Treatment of near-fault directivity in PSHA and ground motion selection

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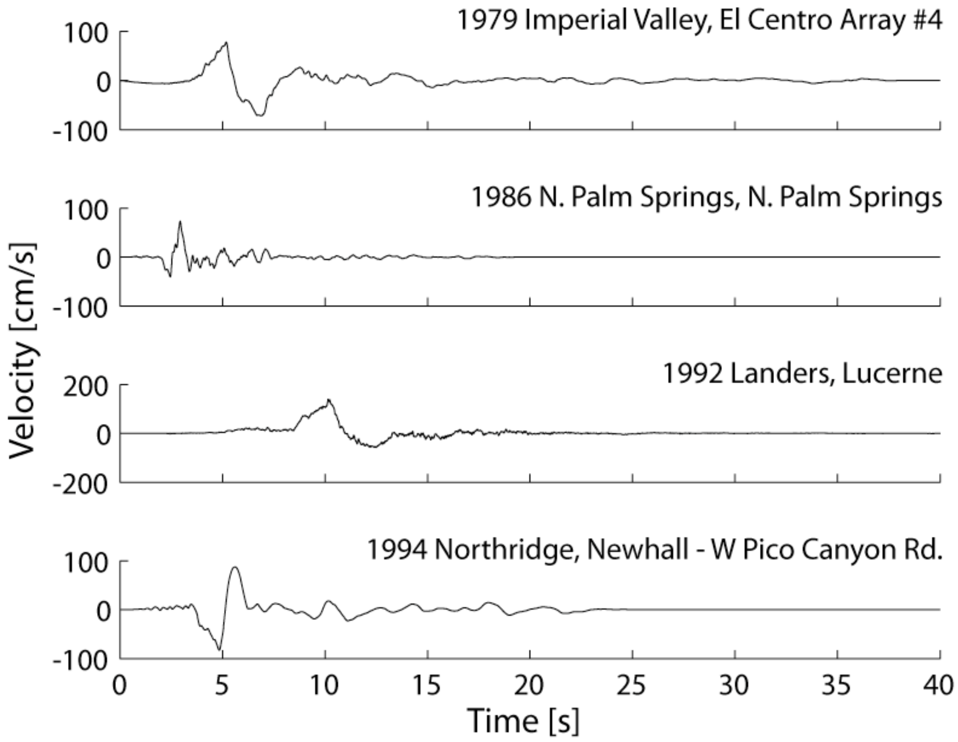
Introduction

Near-fault directivity is an important effect to quantify for performance-based earthquake engineering

We understand that directivity effects may produce a large velocity pulse

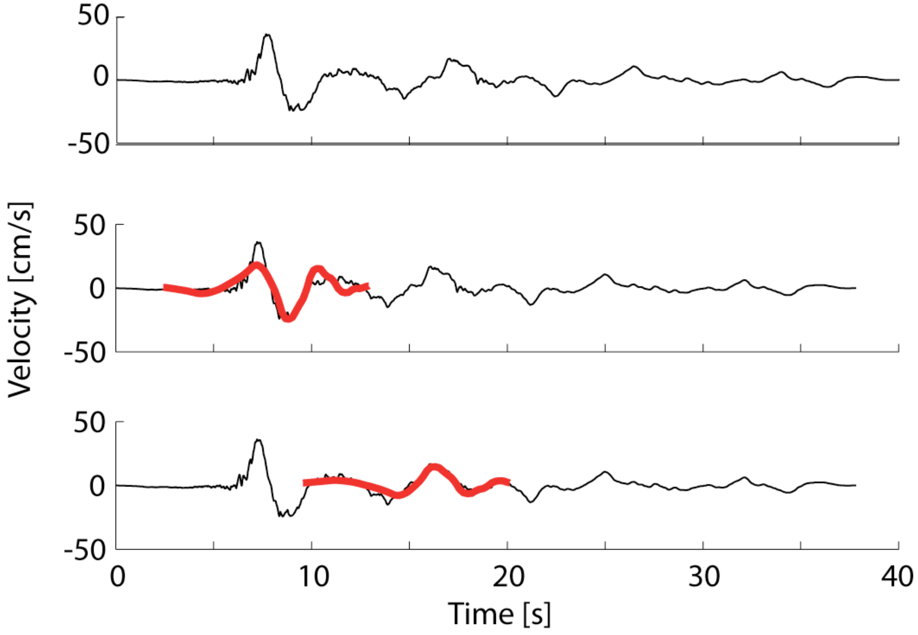
More work is needed to

- Identify these pulses objectively
- Account for their effects in seismic hazard analysis
- Use the hazard analysis results to select ground motions for structural analysis

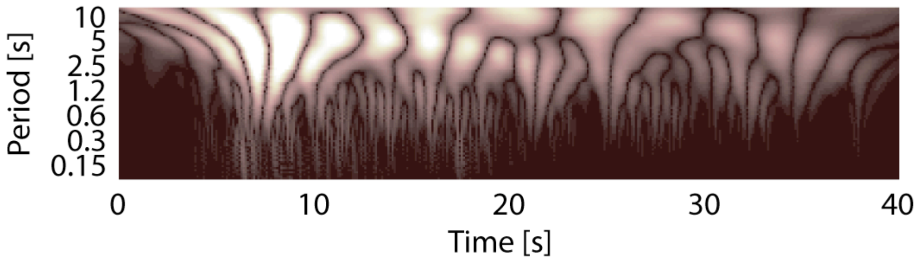


Pulse identification and extraction

Here we will objectively identify pulses by decomposing ground motions into wavelets



Shading indicates wavelet coefficient amplitude

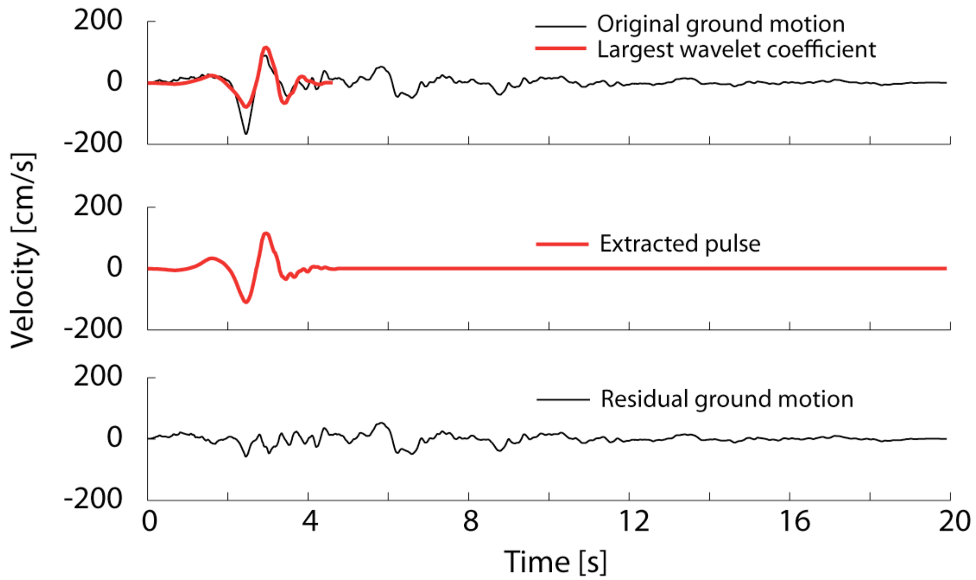


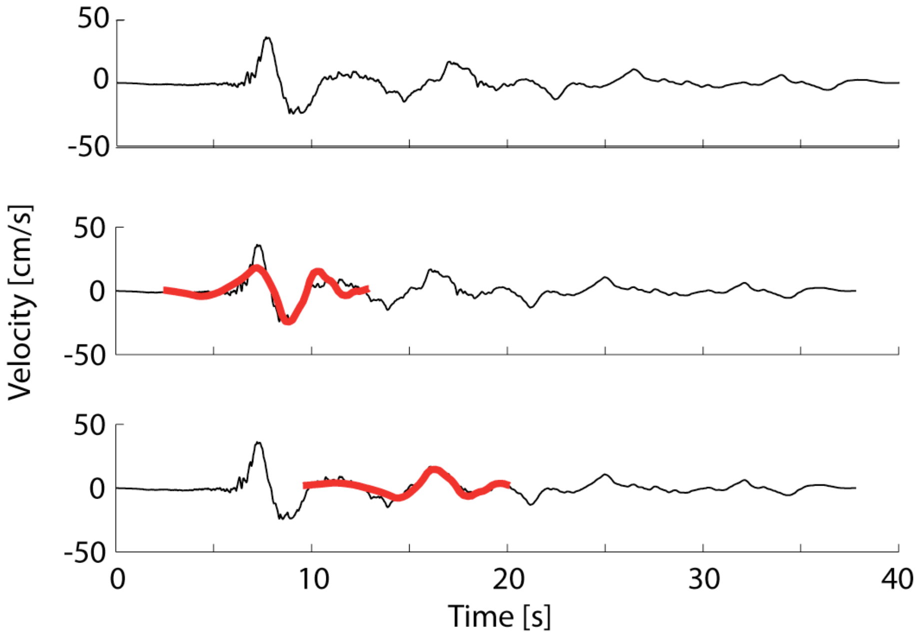
http://www.stanford.edu/~bakerjw/pulse-classification.html

Pulse identification and extraction

Here we will objectively identify pulses by decomposing ground motions into wavelets

If the largest wavelet coefficient is associated with a large portion of the record, a ground motion is identified as containing a pulse





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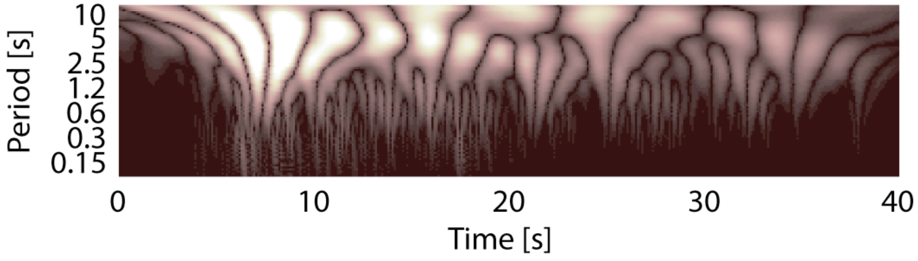

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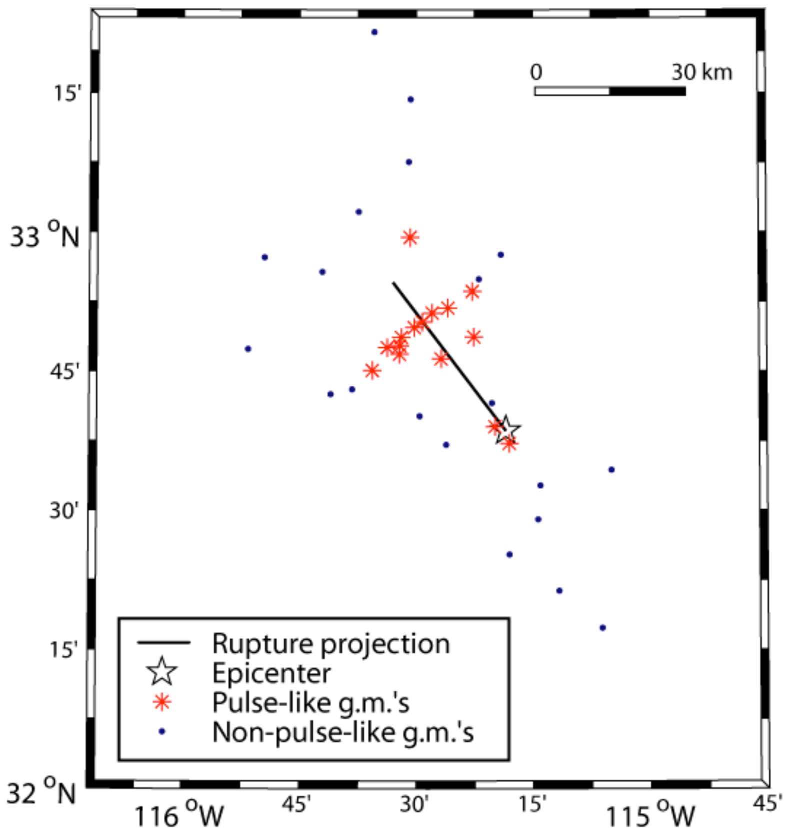
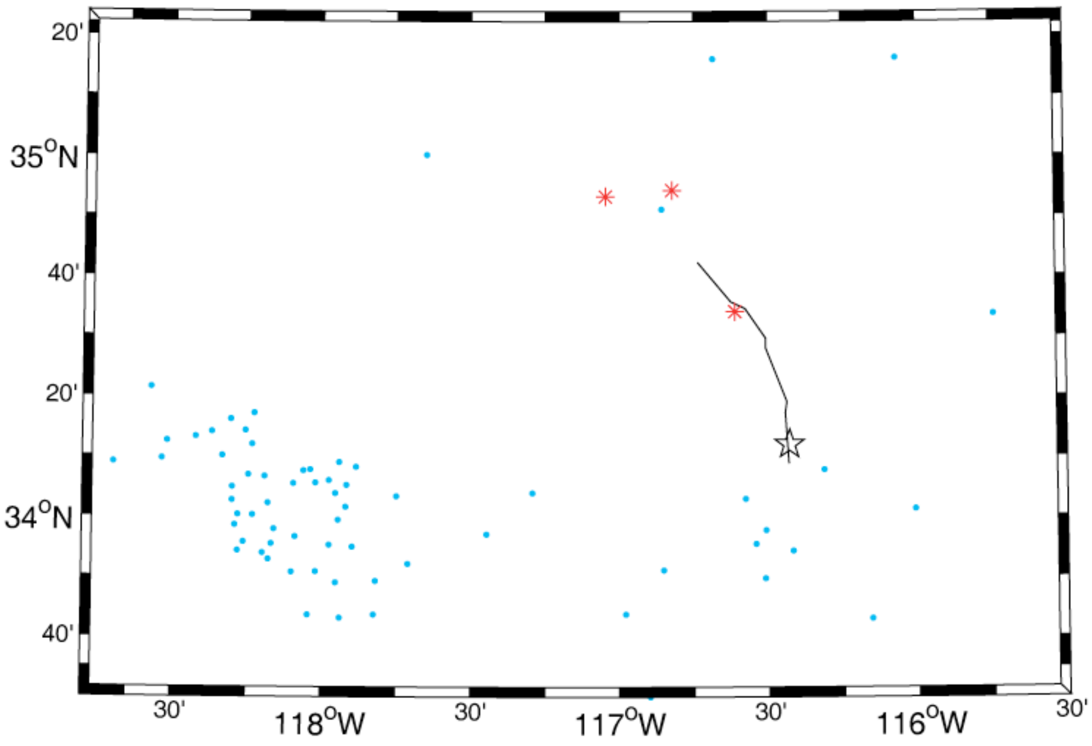
Observations from past earthquakes

1979 Imperial Valley



1992 Landers



The algorithm identifies ground motions with clear pulses, and the identified motions are generally at locations where directivity is expected

Incorporation into seismic hazard analysis

- We have known of directivity effects for many years

- But linking these effects into hazard analysis and ground motion selection remains a challenge
  - Directivity pulse predictions are not certain
  - Pulse periods are not certain
  - We need ground motion intensity predictions for pulse-like ground motions

Background: standard PSHA calculations

Standard PSHA calculation for a single seismic source:

Annual rate of *Sa* > *x*

Annual rate of earthquakes on the source

$$\nu_{S_a}(x) = \nu_{eq} \iint_{m,r} \underbrace{P(Sa > x \mid m, r)}_{} \, \underbrace{f(m,r)}_{} \, dm \, dr$$

Integrate
over all *m, r*

Probability of Sa >x, given an
earthquake with *m* and *r*
(from ground motion
prediction model)

Probability density function
for magnitude (*m*) and
distance (*r*), given an
earthquake

Modified PSHA calculations

Standard PSHA calculation for a single seismic source:

$$\nu_{S_a}(x) = \nu_{eq} \iint_{m,r} P(Sa > x \mid m, r)\, f(m, r)\, dm\, dr$$

Modified PSHA calculation, including directivity effects (adapted from Tothong et al., 2007)

$$\nu_{S_a}(x) = \nu_{eq} \iiint_{m,r,z} P^* \underbrace{(Sa > x \mid m, r, z)}\, \underbrace{f(m, r, z)}\, dm\, dr\, dz$$

Updated ground motion prediction model,
accounting for z

Distribution of magnitude
(*m*) and distance (*r*) and
source-to-site geometry
(z), given an earthquake

Building the new ground motion prediction model

Expand the ground motion model to distinguish between pulses and non-pulses:

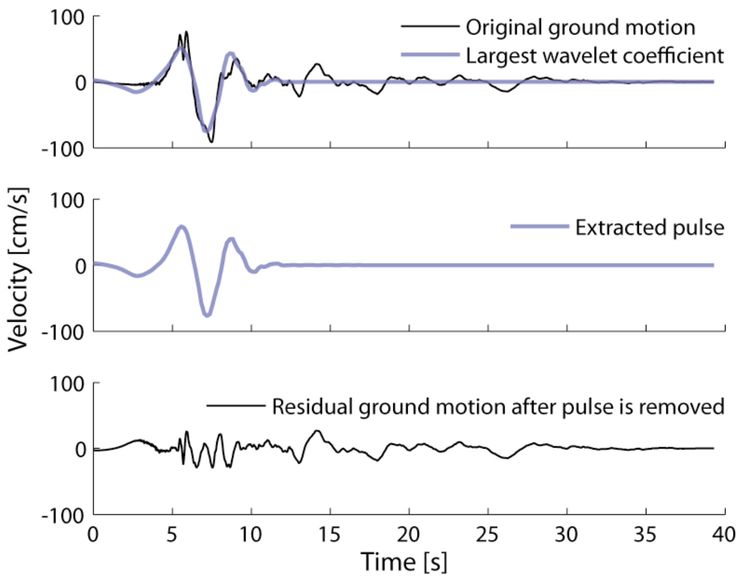
$$P^*(Sa > x \mid m, r, z) = \underbrace{P(Pulse \mid z)}_{\text{Pulses}} \underbrace{P_{Pulse}(Sa > x \mid m, r, z)}_{\substack{\text{Standard ground} \\ \text{motion prediction} \\ \text{model,} \\ \textit{plus a pulse} \\ \textit{amplification function}}} + \underbrace{\left(1 - P(Pulse \mid z)\right)}_{\text{Non-pulses}} \underbrace{P(Sa > x \mid m, r)}_{\substack{\text{Standard ground} \\ \text{motion prediction} \\ \text{model}}}$$

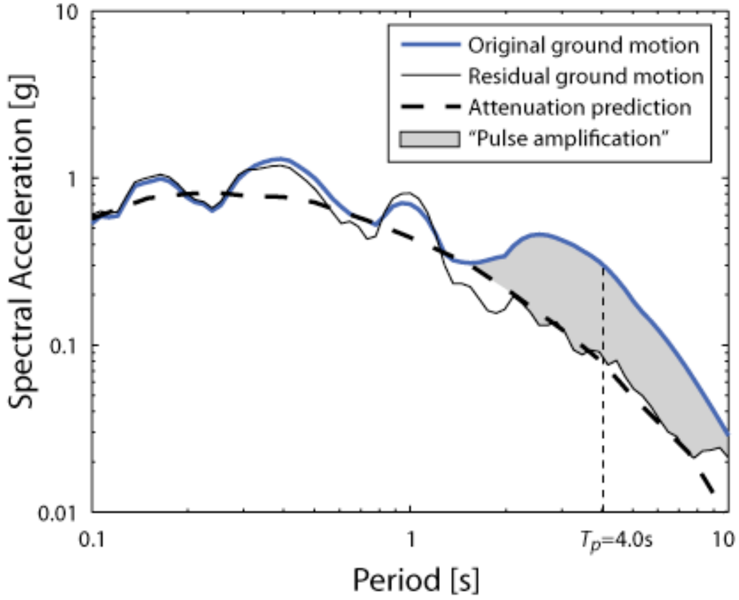
Note that we could re-fit the ground motion prediction models as well, but this appears to be a reasonable model and takes much less effort

Pulse amplification model

Our initial hypothesis:

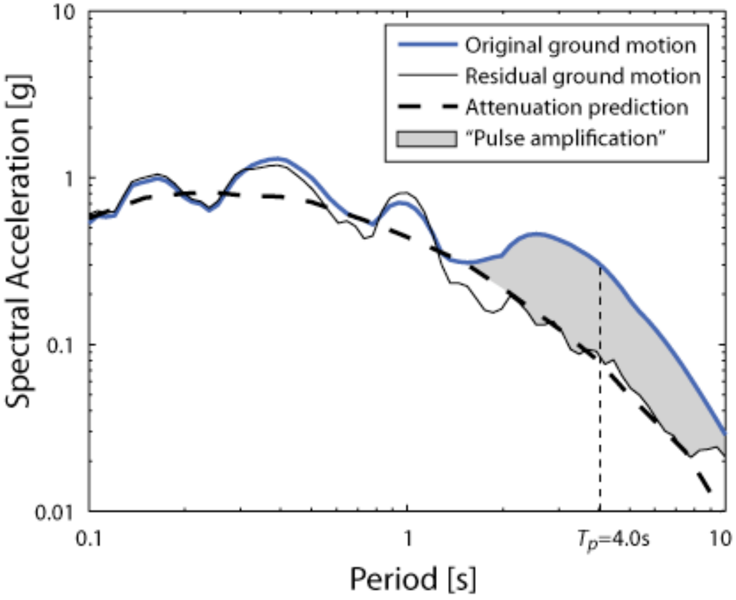
The response spectrum for a pulse-like ground motion is an “ordinary” spectrum plus a “pulse amplification” around the period of the pulse

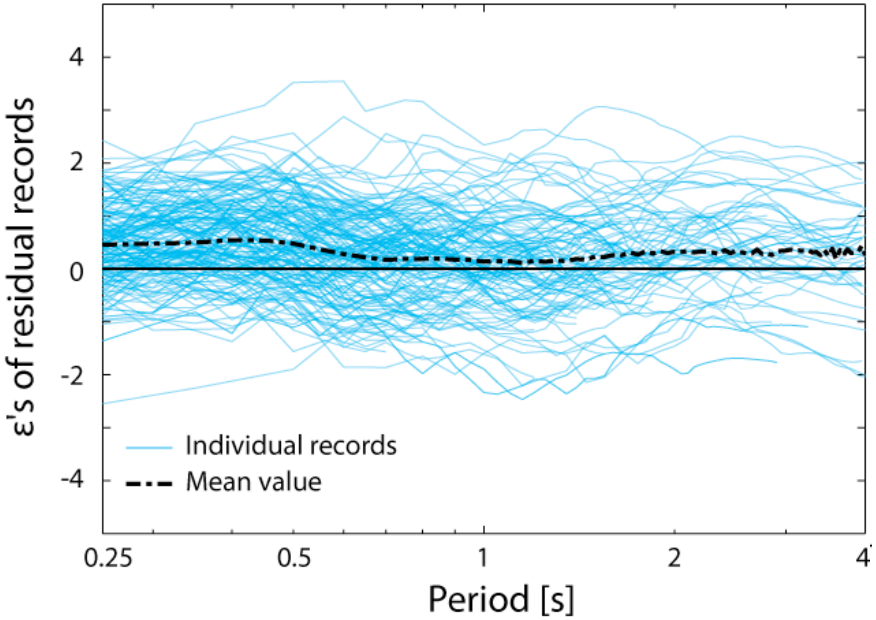




Model development: pulse amplification

A simple predictive model can be built for this for this “narrow-band” pulse amplification:



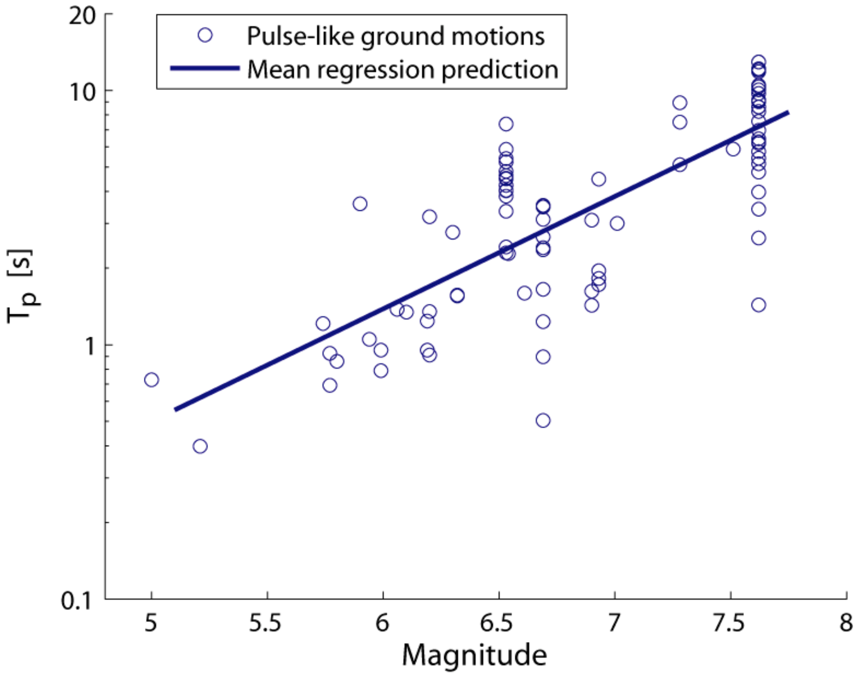


$$ln(Amplification) = \begin{cases} 1.132e^{-\left(ln(\frac{T}{T_p})+0.162 \big/ 0.476\right)^2} + 0.063 \ \text{ if } \ ln\frac{T}{T_p} \leq -0.162 \\ 0.896e^{-\left(ln(\frac{T}{T_p})+0.162 \big/ 0.717\right)^2} + 0.296 \ \text{ if } \ ln\frac{T}{T_p} > -0.162 \end{cases}$$

Pulse period versus earthquake magnitude

There is a strong relationship between earthquake magnitude and pulse period.

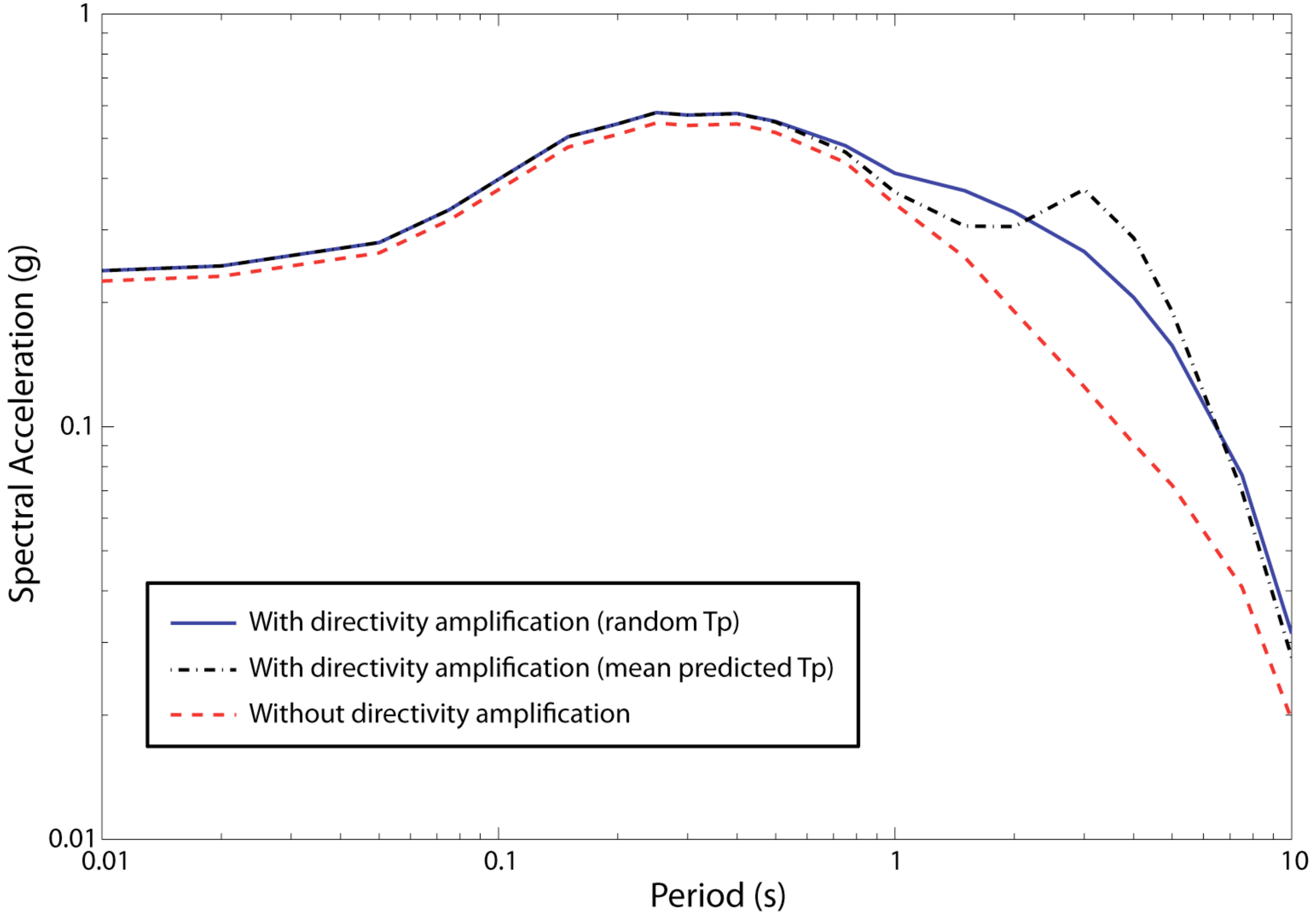
These results are in good agreement with previous studies (e.g., Bray and Rodríguez-Marek 2004; Mavroeidis and Papageorgiou 2003; Somerville 2003)



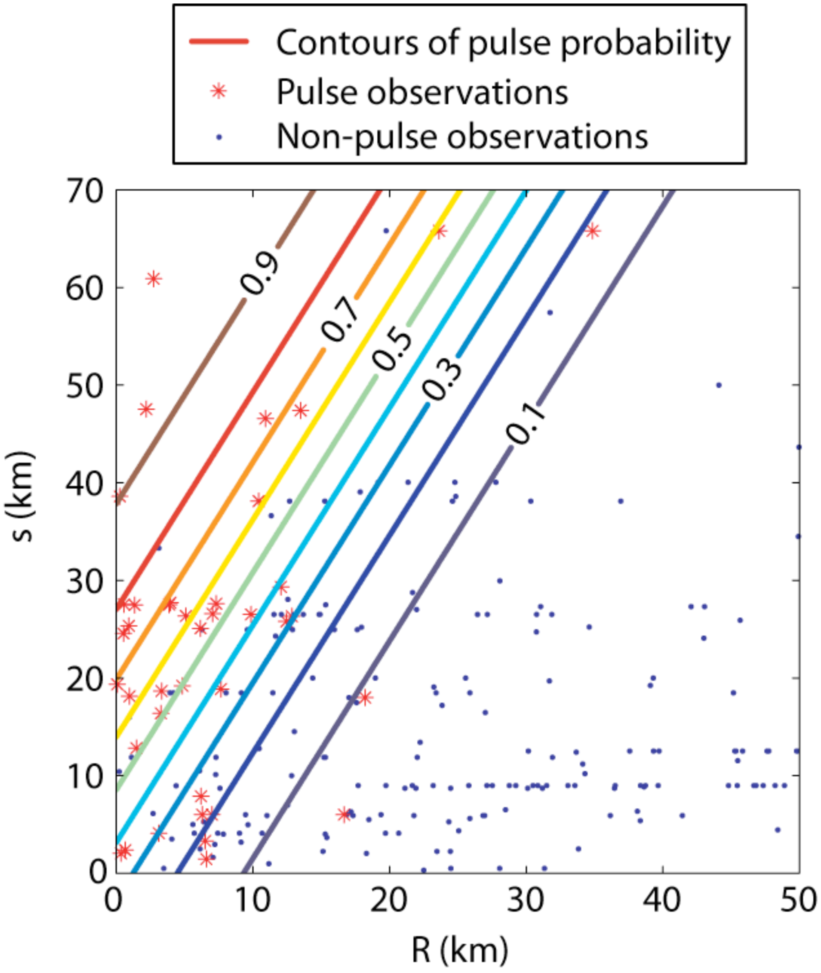
$$E\left[\ln T_p\right] = -5.78 + 1.02M$$

$$\sigma_{\ln T_p} = 0.55$$

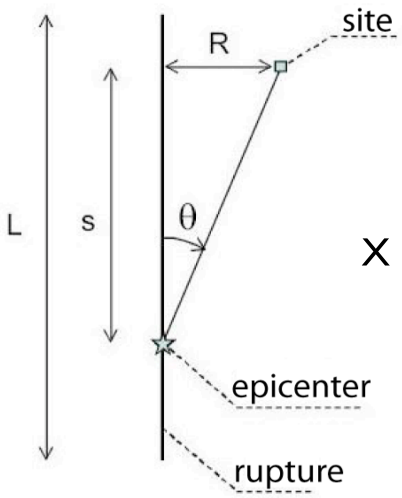
Amplification, with and without pulse period uncertainty



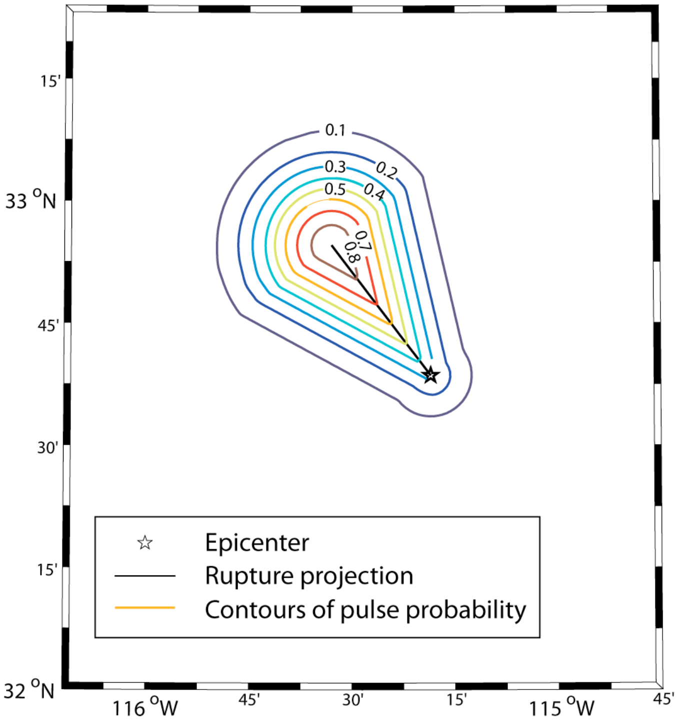
Results: probability of pulse occurrence



$$P(Pulse \mid R,s) = \frac{1}{1-e^{-0.642-0.167R+0.075s}}$$

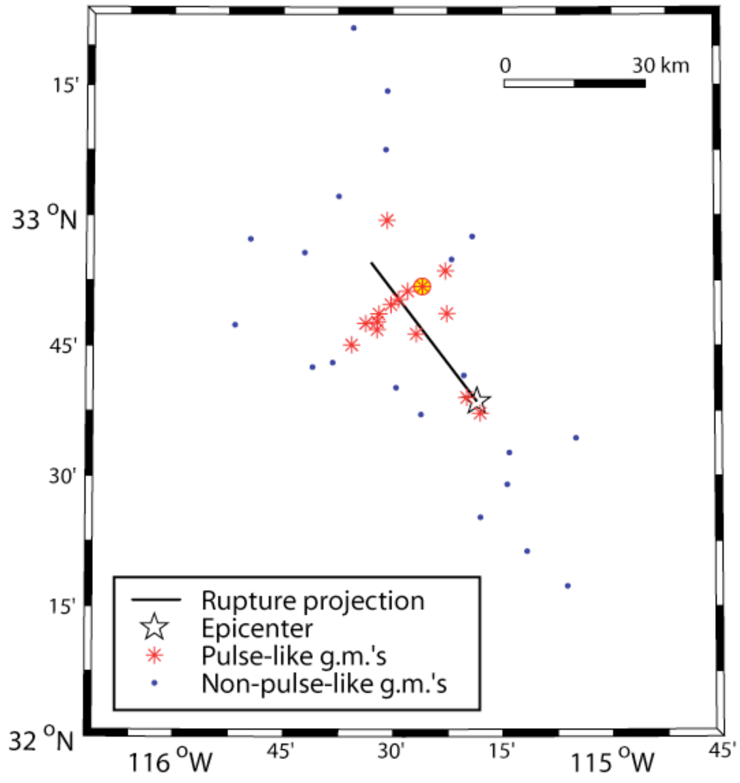


X = s/L



Results: Prediction prediction for an example site

Observations from 1979
Imperial Valley Earthquake



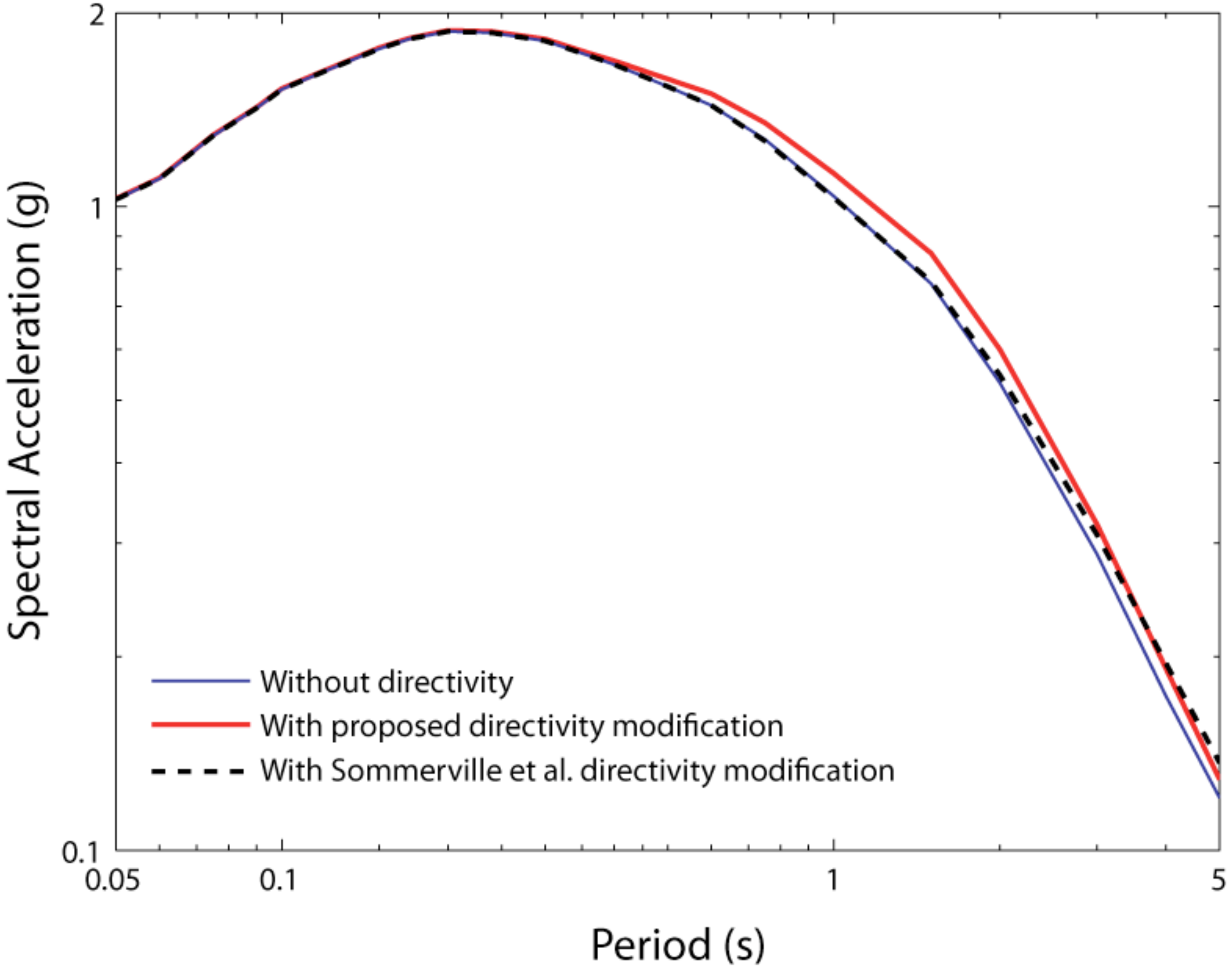
Hazard parameters:

- Single fault
- 0.09 earthquakes/year
- M_{min} = 5
- M_{max} = 7
- G-R “b-value” = 0.9
- V_{s30} = 250 m/s

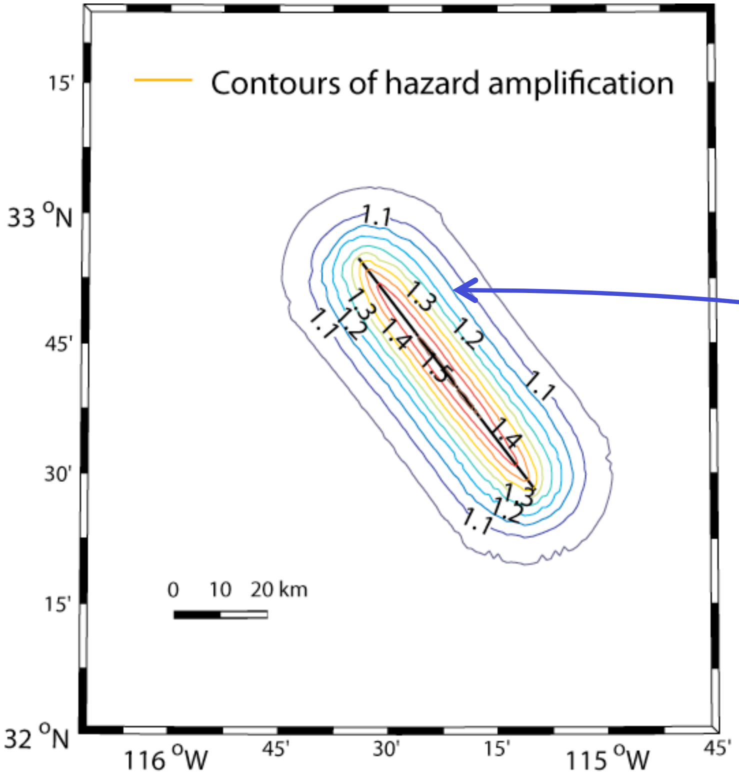
Site located 6.7 km from fault

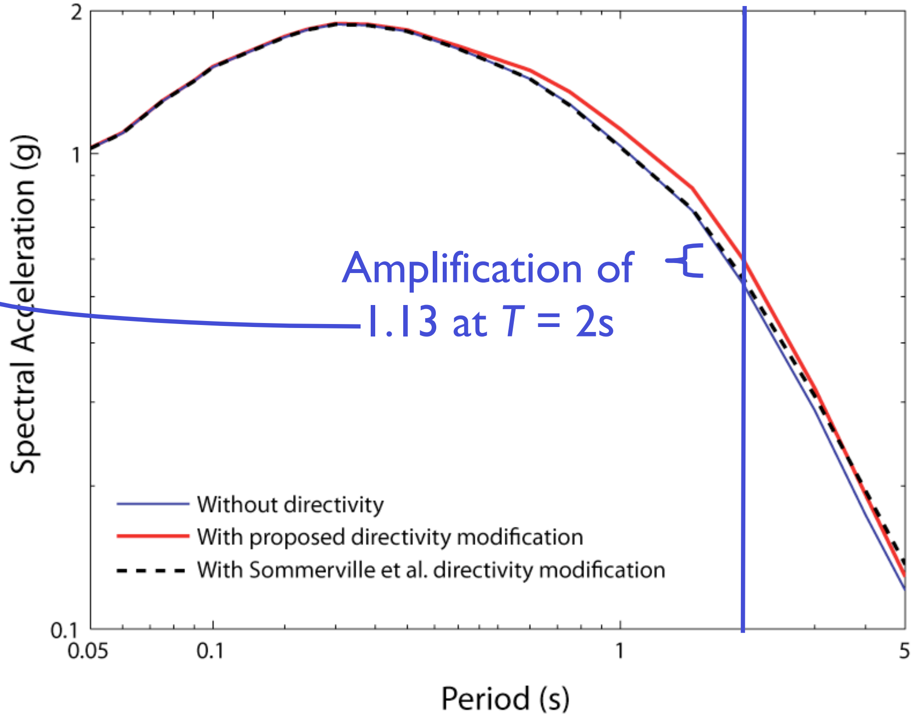
This is approximately the conditions at the Imperial Valley fault, where a pulse was observed

Uniform Hazard Spectrum (2%/50yrs) for the example site



Map of Sa(2s) directivity amplification (2%/50 yrs probability of exceedance)

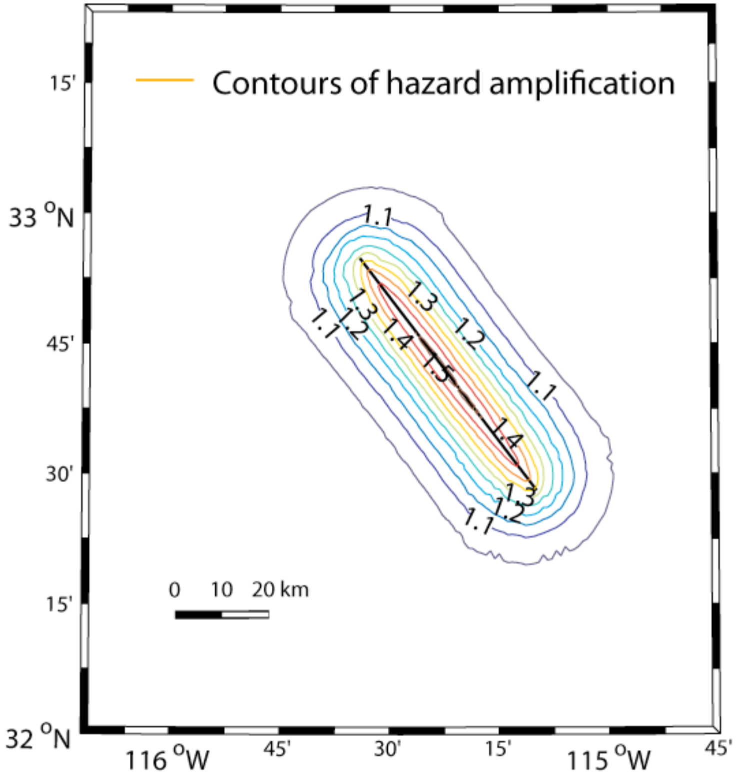




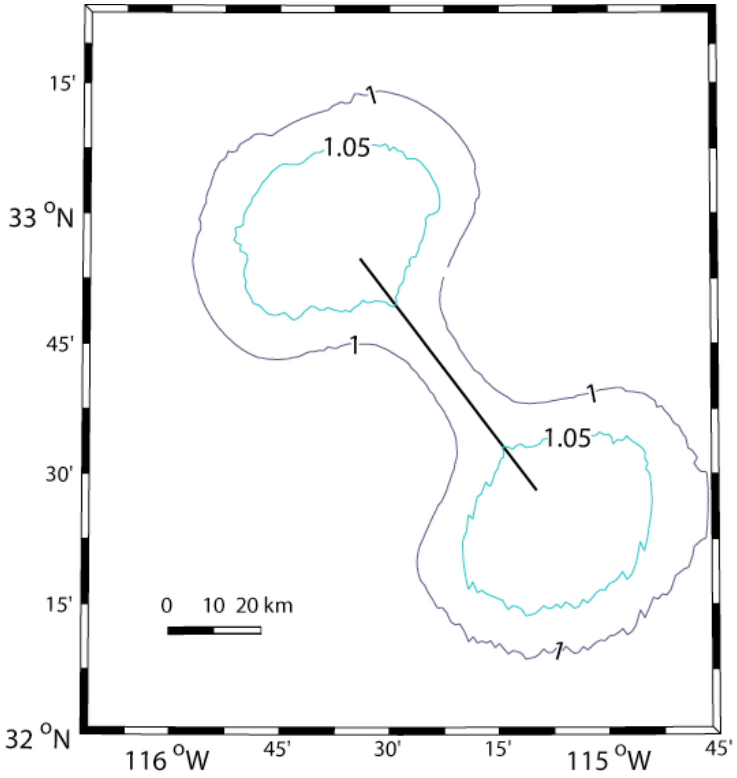
Amplification of 1.13 at *T* = 2s

Map of Sa(2s) directivity amplification (2%/50 yrs probability of exceedance)

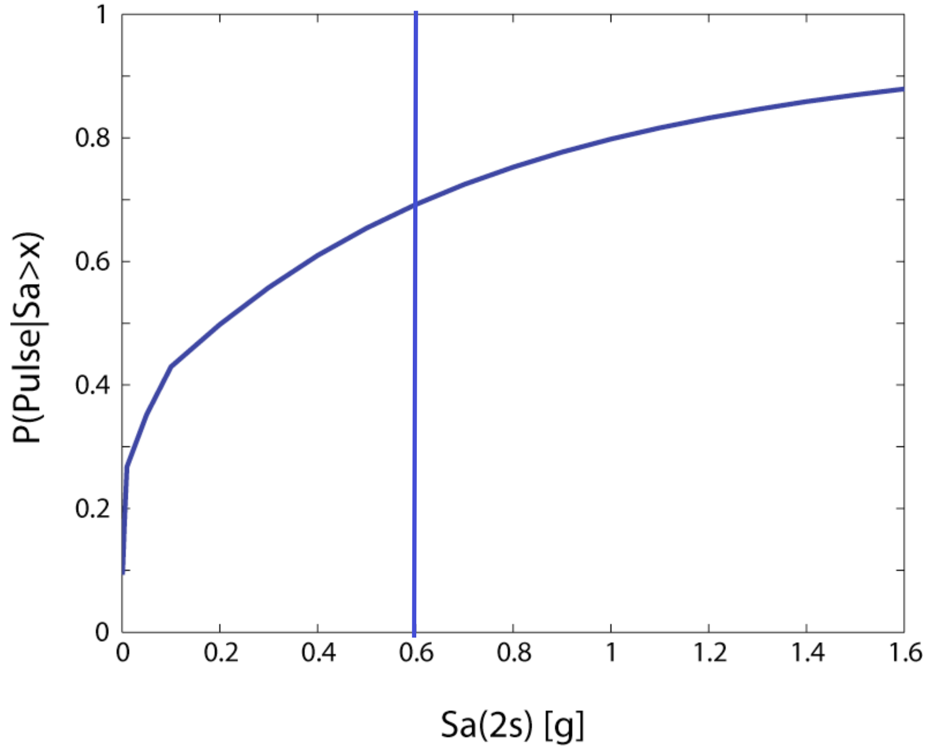
Our model

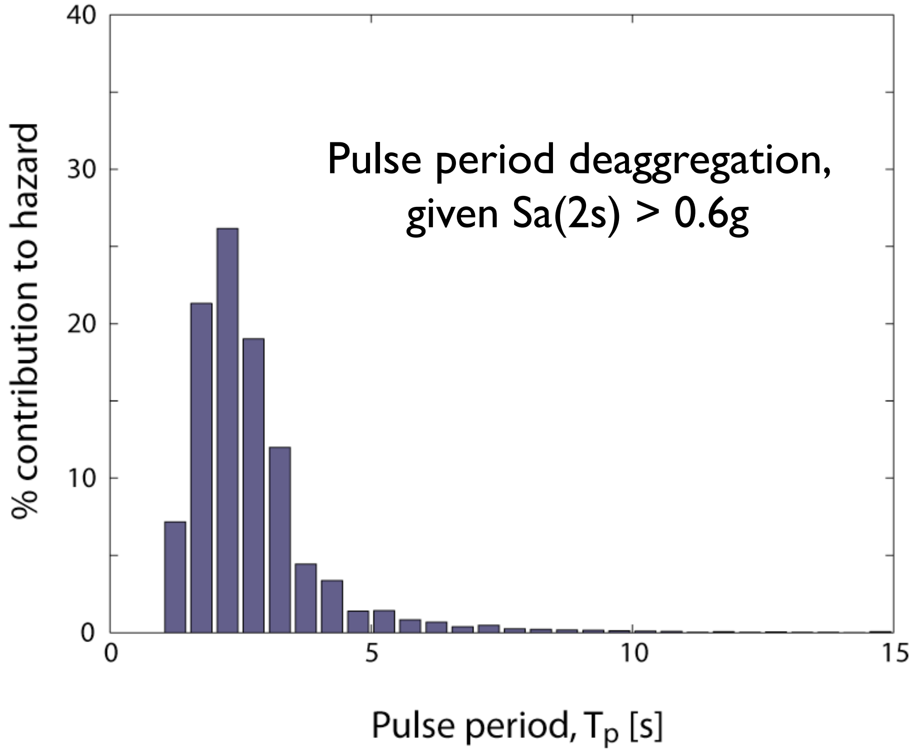


Somerville et al. (1997) model



Results: Deaggregation





- These results can be used for record selection (as we do today with magnitude and distance deaggregation)
- This is one benefit of predicting pulse and non-pulse spectra separately

Conclusions

- We have built statistical models to incorporate near-fault pulse-like motions into PSHA
  - Probability-of-pulse prediction
  - Pulse period predictions
  - A narrow-band ground motion prediction model for pulse-like motions

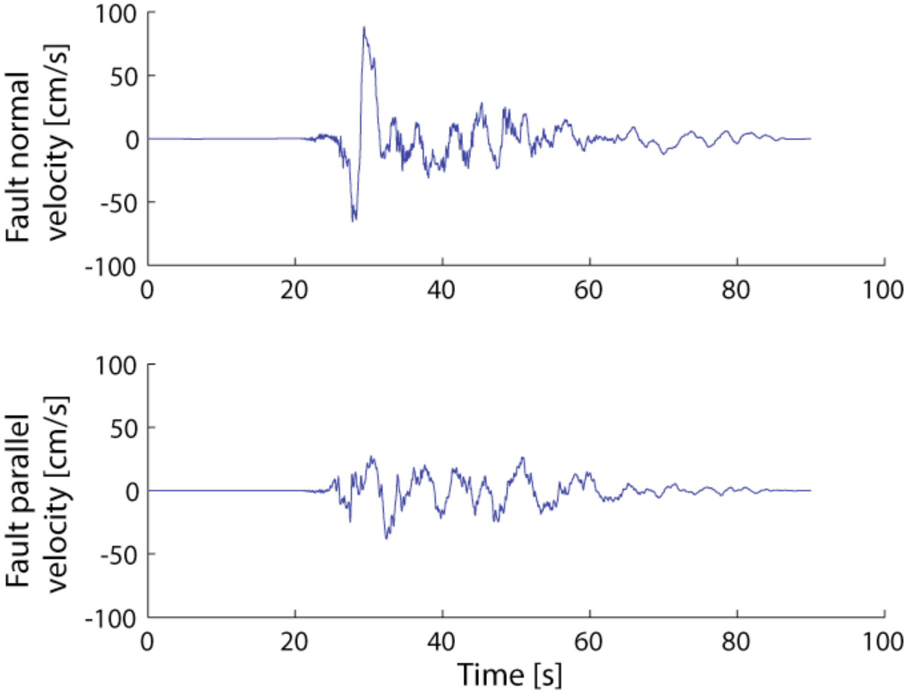
- The results can be used to perform site-specific PSHA, and general studies can be used to investigate "near-fault amplification"

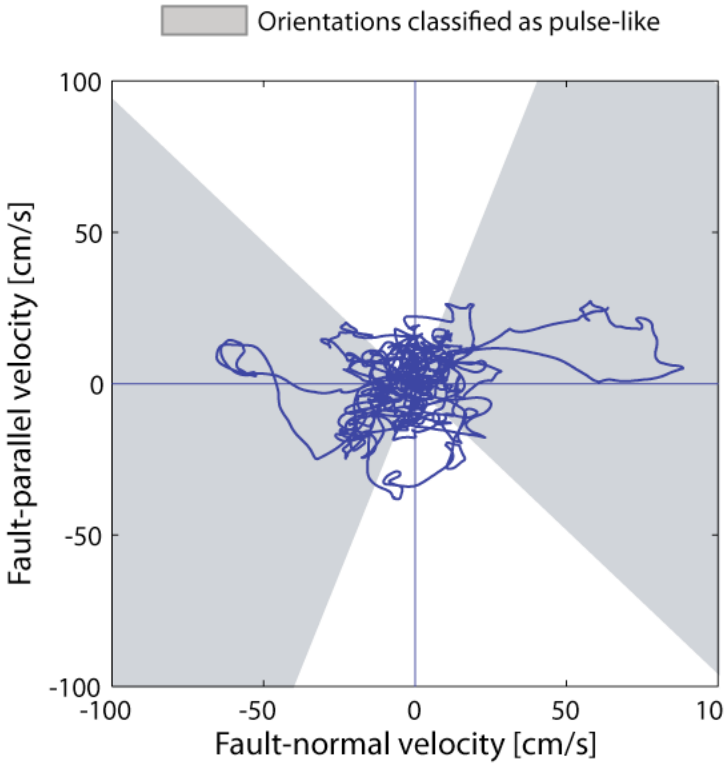
- Deaggregation calculations tell us the probability of a pulse given $Sa(T)>x$ and the distribution of causal pulse periods, facilitating record selection

- Future work will refine the classification scheme, and look at predictions beyond elastic response spectra

http://www.stanford.edu/~bakerjw/pulse-classification.html

Multi-component classification





Pulse periods

Unlike the sine waves from the Fourier Transform, wavelets have no intrinsic period

We define the wavelet's *pseudo-period* as the period associated with its maximum Fourier amplitude

This measure can thus quantify the period of a detected pulse