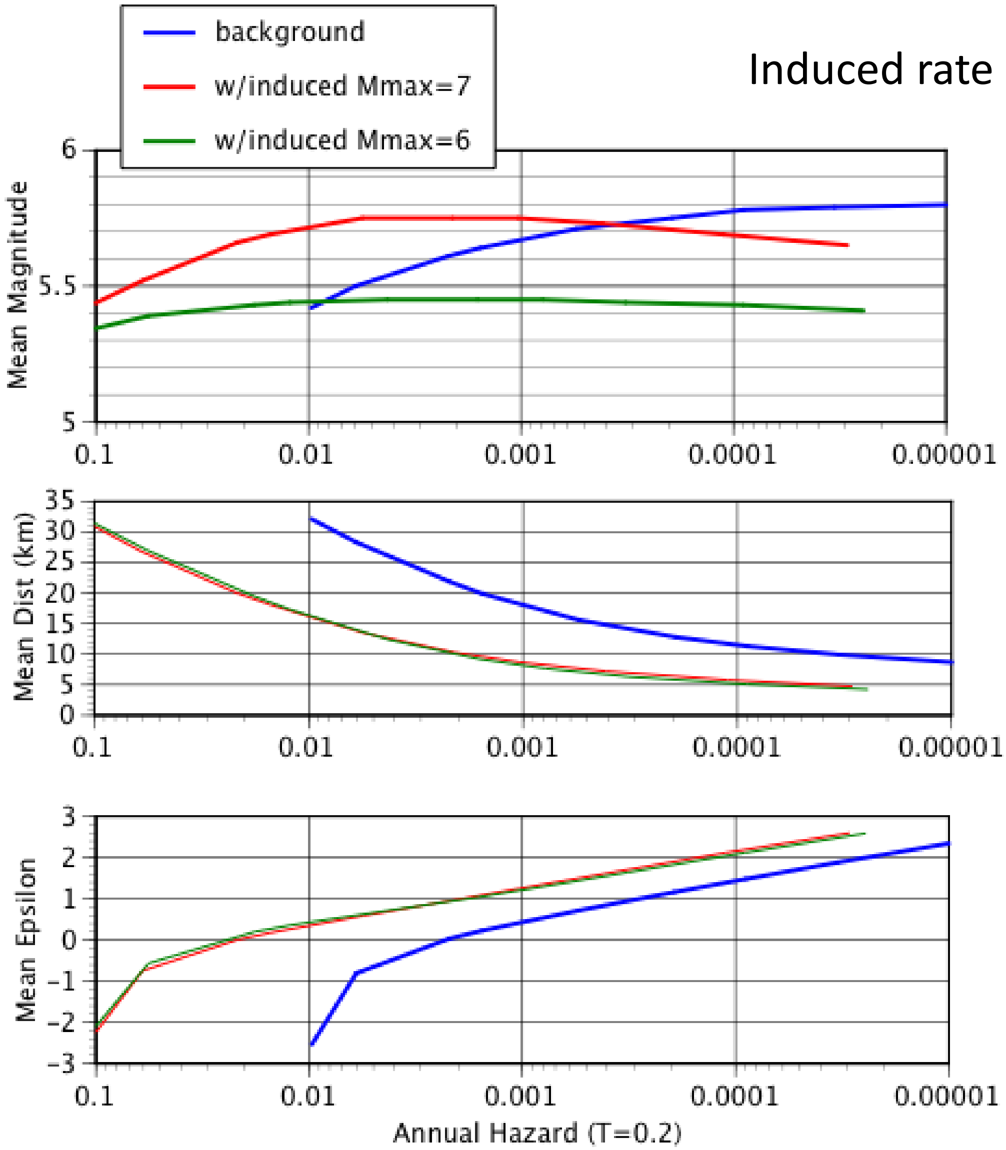
Induced rate assumed = 10 x background rate



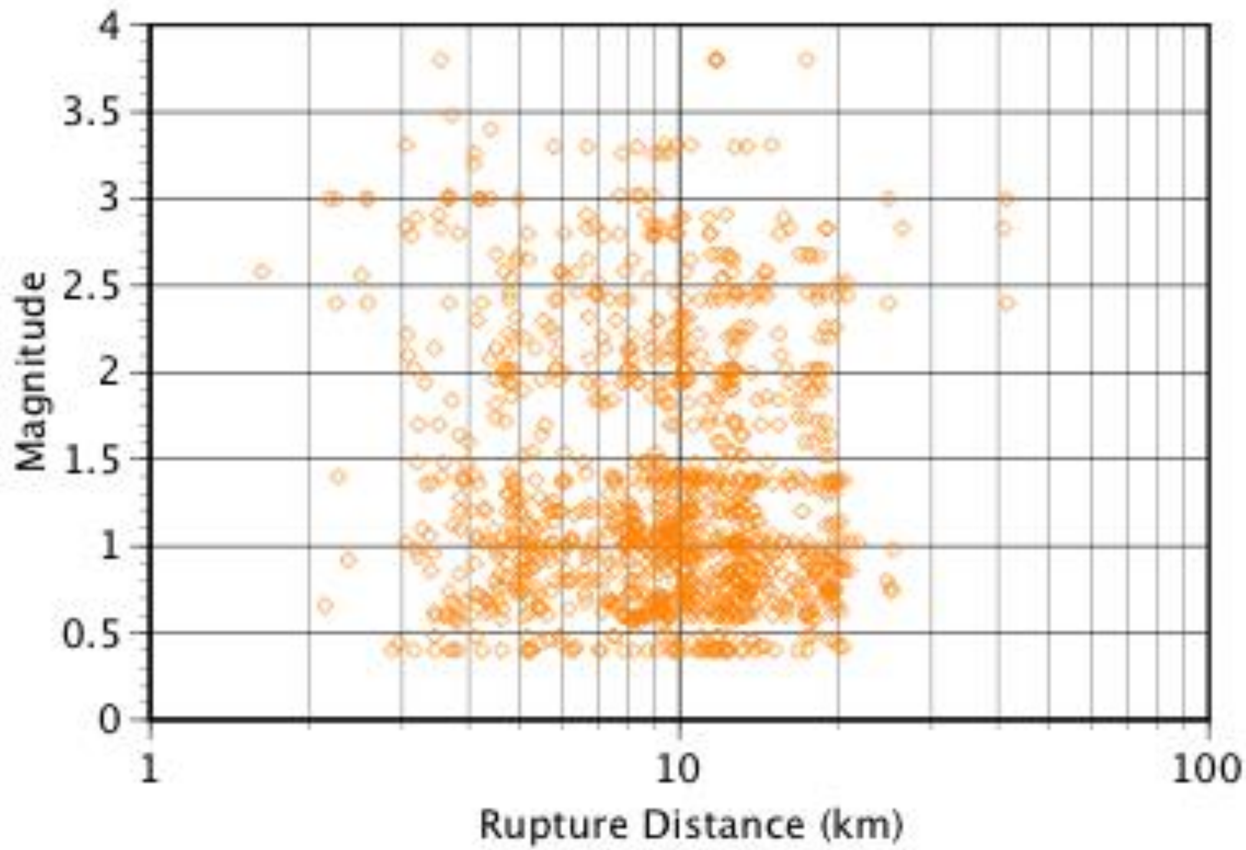


Deaggregation of Hazard for T=0.2 s

Induced rate assumed = 10 x background rate

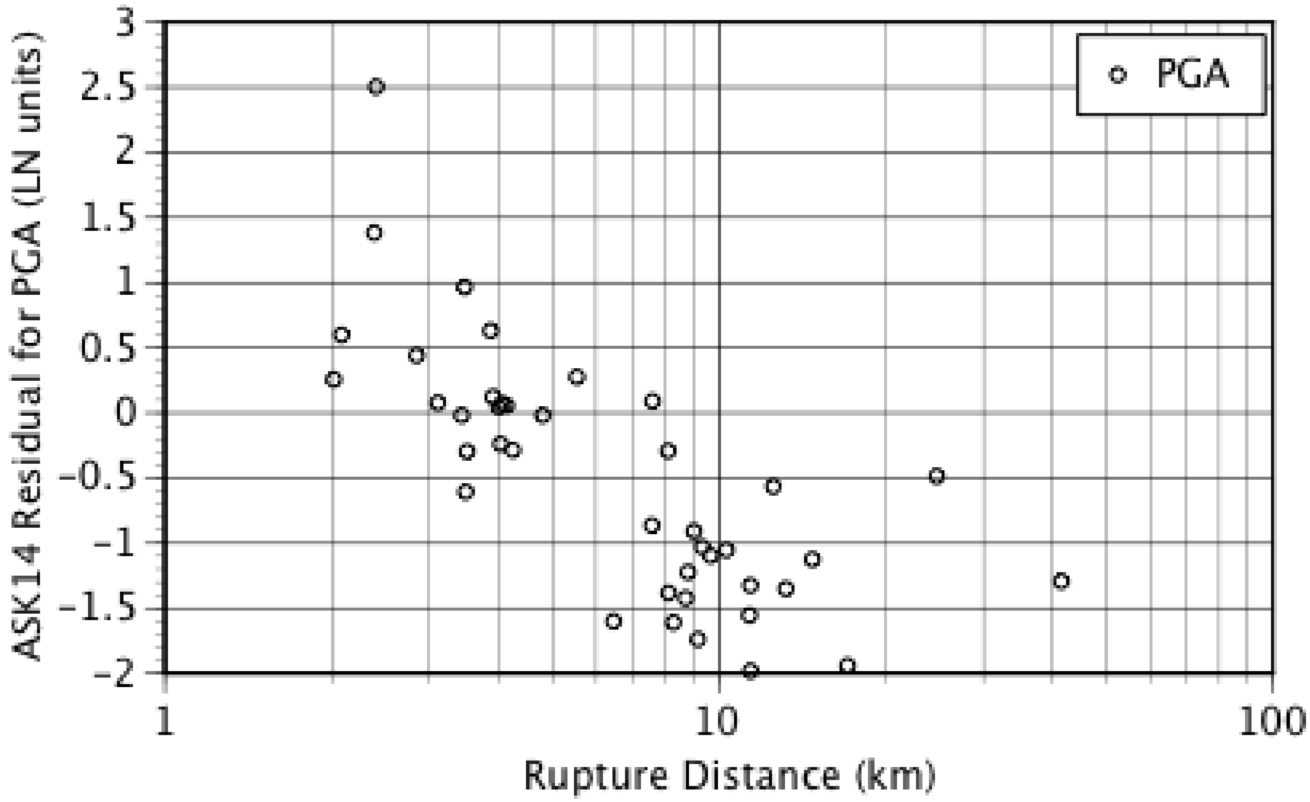


Induced Eqk in Canada (Mostly smaller magnitudes)



ASK14 only applicable for M>3

Residuals Relative to ASK14 for Canada Data (M>3, R<50)



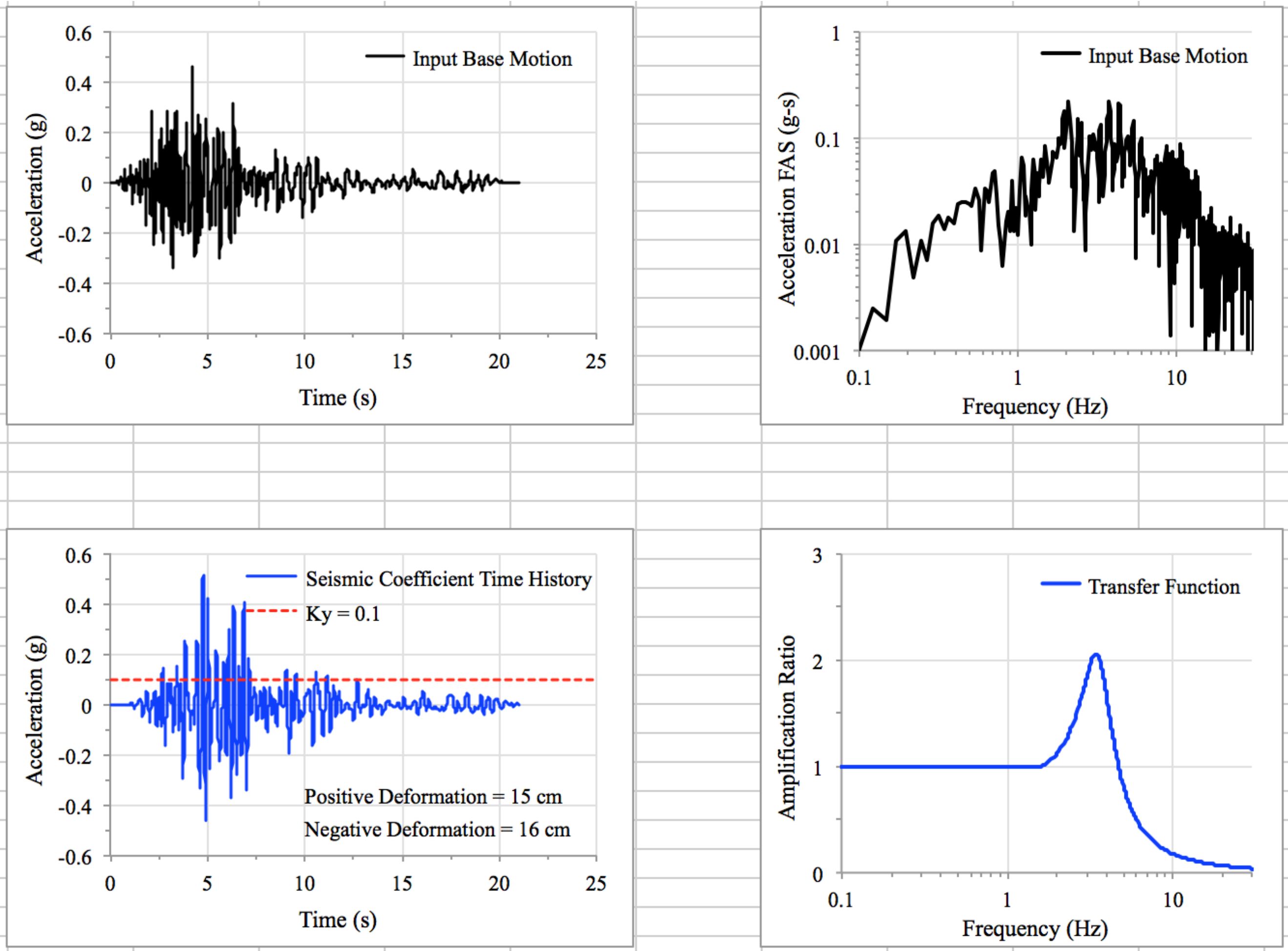
Limitations

- Modified ASK14 model is based mainly on induced earthquakes related to waste-water injection in Oklahoma/Texas region
  - Applicability to induced earthquakes in other regions needs to be evaluated
- Small magnitude induced earthquakes in Canada show lower ground motions than induced earthquakes in the Oklahoma/Texas region
  - Is the ground motion from fracking induced earthquakes smaller than for other induced earthquakes?
  - Will larger magnitude (M5) induced earthquakes follow the scaling from the modified ASK14 model?

Potential Effects on Earth Dams

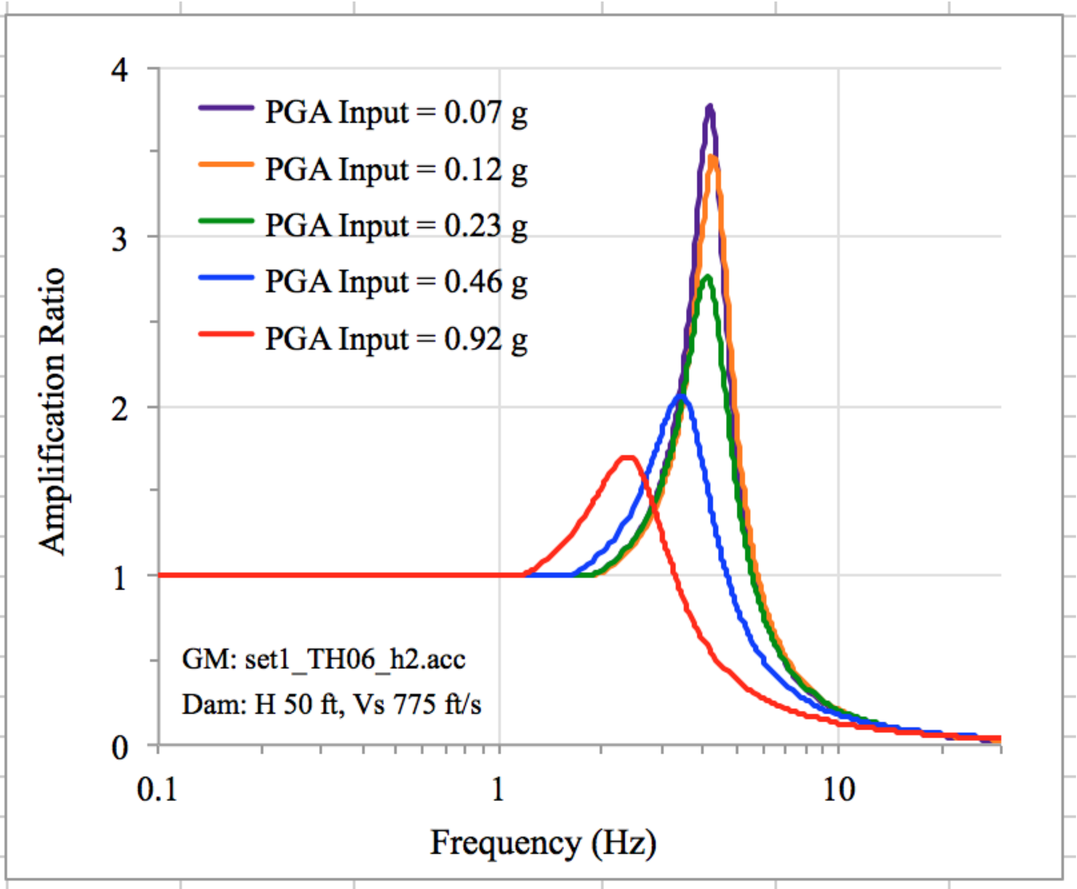
- Consider the effects on the structure, not just the occurrence of an earthquake
  - Here, use seismic deformation for existing earth dams
- Aleatory variability in the ground motion and the structural response is a key factor
  - The rate of the seismicity can be so high that we need to be concerned with much higher epsilon values than for tectonic earthquakes
- Preliminary Evaluation
  - Using a simplified model for the response of the sliding mass (equivalent linear model)
  - Combine sliding mass response with the ground motion and compute the Newmark displacement

Simplified Deformation for Earth Dams



Model of the Impulse response of sliding mass (equivalent linear)

Example Nonlinear Behavior of Simplified Sliding Mass Model

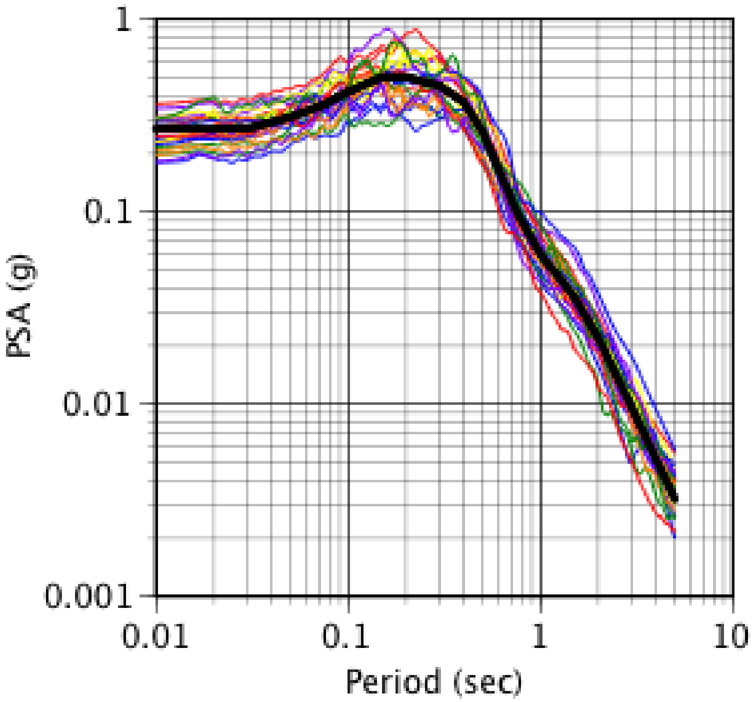


Dam Deformation Hazard

$$Haz(Dam\,Def > d) = \sum Rate(M_i, R_i)\, P(Def > d | M_i, R_i)$$

Structural Response Approach

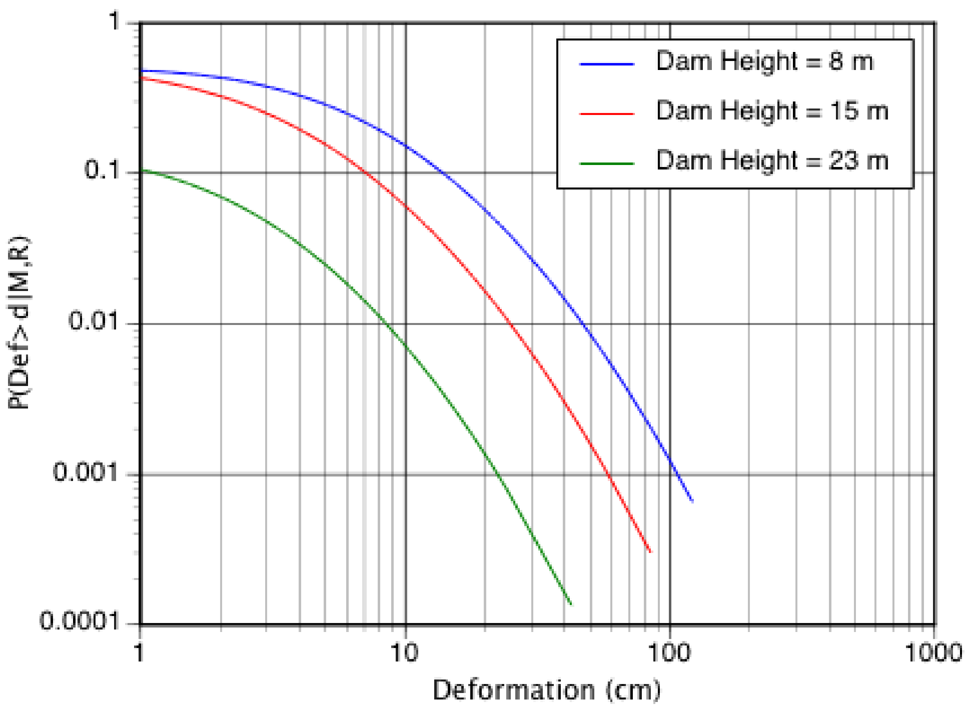
- Selected Representative time histories for mag and distance
- Spectral matched 11 sets of 2 horiz comp to median
- Used incremental dynamic analysis approach to capture range of ground motions
  - for one mag only
- Computed distribution of Newmark displacements
- Computed P(def>d|M,R)



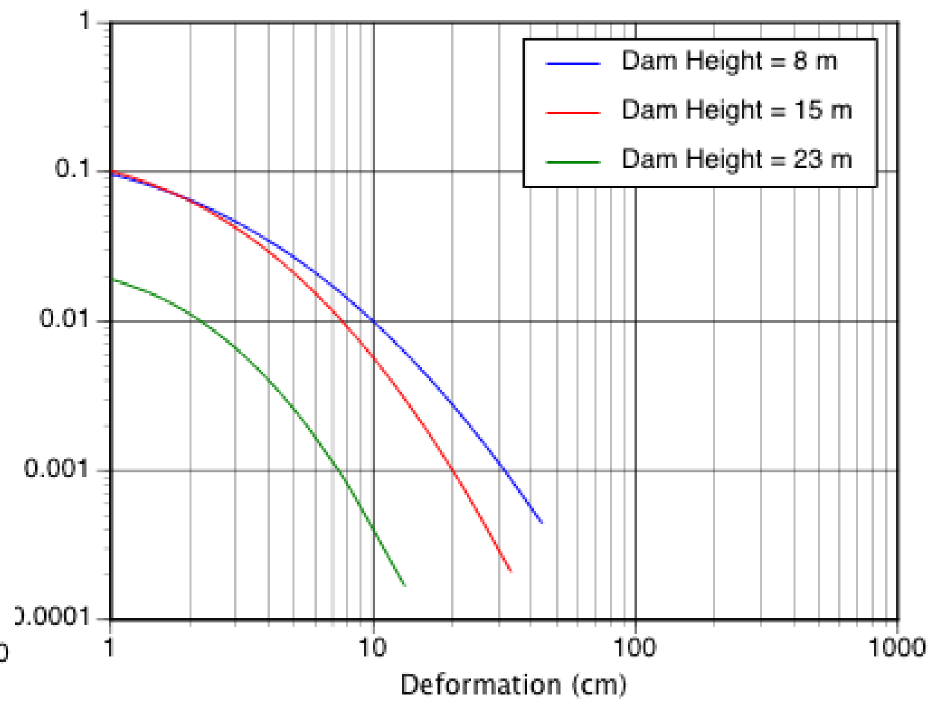
Example Conditional Probability of Exceedance for Deformation

Scenario: M=5, ZTOR=1 km

Rrup = 5 km



Rrup = 10 km



Summary

- Ground-Motion Models
  - Standard GMPEs used in seismic hazard do not scale properly for shallow small/moderate magnitudes at short distances
    - Main issue is the finite-fault term
    - Can underestimate of the short-period ground motion by factors of 3 to 5 for M3 and M4 at distance < 3 km
  - Not clear how this effect applies to M5-M6 range
    - Can the M5 earthquakes lead to larger short-period ground motions than M6.5 earthquakes?
    - Currently, not allowing oversaturation
  - For ease, a current GMPE (ASK14) was modified with an additional term. May be better to develop a new GMPE from scratch
    - No change in magnitude scaling

Summary

- Seismic Risk
  - Risk is difficult given the changing seismicity rates for induced events
  - Alternative is for focus on the hazard for the structural response at lower probability levels (0.01 to 0.001 range) than the traditional 0.5 or 0.16 levels
  - Short-period structures will be more sensitive to the induced earthquakes
    - Short earth dams
    - Concrete dams
    - Dam Gates

Next Steps

- Ground-Motion Models
  - Classify induced earthquakes as fracking events or other events
    - There may be a large difference in the short-period ground motions for these two classes of events.
  - Develop additional alternative GMPEs for induced earthquakes
  - Consider developing updated GMPEs allowing for a revision to the small magnitude scaling, not just the distance scaling
- Seismic Response of Dams to Induced Earthquakes
  - Check simplified methods used for earth dams for enriched high-frequency content
  - Evaluate response of concrete dams and gates to high-frequency ground motion