Methods for Earthquake Ground Motions in Practice:

(1) Implementing rupture directivity in seismic hazard
(2) Time histories with permanent displacement

AECOM

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With contributions from
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Biography

PhD: University of California, Davis
MS, BS: University of California, Los Angeles

Mentors Paul Somerville, Norman Abrahamson, Christine Goulet

Experience in practice is mostly with ground shaking seismic hazard

Research interests include all types of ground motion studies:
near-field effects, attenuation, simulations, site response, etc.

Introduction

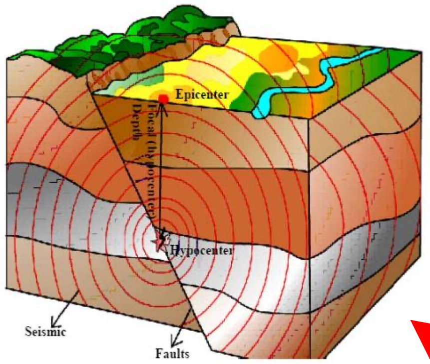
Part 1: Rupture directivity

Part 2: Permanent displacements

Engineering seismology is the interface between earthquake science and earthquake engineering

These fields (and the mindsets of practitioners) can differ!

Earthquake science
(**Geoscientists**)
seek to understand the workings of nature

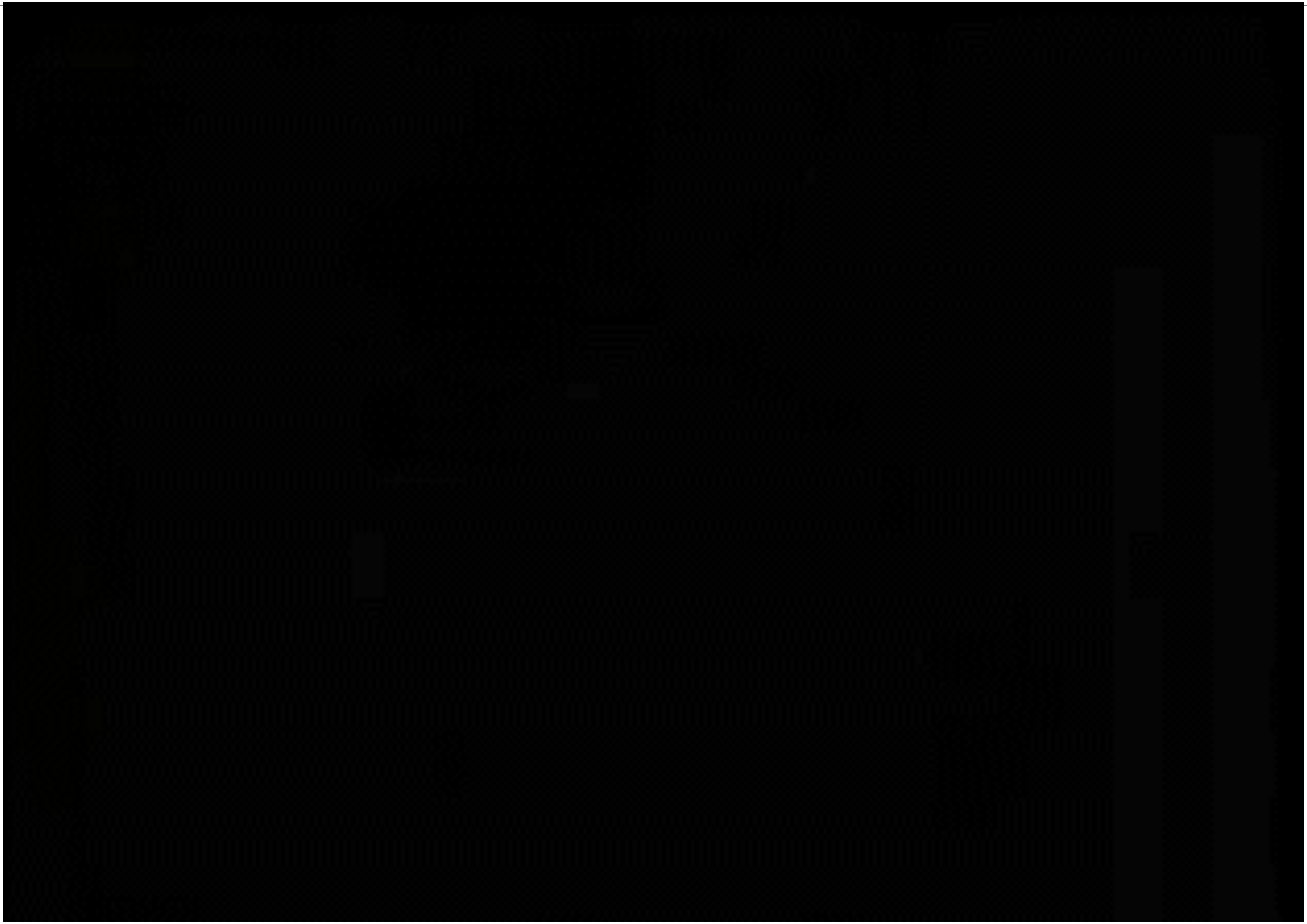


Earthquake engineers
seek to design and analyze infrastructure

At AECOM Los Angeles, we provide earthquake ground motions that are needed by earthquake engineers for design and analysis.
This seminar covers two such examples.

Part 1: Rupture Directivity

1995 Kobe earthquake at NHK building



Rupture Directivity

Background

Challenges in Probabilistic Seismic Hazard Analysis (PSHA)

Review of Models

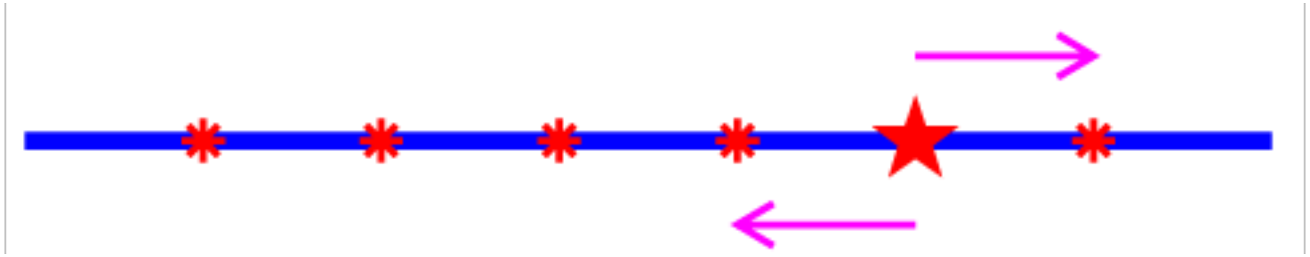
Review of Implementation Methods

Future Steps

Rupture Directivity

Earthquake rupture directivity is the focusing of wave energy along the fault in the direction of rupture.

This is caused by the constructive interference (piling up) of the S-waves, due to the rupture propagation.



(USGS)

Doppler Effect

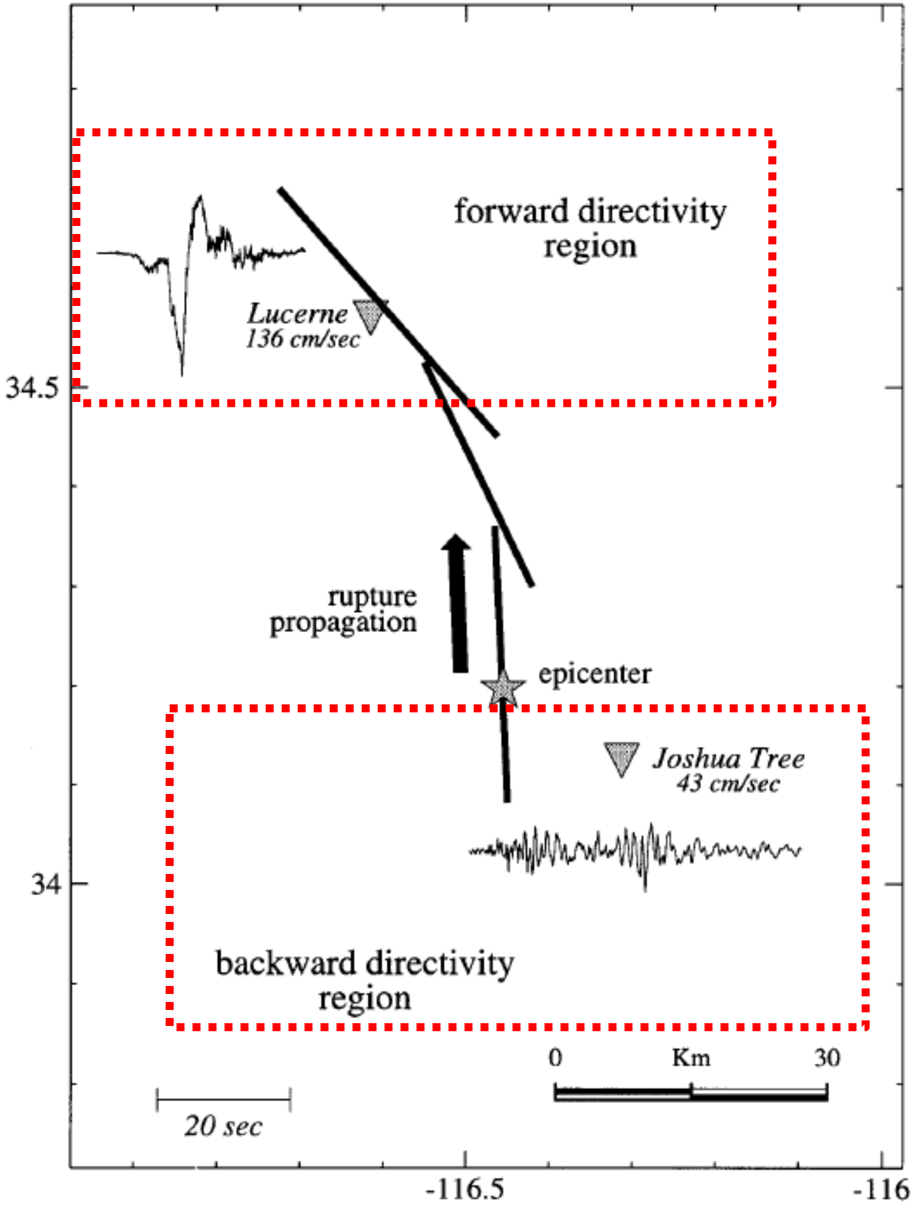
(Animation courtesy of Dr. Dan Russell, Grad. Prog. Acoustics, Penn State)

In engineering seismology, effects categorized jointly under “rupture directivity” are due to

rupture propagation (above)
source radiation pattern, (azimuthal dependence of S-wave amplitudes)
polarization of seismic waves (particle motion orientation)**.**

These have varying impacts on ground motion amplitudes, durations, and orientations.

1992 Landers earthquake as an example



(Somerville et al., 1997)

Rupture Directivity in PSHA

Is this typically accounted for in Probabilistic Seismic Hazard Analysis (PSHA) practice?

No.

(But it will be soon!)

(Baker et al., 2021)

$$\underbrace{\lambda(IM > x)}_{\text{Ground motion exceedance rate}} = \sum_{i=1}^{n_{sources}} \underbrace{\lambda(M_i > m_{\min})}_{\text{Earthquake occurrence rate}} \int_{m_{\min}}^{m_{\max}} \int_{0}^{r_{\max}} \underbrace{P(IM > x|m,r)}_{\text{Probability of ground motion exceedance (from GMM)}} \underbrace{f_{M_i}(m) f_{R_i}(r)}_{\text{Magnitude and distance PDFs}} \, dr \, dm$$

Rupture Directivity in PSHA

The GM exceedance probability calculation uses empirical GMMs:

$$\ln IM = \overline{\ln IM}(\boldsymbol{M}, R, \theta) + \sigma(\boldsymbol{M}, R, \theta) \cdot \varepsilon$$

No directivity:

$$\overline{\ln IM}(\boldsymbol{M}, R, \theta) = f_{Event} + f_{Path} + f_{Site}$$

With directivity:

$$\overline{\ln IM_D}(\boldsymbol{M}, R, \theta, \theta_D) = f_{Event} + f_{Path} + f_{Site} + f_D$$

$$\sigma_D(\boldsymbol{M}, R, \theta, \theta_D)$$

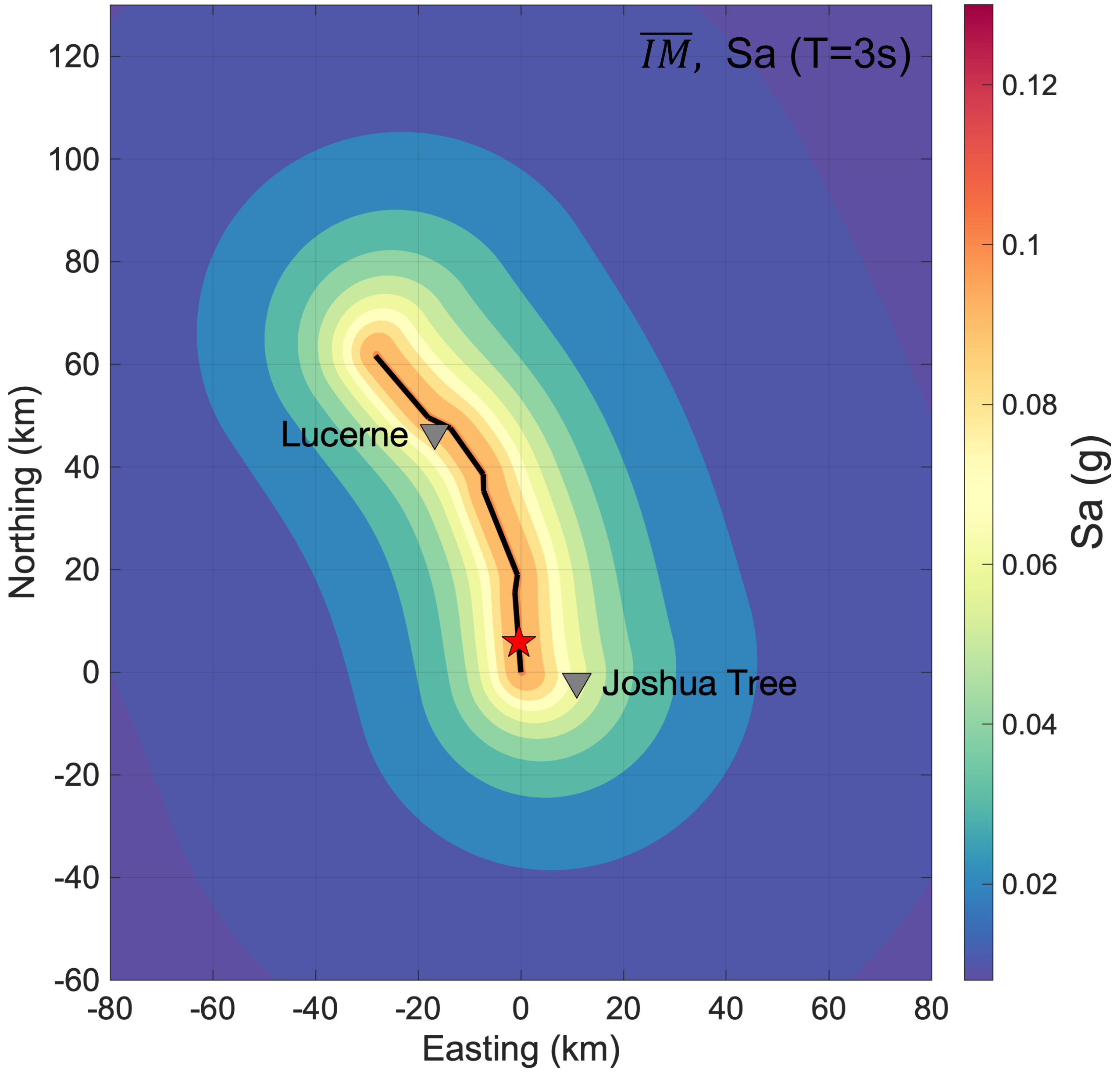
Rupture Directivity in PSHA

Boore et al. (2014) GMM

Reference site condition

$$\overline{\ln IM}(\boldsymbol{M}, R, \theta) =$$

$$f_{Event} + f_{Path} + f_{Site}$$



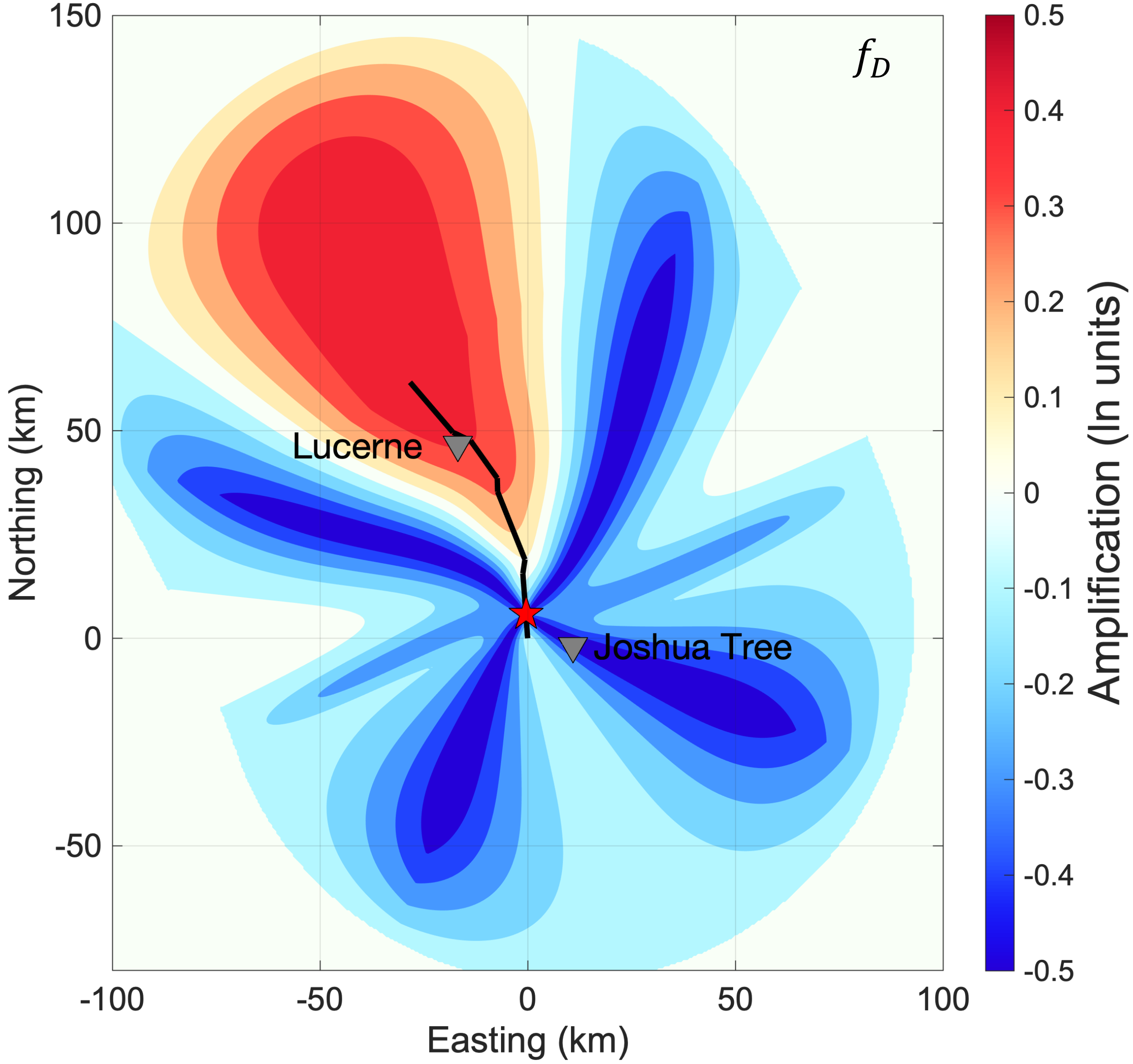
Rupture Directivity in PSHA

This map shows f_D using the Bayless et al. (2020) directivity model (DM).

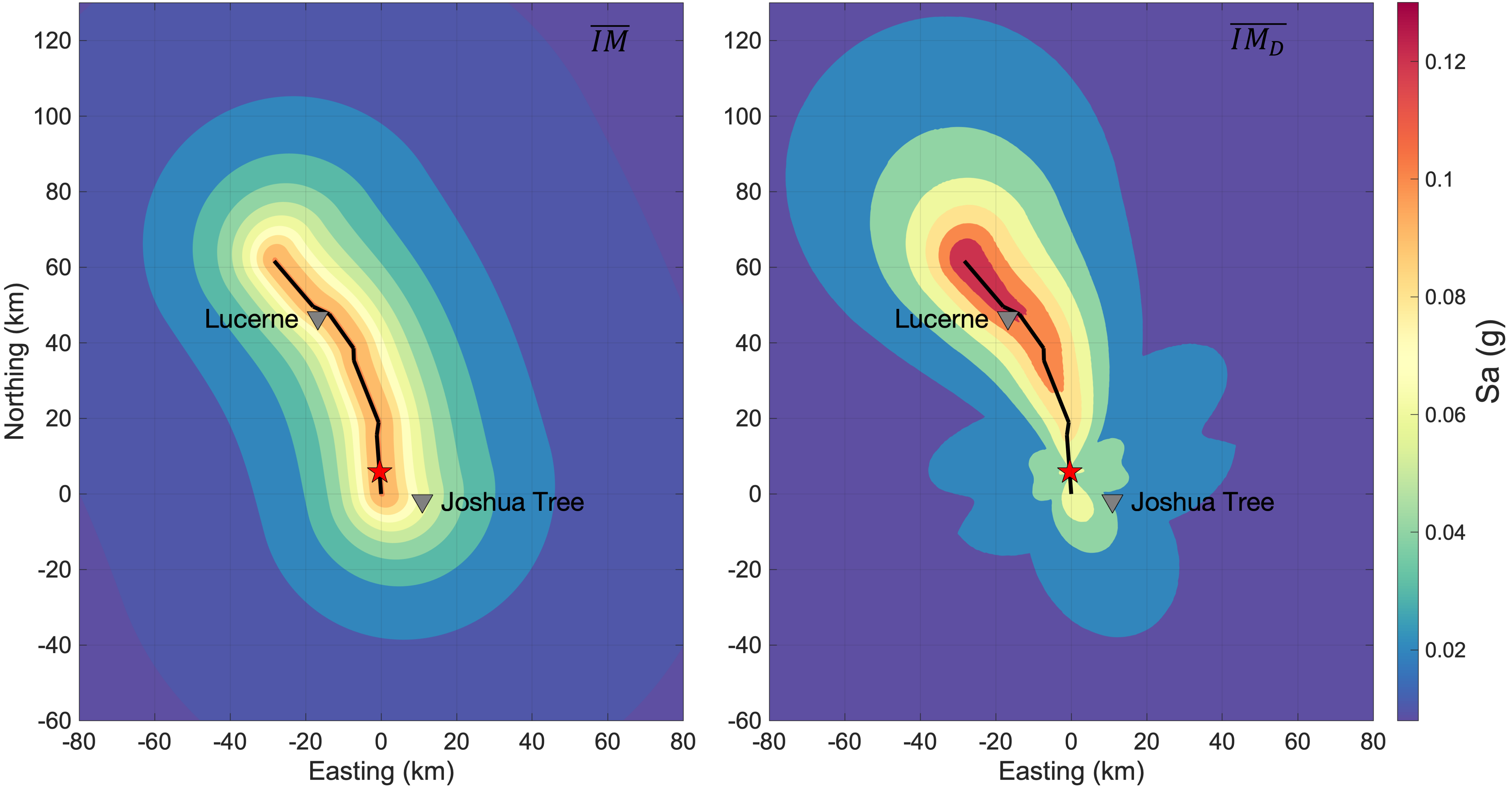
$\exp(f_D)$ is the median directivity amplification factor relative to $\overline{IM}$(T=3 sec)

$$\overline{\ln IM_D}(\boldsymbol{M}, R, \theta, \theta_D) =$$

$$f_{Event} + f_{Path} + f_{Site} + f_D$$



$$\overline{lnIM_D}(\boldsymbol{M}, R, \theta) = \overline{lnIM}(\boldsymbol{M}, R, \theta) + f_D$$



Rupture Directivity in PSHA

Can increase or decrease the hazard at a site relative to traditional methods, especially at long spectral periods and return periods.

So - why aren’t directivity effects typically included in PSHA?

(1) Challenges in developing directivity models

- Shortage of recorded near-fault data, especially azimuthally
- Implicit directivity effects in GM residuals
  - To what extent is it already accounted for in the median? (Donahue et al., 2019)
- Models should not alter the magnitude and distance scaling of existing GMM (“centered”)
- **Complex phenomenon/simple model predicament**

Rupture Directivity in PSHA

Can increase or decrease the hazard at a site relative to traditional methods, especially at long spectral periods and return periods.

So - why aren’t directivity effects typically included in PSHA?

(2) Challenges in PSHA implementation

- The added computational complexity
  - hypocenter location modeling – additional integrals for each rupture

- Uncertainty about directivity models
  - which models to use,
  - how to use them,
  - how to calculate the parameters,
  - compatibility with GMMs (centering),
  - how to handle aleatory variability

- Especially difficult for rupture forecast models with very complex ruptures (multi fault)

Rupture Directivity in PSHA

Can increase or decrease the hazard at a site relative to traditional methods, especially at long spectral periods and return periods.

So - why aren't directivity effects typically included in PSHA?

(1) Challenges in developing directivity models

(2) Challenges in PSHA implementation

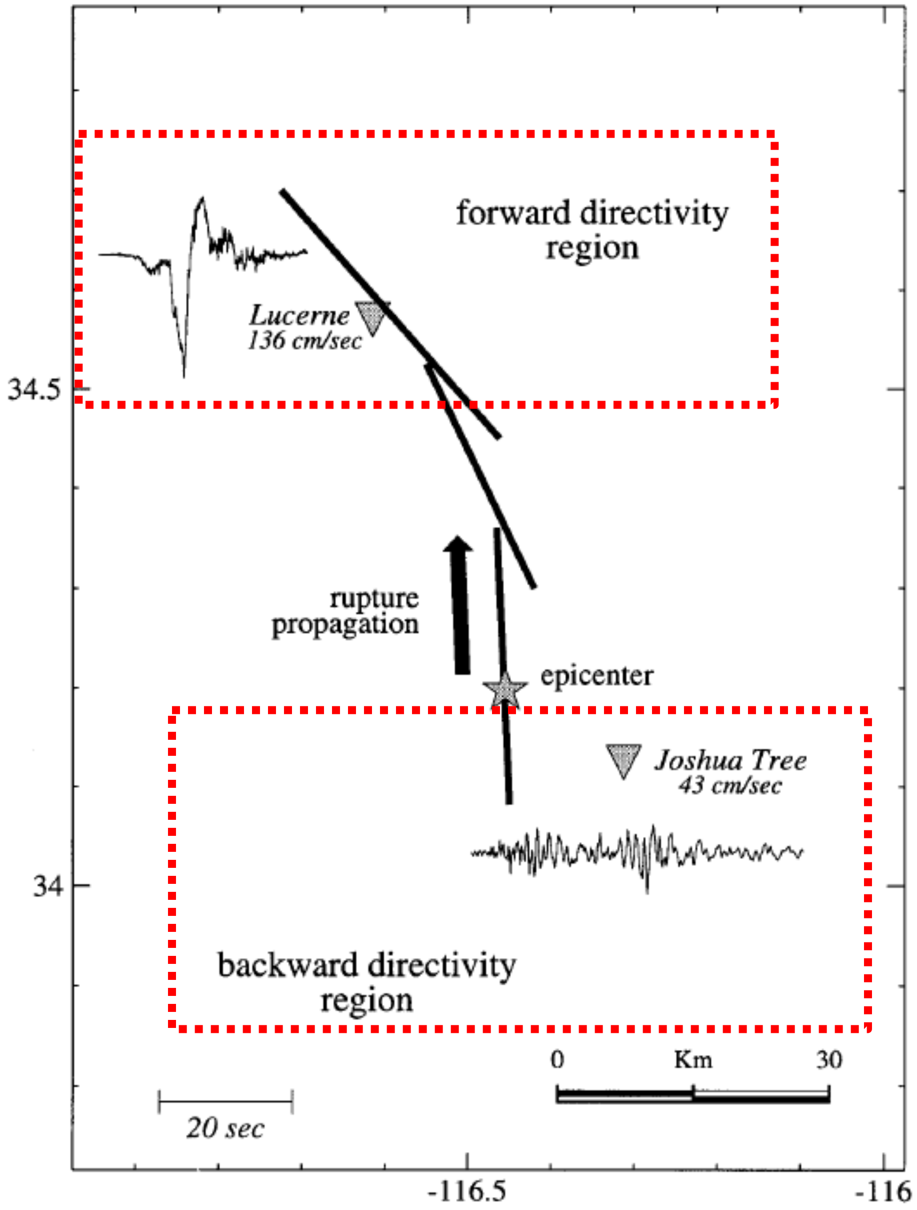
Recent models and implementation advances address these!

Review of Rupture Directivity Models

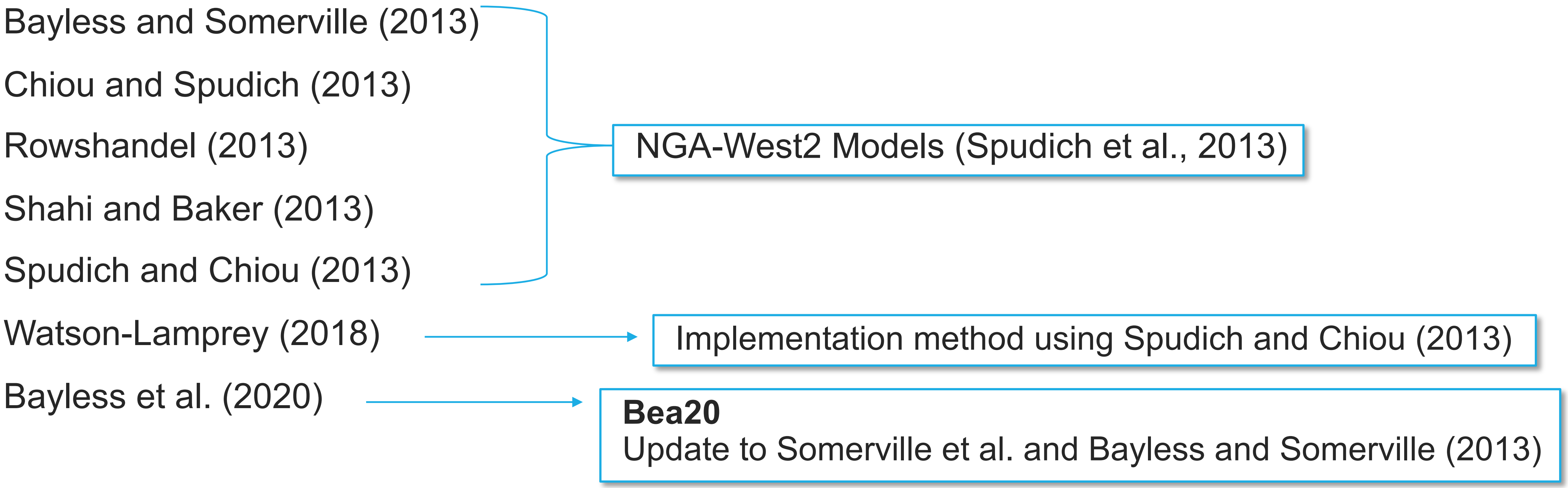
The innovative Somerville et al. (1997) paper was the first empirical model for modifying GMMs to account for rupture directivity effects.

Still useful but has a few shortcomings:

- Limited data
- Broadband
- No distance limits
- Parameters undefined for complex faults
- Aleatory Variability



Review of Rupture Directivity Models



Bayless and Somerville (2013)

Chiou and Spudich (2013)

Rowshandel (2013)

Shahi and Baker (2013)

Spudich and Chiou (2013)

NGA-West2 Models (Spudich et al., 2013)

Watson-Lamprey (2018) → Implementation method using Spudich and Chiou (2013)

Bayless et al. (2020) → **Bea20**
Update to Somerville et al. and Bayless and Somerville (2013)

Bea20 Model Overview

Fast facts:

Developed from residuals of simulations and the NGA-W2 database (Ancheta et al, 2014).

Supersedes our previous models.

Based on the two Somerville et al., (1997) conditions for forward directivity:

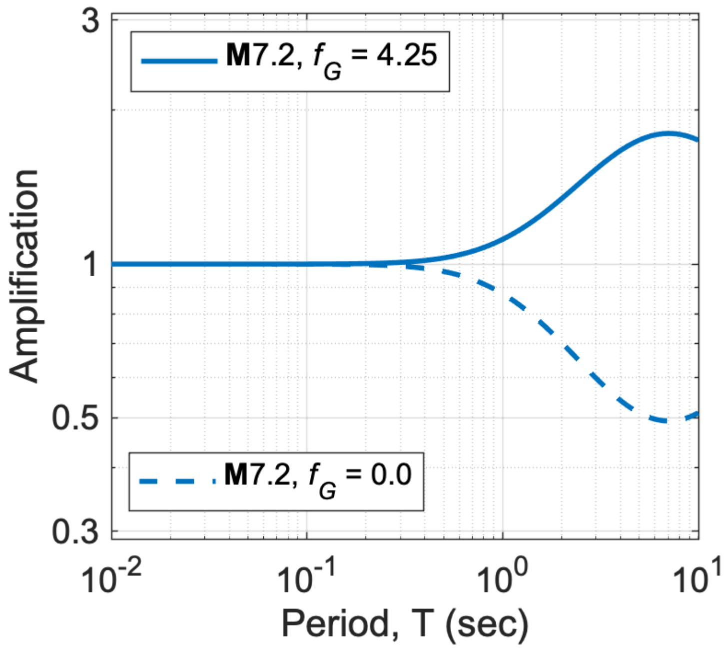
- the rupture front propagates toward the site (at velocity close to Vs)
- the direction of slip on the fault is aligned with the site

Maintains the relative simplicity of previous models.

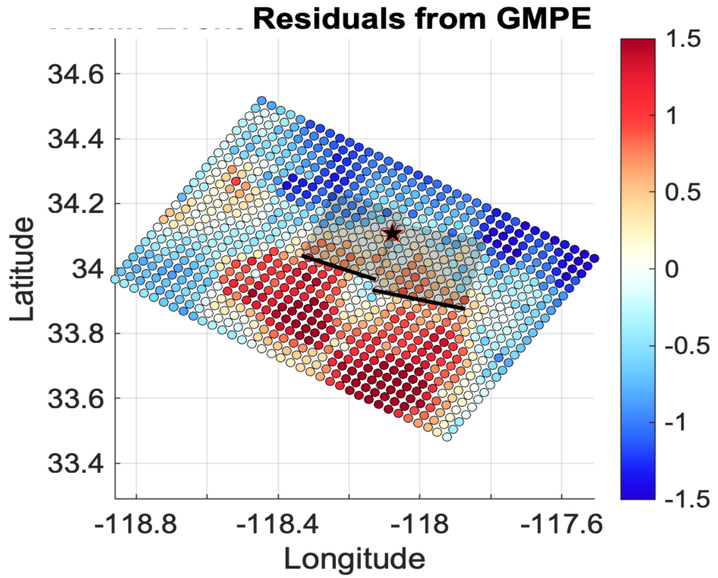
Bea20 Model Overview

New features:

- Narrowband - the peak period of the effect scales with magnitude



- finite-fault simulations have dense station arrays over all azimuths

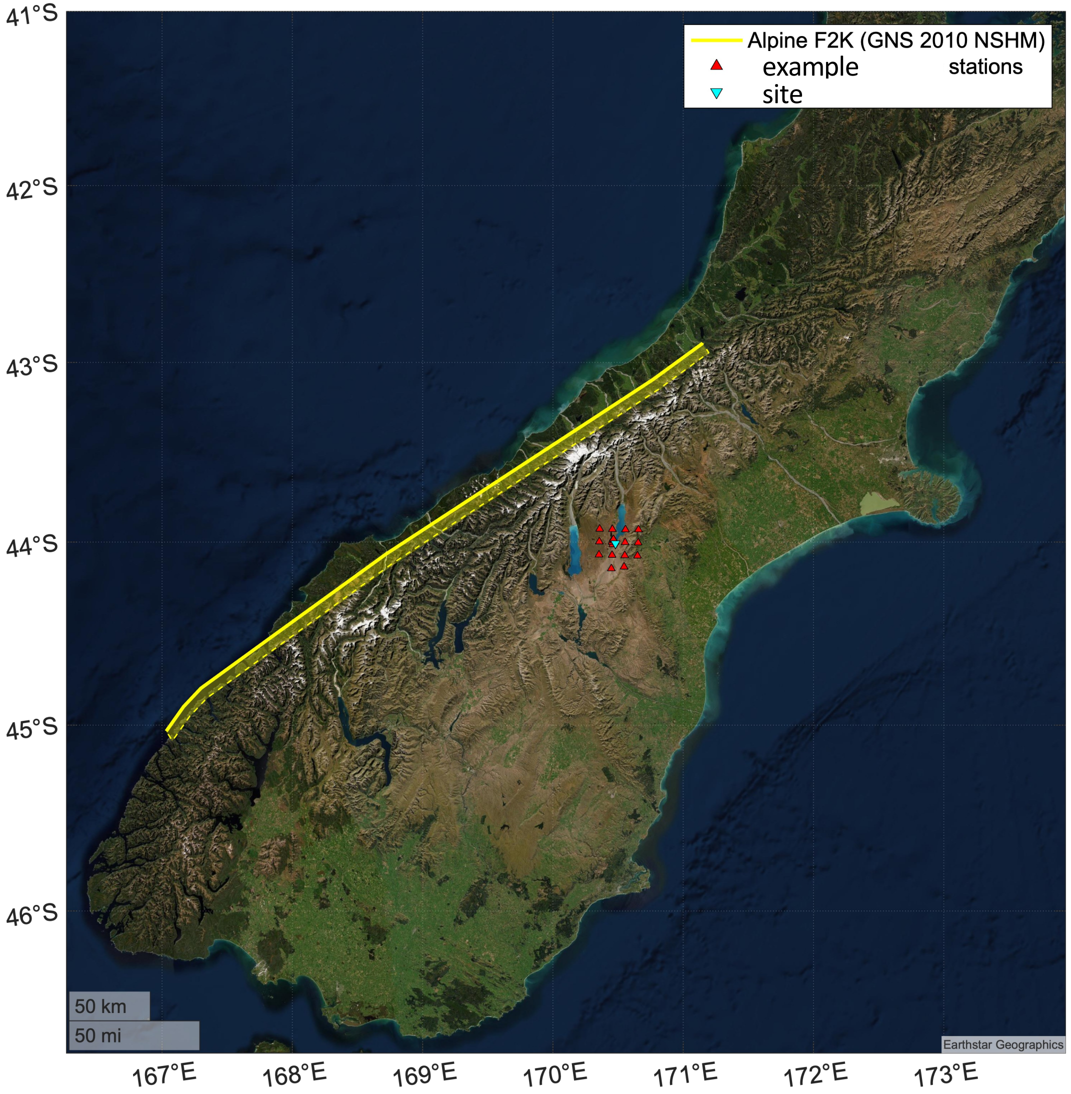


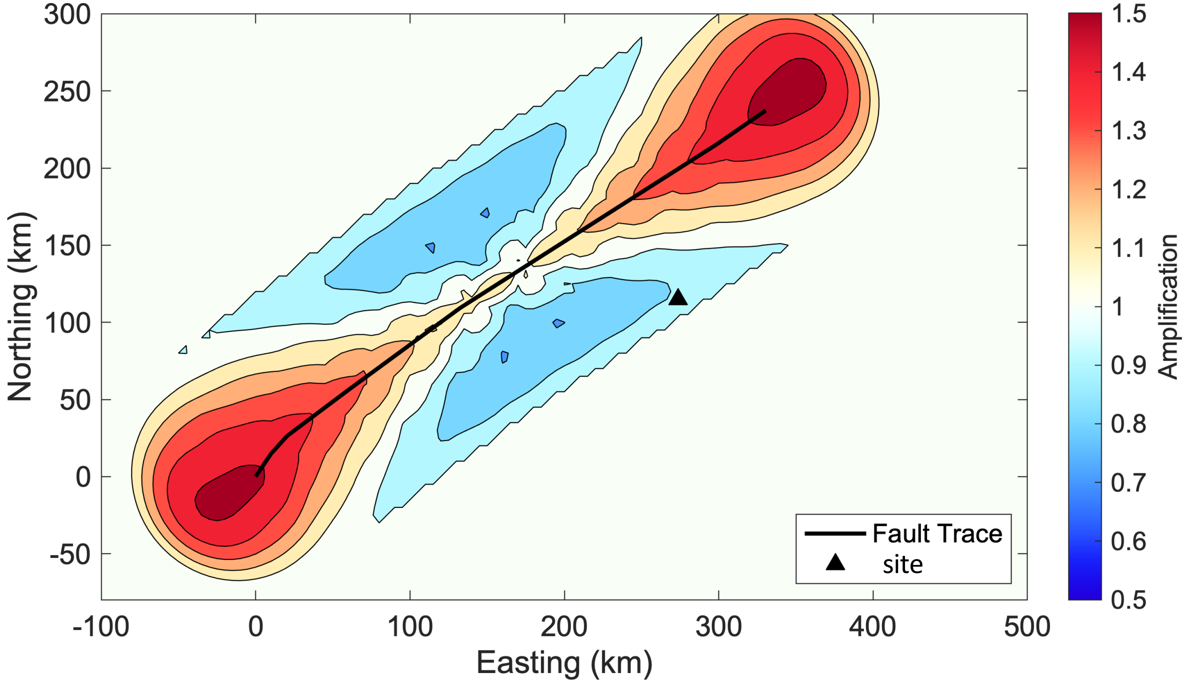
- Aleatory variability adjustment

- Enhanced documentation/instruction

Bea20 Model Overview

Example Application: Alpine Fault with Hypocenter Modeling





Weighted mean amplification for hypocenter locations modeled with probability density functions from Melgar and Hayes (2019)

PSHA Implementation

Method 1: Explicit Directivity Modeling

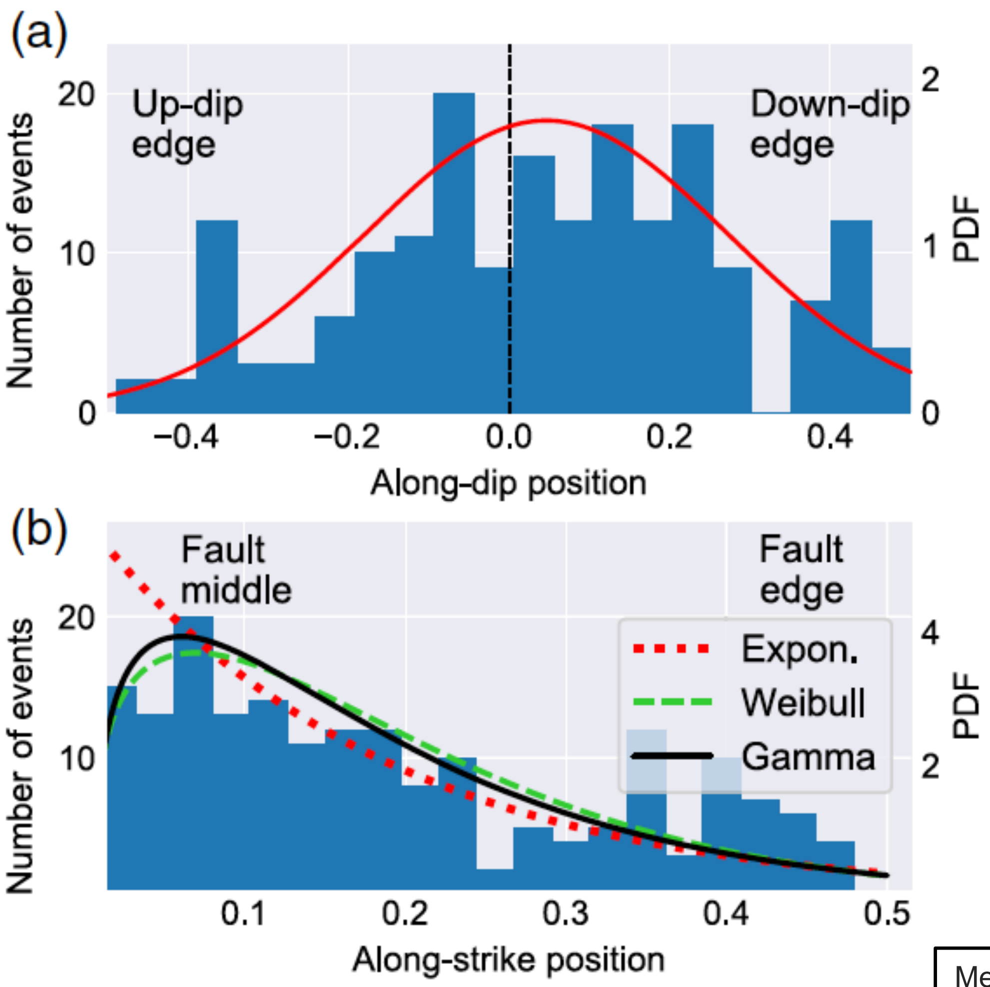
The directivity adjustments is dependent on hypocenter location within the rupture plane.

Because future hypocenter locations are not known, they must be modeled with PDFs.

- Uniform distribution (simplest)
- Melgar and Hayes (2019)
- Others?

This requires an additional PSHA integral over hypocenter location probability distribution

- For each rupture on each relevant fault



Melgar and Hayes (2019)

PSHA Implementation

Method 1: Explicit Directivity Modeling

$$\lambda(IM > x) \sum_{i=1}^{n_{sources}} \lambda(M_i > m_{min}) \int_M \int_R P(IM > x|m,r) f_M(m) f_R(r)\; dr\, dm$$

$$\lambda(IM > x) \sum_{i=1}^{n_{sources}} \lambda(M_i > m_{min}) \int_M \int_R \int_H P(IM > x|m,r,\theta_D) f_M(m) f_R(r)\, f_{DM}(\theta_D)\, dr\, dm\, d\theta_D$$

This method can be computationally demanding

- May be better for smaller scale studies (single site)
- There are implementation challenges with regional studies, but it has been done recently.

$P(IM > x|m,r,\theta_D)$ contains both a median and standard deviation adjustment

PSHA Implementation

Method 1: Explicit Directivity Modeling

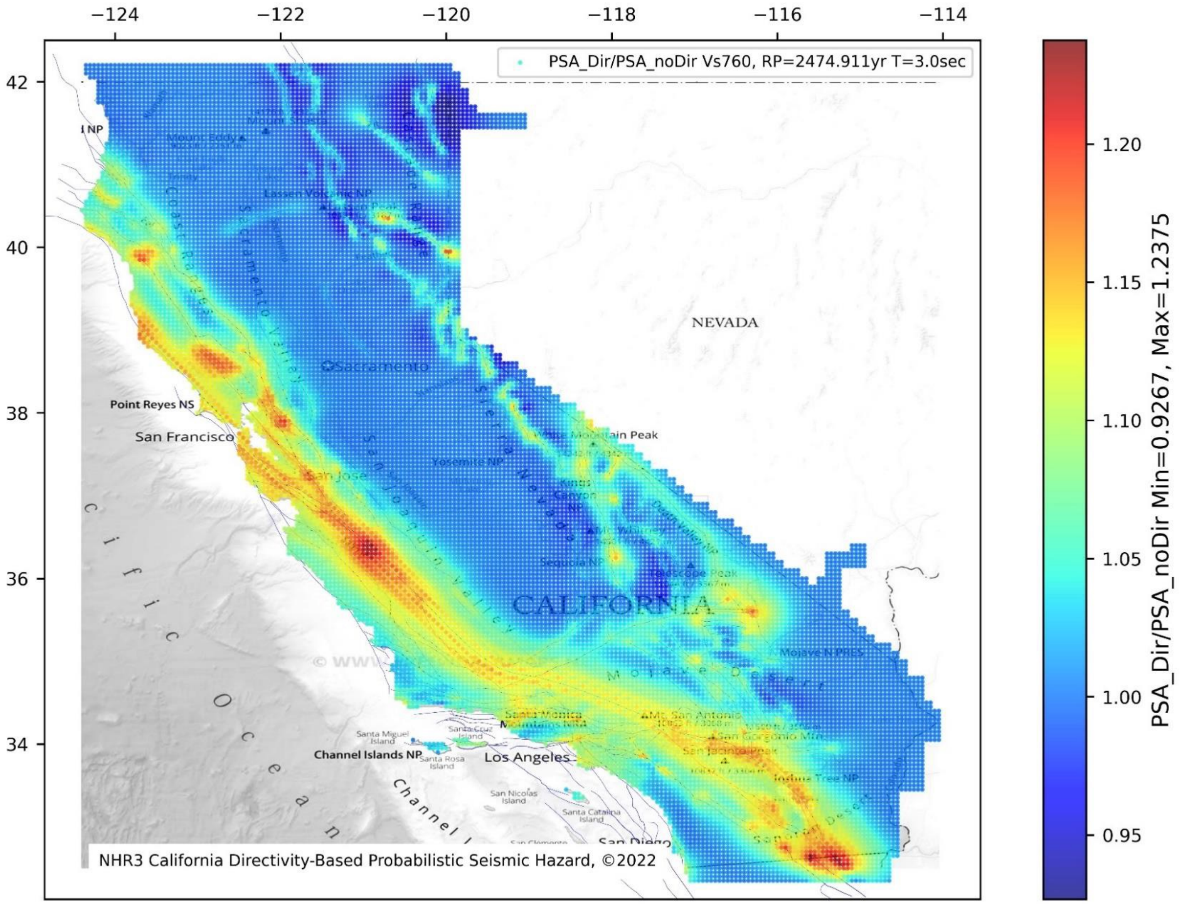
Al Atik et al. (2023) utilized explicit directivity modeling across California.

The first attempt to implement current generation directivity models with complex UCERF3 fault ruptures in a statewide framework.

- AWS parallel computing required

Three directivity models:

- Chiou and Spudich (2013)
- Bayless and Somerville (2013)
- Bayless et al., (2020)



Directivity adjustment map for the 2,475-year return period for T = 3 sec using three directivity models.

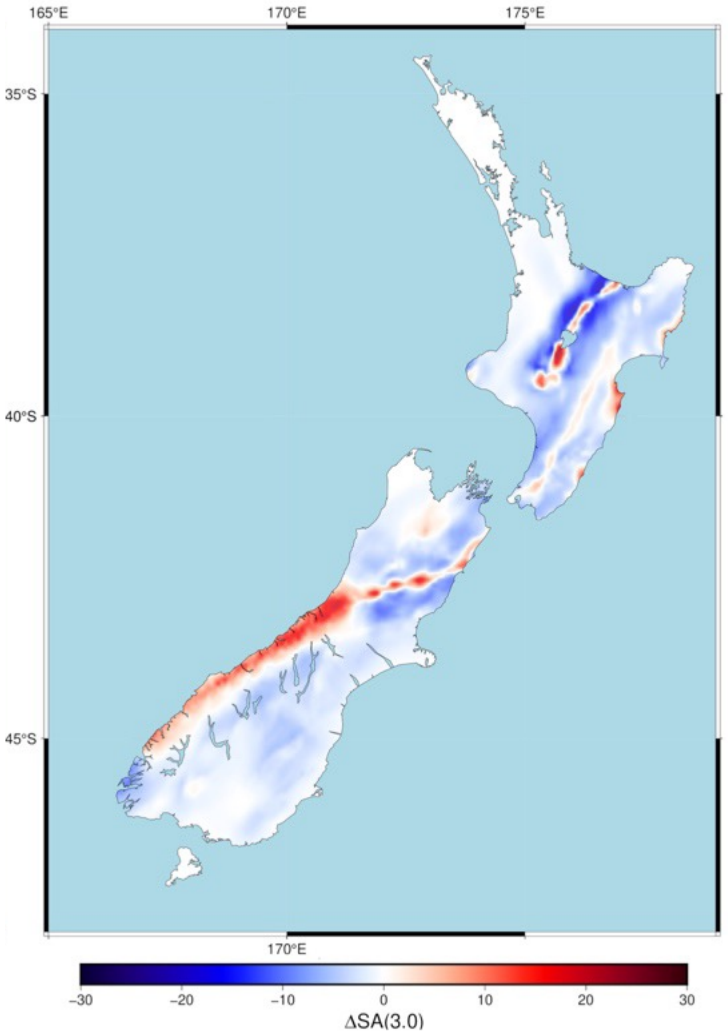
PSHA Implementation

Method 1: Explicit Directivity Modeling

Weatherill (2022) utilized explicit directivity modeling across New Zealand.

As large as 20-30% increase at T=3 sec near active faults capable of hosting large earthquakes.

Implemented in the OpenQuake software.



Percent change in seismic hazard with a 475-year return period using Bea20, T=3 sec

PSHA Implementation

Method 2: Modified Moments

Takes the computationally demanding directivity calculations outside of the hazard integral.

Modify the moments of the GMM (median and variance) to reflect directivity based on the hypocenter location probability distributions.

The moment modifiers ($\overline{\Delta f_D}$ and σ_H^2) can be determined using:

- parametric equations (Watson-Lamprey 2018).
- parametric equations with machine learning techniques (Kelly et al., 2022).
- machine learning techniques for the pre-defined inventory of earthquake ruptures for the hazard calculation (Weatherill and Lilienkamp, 2023).

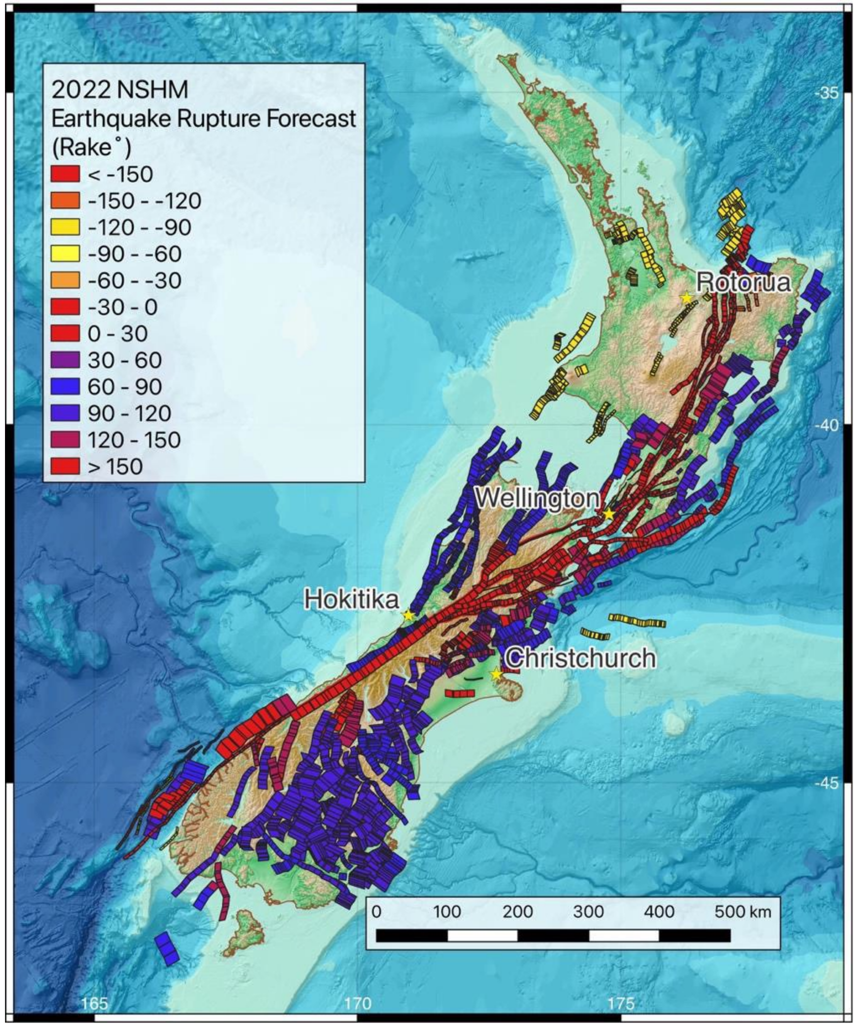
PSHA Implementation

Method 2: Modified Moments – Weatherill and Lilienkamp (2023)

The earthquake sources are known before the regional PSHA is performed.

Weatherill and Lilienkamp (2023) use this knowledge to calculate the impact of directivity outside of the PSHA calculation.

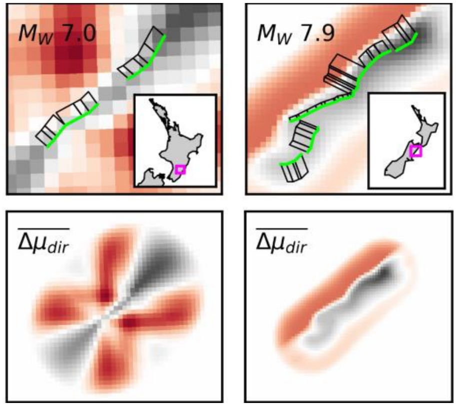
The computational costs are separated, reducible, and the directivity effects on the median and standard deviation are still captured explicitly.



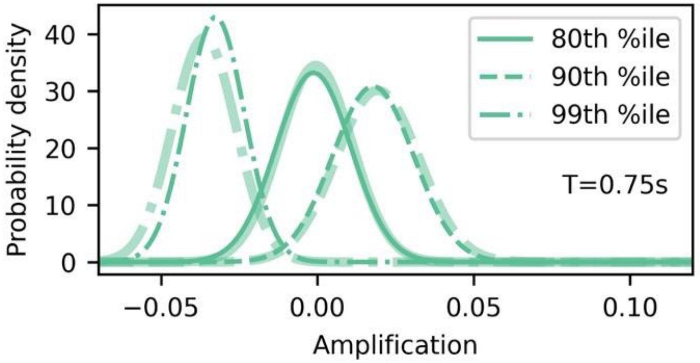
PSHA Implementation

Method 2: Modified Moments – Weatherill and Lilienkamp (2023)

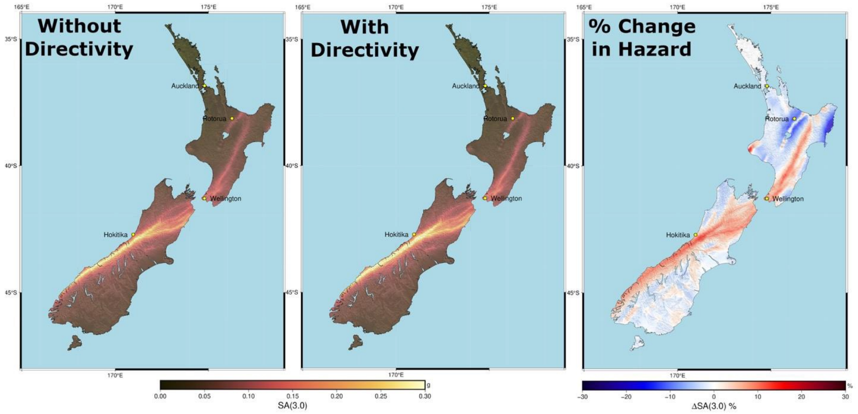
1. Calculate the directivity moment modifiers ($\overline{\Delta f_D}$ and σ_H^2) for all PSHA sources and all sites.



2. Create a computationally efficient look-up table by fitting a neural network to the data contained within it.



3. Perform the PSHA with modified GMM moments using the look-up table. (No modeling of hypocenters)



Summary

Current State of Practice

Rupture directivity effects can increase or decrease the PSHA hazard at a site relative to traditional methods, especially at long spectral periods and return periods.

Still not typically implemented in practice (yet!)

Recent directivity models combined with ongoing implementation advances are promising.

Summary

Looking Forward

Epistemic uncertainty:

- Alternative directivity models.
- Hypocenter distributions (fault specific or preferential rupture directions, e.g. Ben-Zion & Sammis, 2003).
- Other types of earthquake sources besides shallow crustal.

Improved directivity models

- Calibrated for very complex ruptures (e.g. those with gaps or changes in mechanism).
- Centering
- Better agreement for reverse and normal faulting ruptures

Be on the lookout for implementation in standard practice.

Part 2: Permanent displacements

Permanent Displacements

Introduction

Description of the dilemma

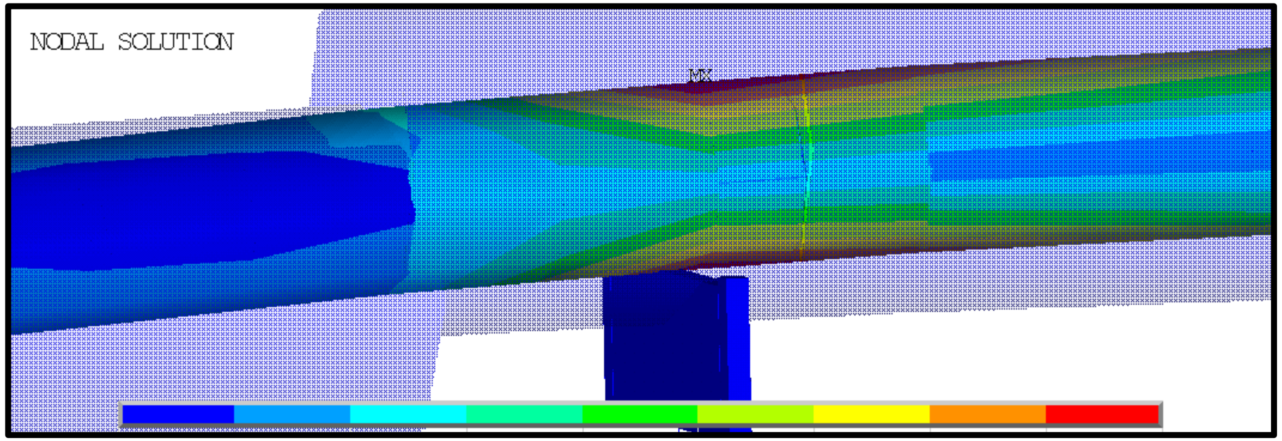
Modification procedure

Limitations

Summary

Introduction

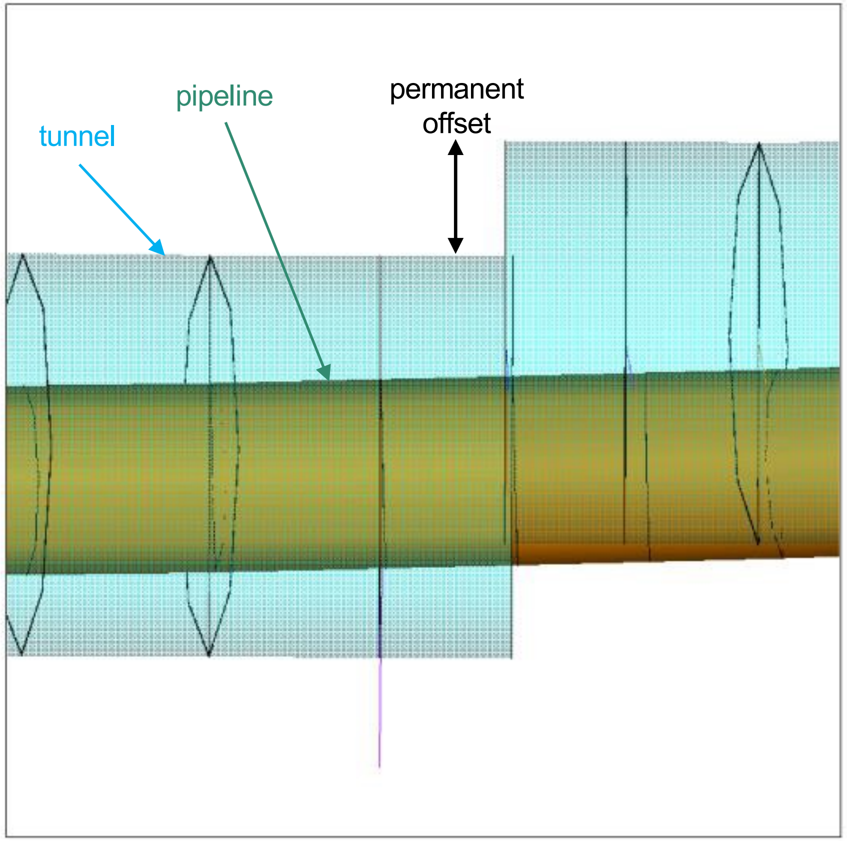
- Dynamic (time history) response analysis
  - involves solving the dynamic equation of motion throughout the duration of the ground shaking (or ground displacement) and the subsequent system vibration.
- Usually done by application of the earthquake ground motions in three orthogonal directions simultaneously to a finite-element model of the system.
  - obtains time history excitations of the system, including stresses, strains, and reaction forces



Finite element model of a dam outlet pipe (stresses)

Introduction

- This method requires ground motion time histories established from a seismic hazard analysis.
- In some instances, ground shaking and dynamic displacement are both critical seismic load conditions (e.g., fault crossings).
  - Then the ground-motion time histories should match both the target **response spectrum** and contain a dynamic displacement with permanent offset (**fling-step**).
  - Until now, there is no standardized procedure for this.



Finite element model showing the tunnel (blue) and pipeline (brown) on sliding supports, subject to displacement at a fault crossing

Introduction

Fling-step

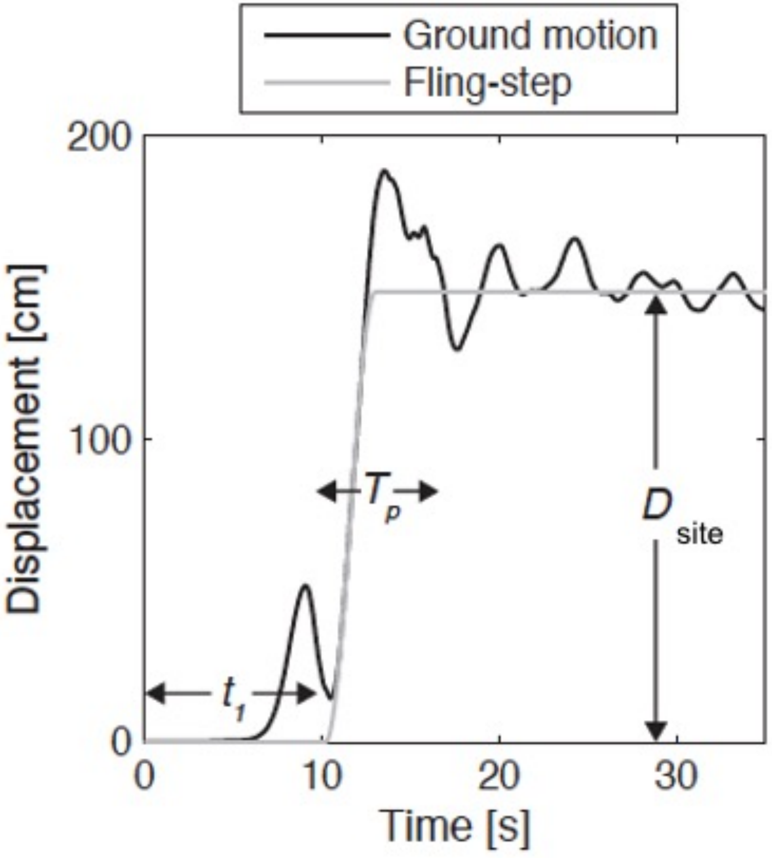
- engineering term for the effects of the permanent tectonic offset of a rupturing fault in the recorded ground motions near the fault.
- expressed by a single-cycle acceleration pulse, a one-sided pulse in ground velocity and a nonzero final displacement at the end of shaking.

The notation used by Kamai et al. (2014) is:

D_{fault} = mean fault slip (displacement) over the rupture plane.

D_{site} = component-specific amplitude of the tectonic displacement (fling-step) observed or modeled at a site.

T_p = the period in seconds of the single-cycle acceleration sine wave used to model D_{site}.



Ground motion displacement from the 1999 Kocaeli, Turkey earthquake.

Figure modified from Burks and Baker (2016)

Description of the Dilemma

There are challenges in modifying time histories to contain both a fling-step (with a specified duration and amplitude) and to acceptably match a target response spectrum.

Difficulty arises due to the inherent relationship between the response spectrum and the acceleration time history.

Three potential methods are outlined next – each have significant shortcomings.

Option 1: Simple scaling of a recorded time history containing a fling-step.

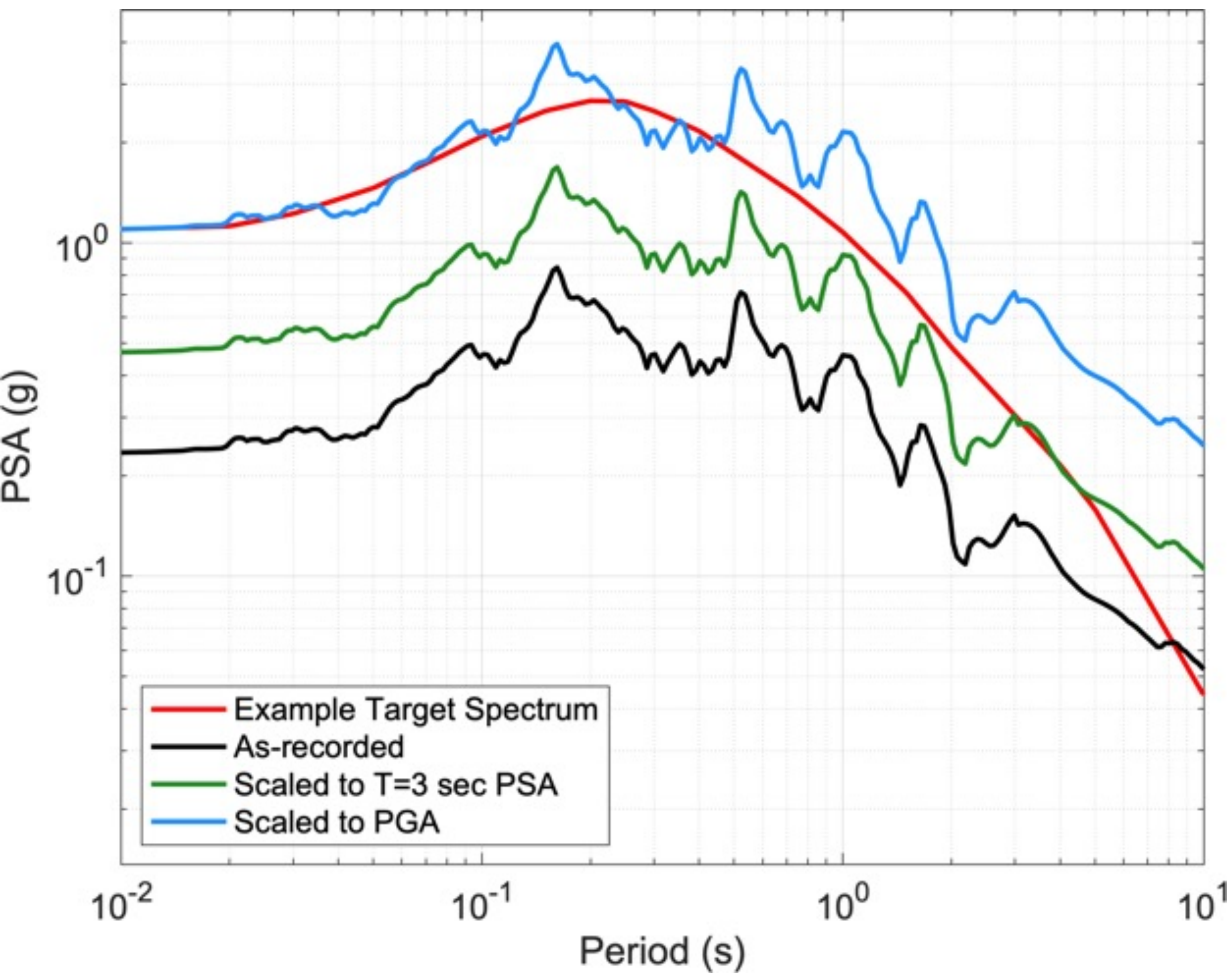
Option 2: A combination of simple scaling, followed by spectral matching.

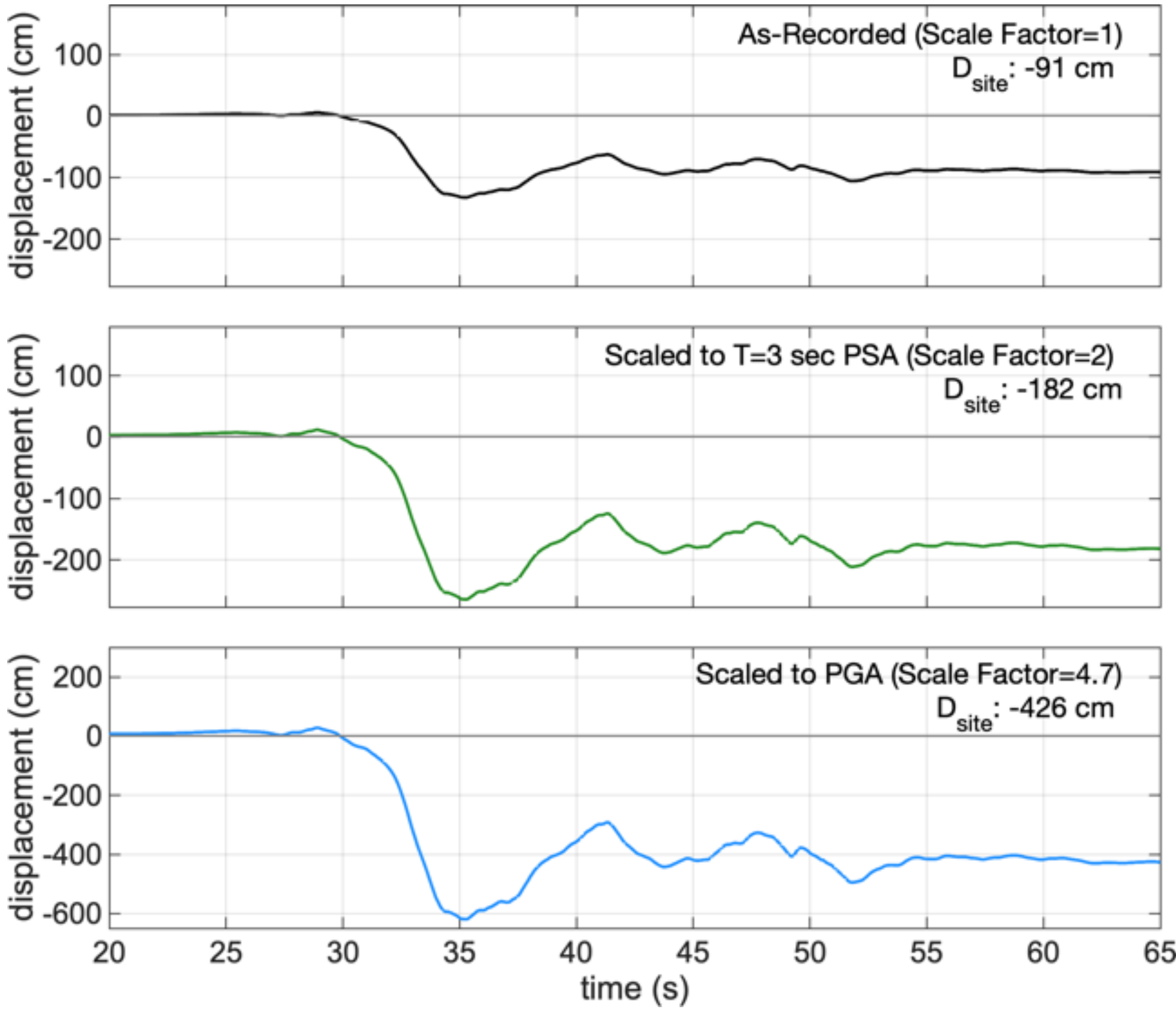
Option 3: Add the fling-step to an acceleration time history without an existing fling-step, followed by spectral matching.

Then,

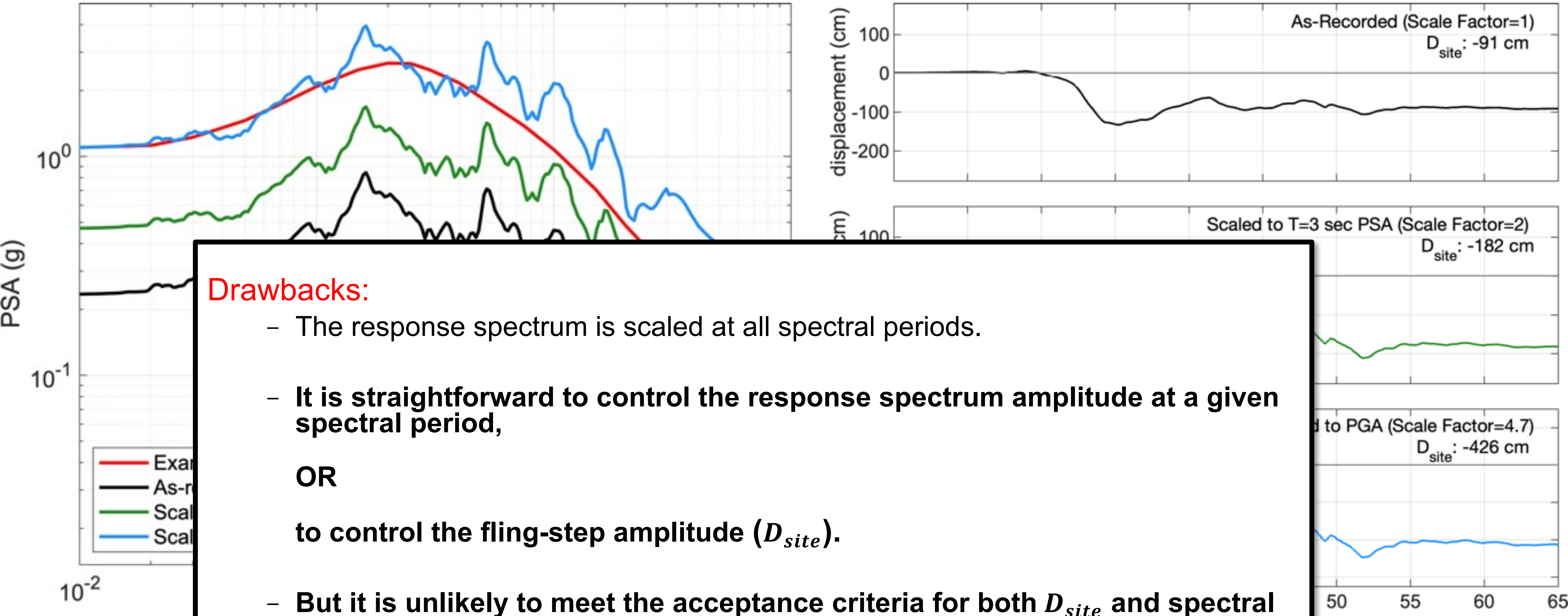
Proposed Method: Like Option 3, using a modified target response spectrum for spectral matching.

Option 1: Simple scaling





Option 1: Simple scaling



Drawbacks:

- The response spectrum is scaled at all spectral periods.
- **It is straightforward to control the response spectrum amplitude at a given spectral period,**

  OR

  to control the fling-step amplitude (D_{site}).
- **But it is unlikely to meet the acceptance criteria for both D_{site} and spectral acceleration (match to the target spectrum).**

Option 2: A combination of simple scaling (to reach the target D_{site}), followed by spectral matching.

Drawbacks:

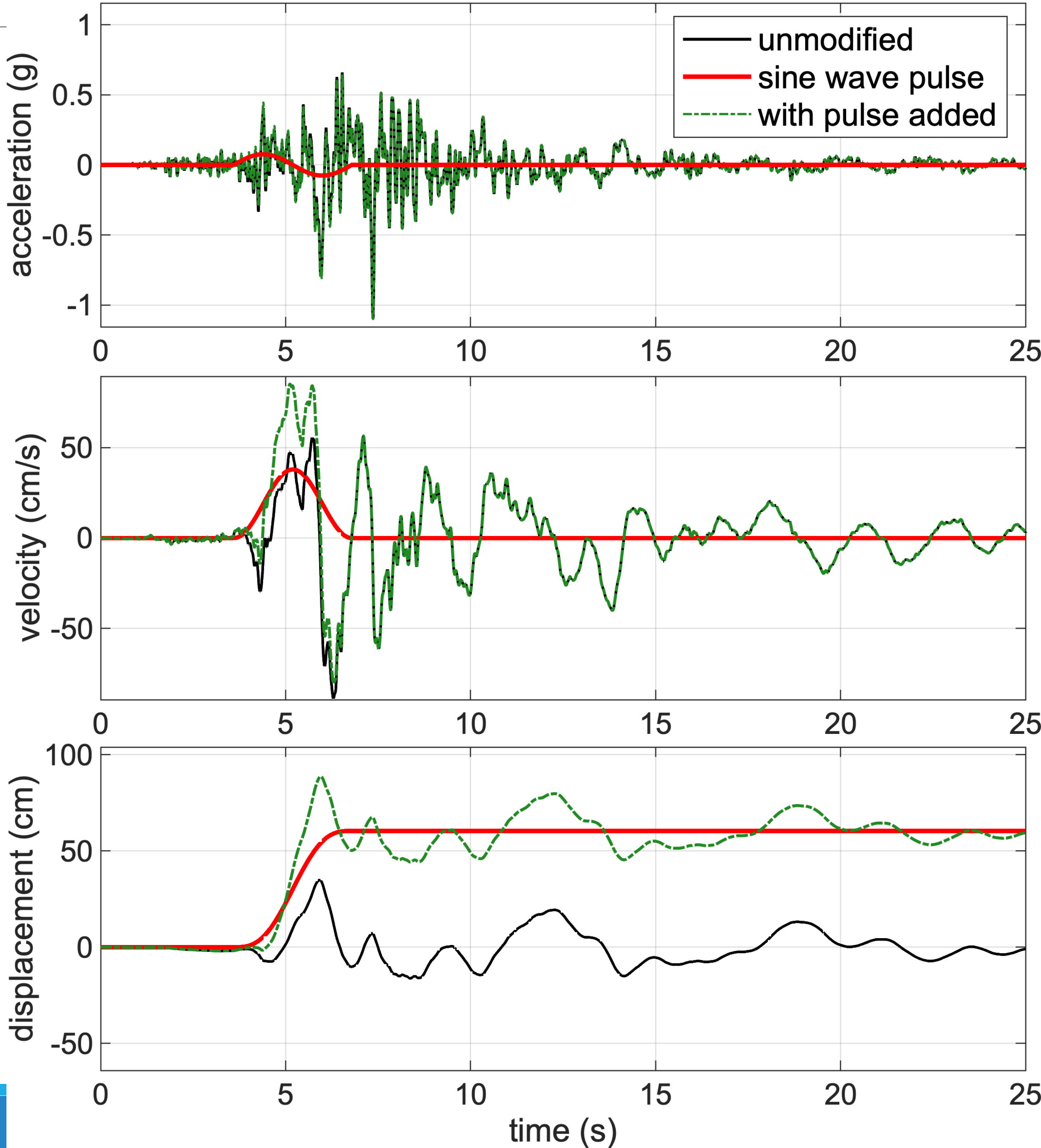
- Does not lend itself to specifying the fling-step duration.
- Has potential for destructive interference because:

  The fling-step (with a given period and amplitude) is related to the response spectrum amplitude in that period range, and modification to one will affect the other.

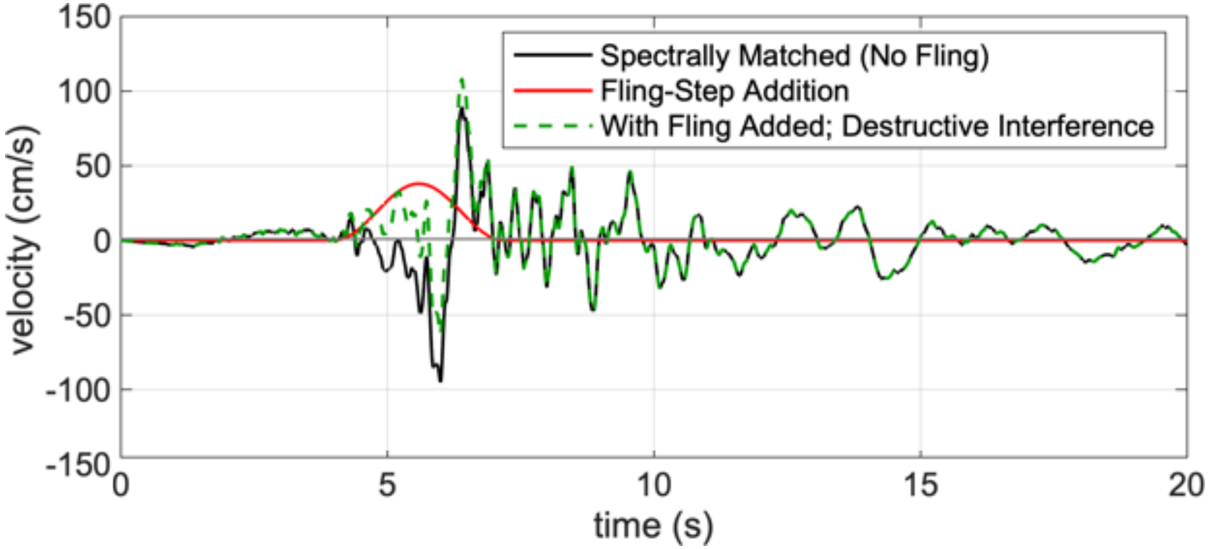
More on this next

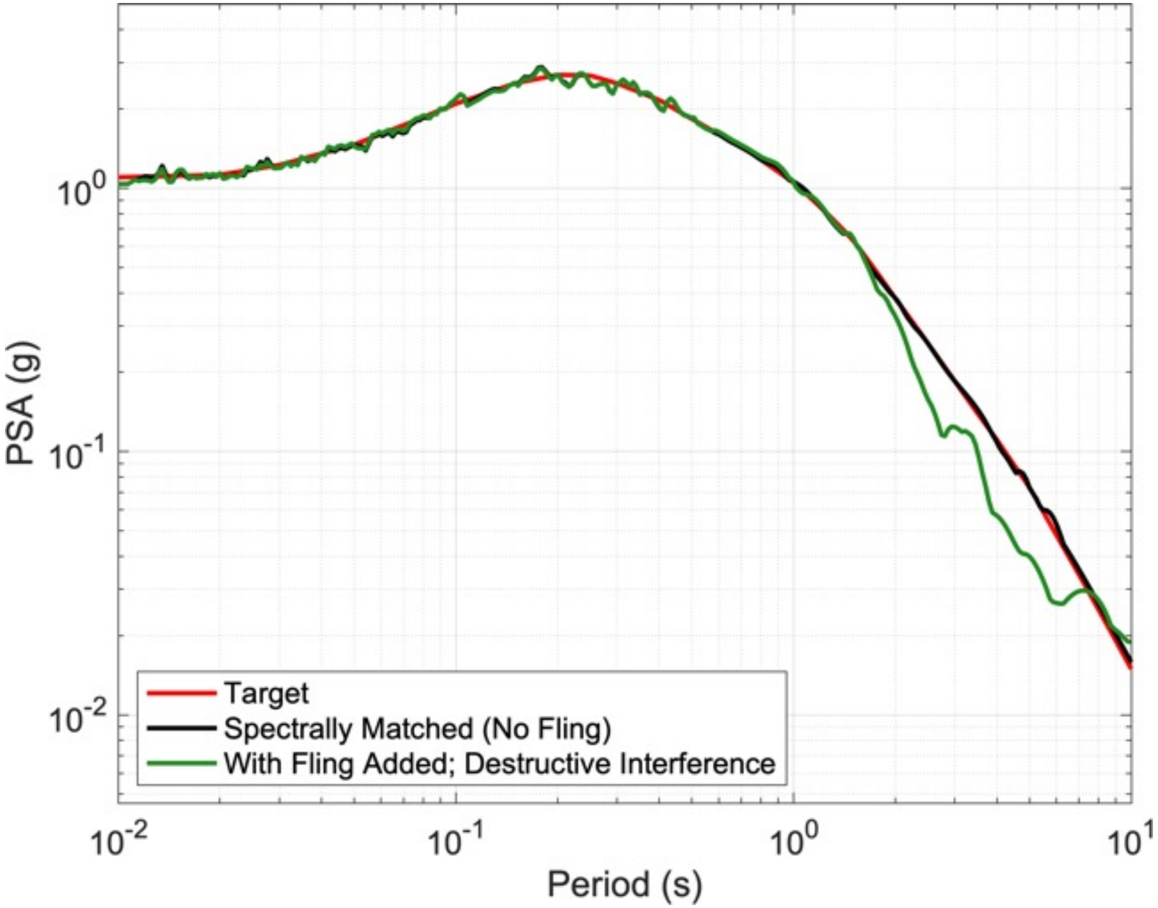
Option 3: Add the fling-step to an acceleration time history without an existing fling-step, following Kamai et al. (2014), then perform spectral matching.

- The Kamai et al. (2014) method is to add a single-cycle sine wave in acceleration.
- Allows specification of the pulse period and fling-step amplitude.
- Drawback:
  - The same potential for destructive interference, **because of the relationship between the pulse and the response spectrum**.



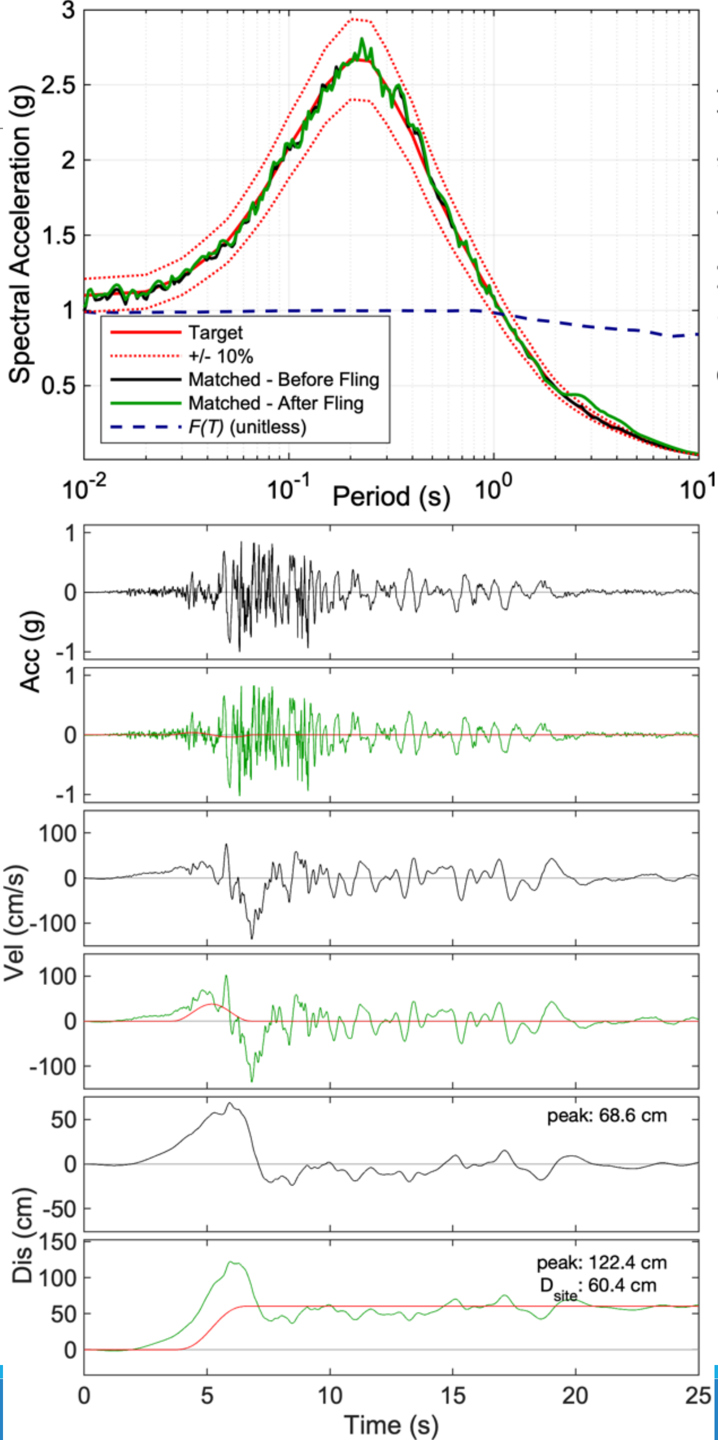
Destructive interference - example

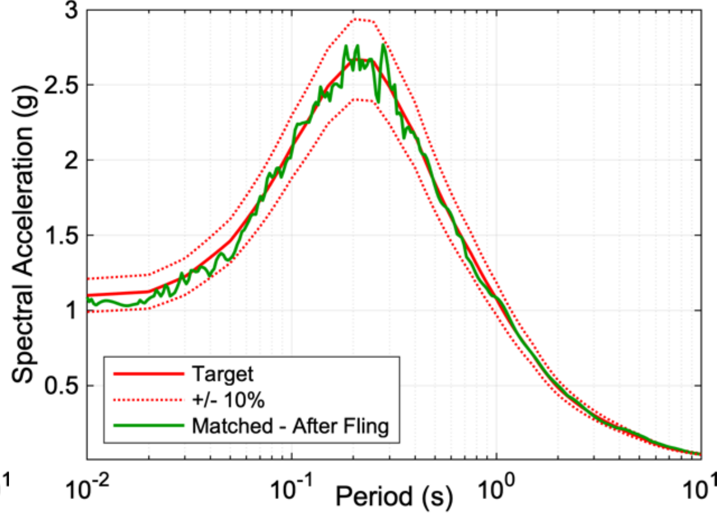




Modification Procedure

1. Select a time history without a fling step.
2. Spectrally match to the target spectrum.
3. Add the fling-step following Kamai et al. (2014).
4. Calculate F(T): the ratio of the response spectrum before and after adding the fling-step.
   Scale the target response spectrum by F(T).
5. Spectrally match the original time history to the modified target spectrum.
6. Add the fling step as in Step 3.





Modification Procedure (cont.)

7. Check the resulting time history for its non-stationary characteristics and for compatibility with the target response spectrum ($Target$) and the target permanent displacement (D_{site}).

This method *should* retain the non-stationary characteristics of the time history and maintain the physically important features of the fling step.

Limitations of the Procedure

The main limitation – it doesn't always work!

- There is potential for the addition of the fling-step (sine wave in acceleration) to destructively interfere with the vibratory ground motion, leading to the spectrum of the final time history falling below the target at long periods.

- Steps 2-4 of the procedure are intended to reduce the likelihood of destructive interference.

- **Still, users of the method will need to be cognizant of the effect each step has on the time history.**

- Troubleshooting tips are provided in the Bayless and Abrahamson (2022).

Summary

- For engineering projects in which dynamic analyses are performed, ground-motion time histories are required as input.

- In circumstances where both ground shaking and dynamic displacement are critical seismic load conditions, ground-motion time histories may be required which simultaneously match a target response spectrum and contain a fling-step with a specified duration and amplitude.

- This presentation proposes a straightforward procedure for developing earthquake ground motion time histories containing both features while maintaining the physically important features of the fling-step.

Thank you

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