ETH Eidgenössische Technische Hochschule Zürich

Schweizerischer Erdbeben Dienst — Swiss Seismological Service

Ground Motion Parameterization (and later simulation) for Structural and Geotechnical Analysis

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Motivation

► How to optimally search existing strong-motion data bases for ground-motion records that are likely to show a "desirable" response in terms of

(a) their structural demands, i.e. the response of buildings
(b) liquefaction potential, i.e. the behavior of certain soils

→ **Need to define a simple, but effective, ground-motion parameterization that allows for automated search and classification**

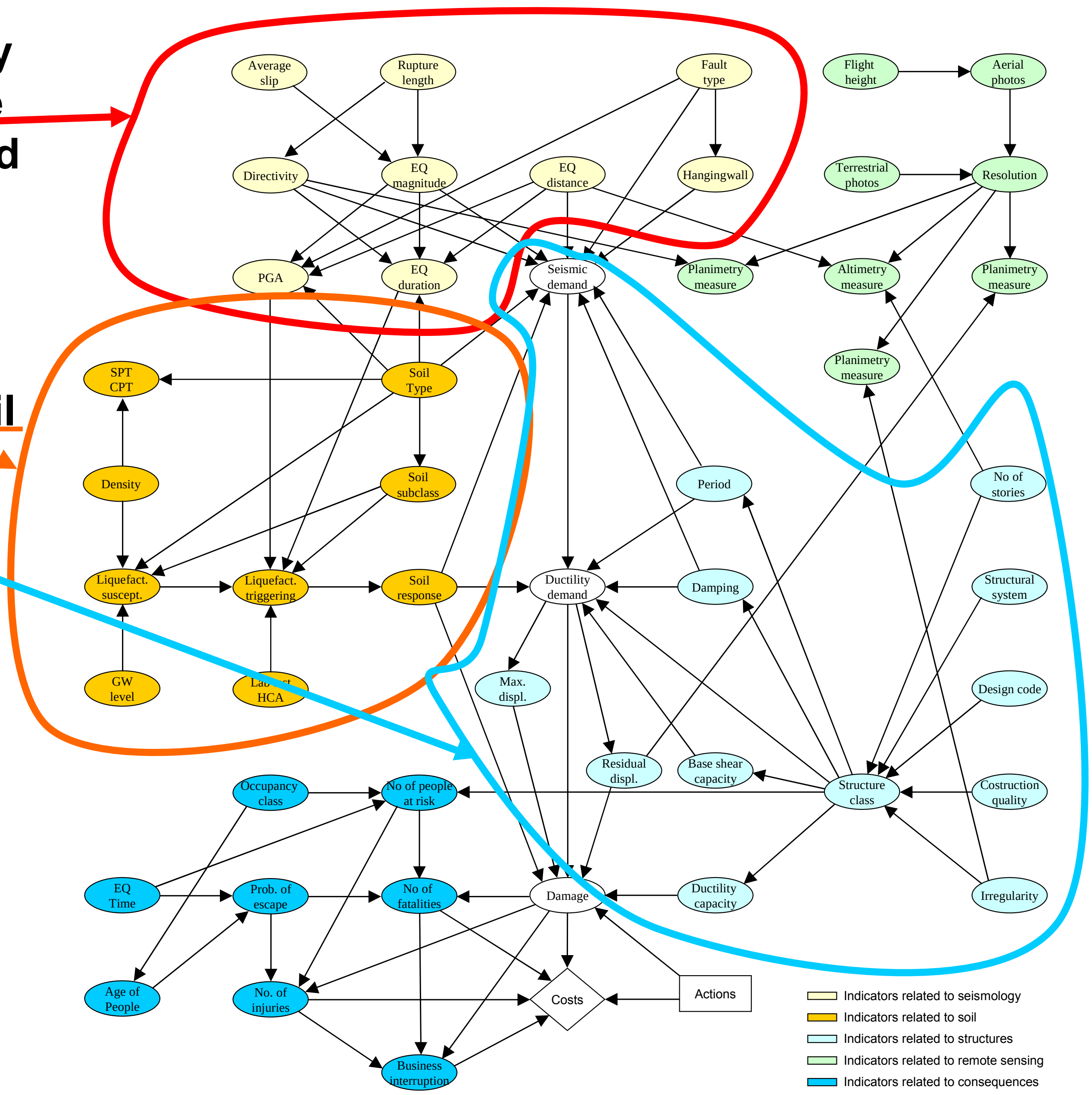
► Characteristics of such near-fault recordings are needed to guide innovative procedures for ground-motion simulation:

(a) include dynamic-rupture effects (either directly through dynamic modeling or indirectly by means of a pseudo-dynamic source characterization)

(b) incorporate realistic high-frequency components into the simulated wave-field (e.g. by means of scattering theory that considers the physical properties of the medium)

Motivation

► In a Bayesian Probability Network (BPN), earthquake source characterization and the parameterization of the resulting near-source motions stands at the top, directly affecting the condition indicators for soil and structural response

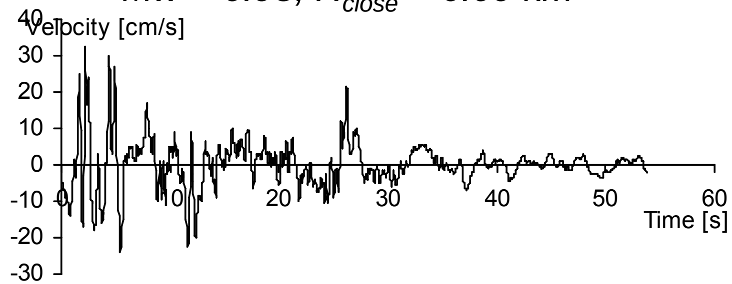


Motivation

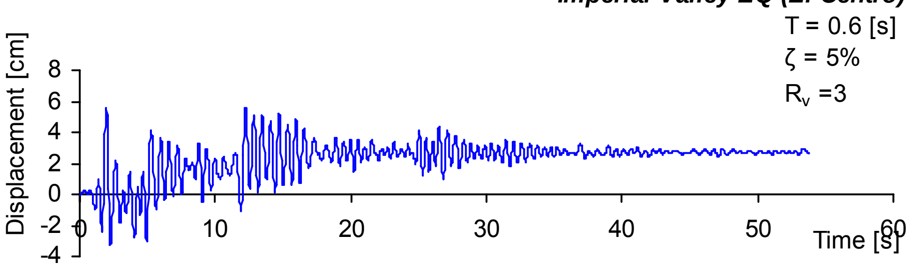
► **How to optimally search existing strong-motion data bases for ground-motion records that are likely to show a "desirable" response in terms of**

(a) their structural demands: residual displacement

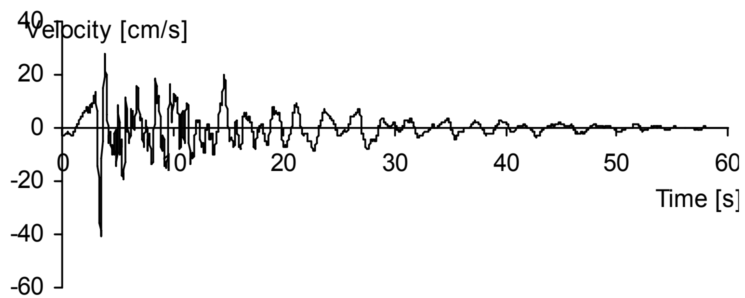
Imperial Valley (1940) record (El Centro)
Mw = 6.95; R_{close} = 6.09 km



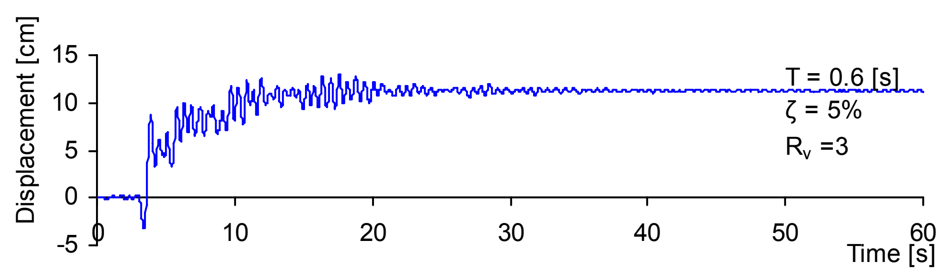
Imperial Valley EQ (El Centro)



Northridge (1994) record (Arleta)
Mw = 6.69; R_{close} = 8.66 km



Northridge EQ (Arleta St.)

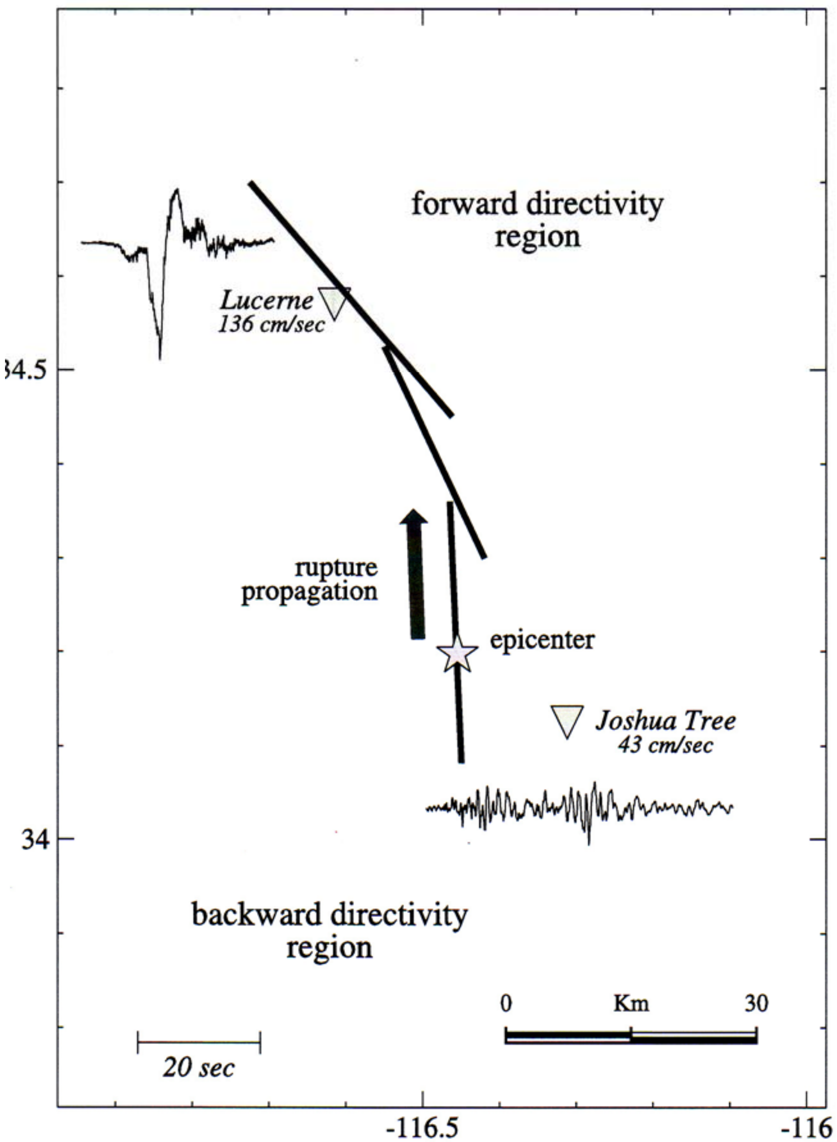


Courtesy Ufuk Yazgan; residual displacement computed with a bilinear force deformation model

Ground-motion parameterization

► **Forward-directivity, creating large pulses on the fault-normal velocity records**

- **The pulse-period scales with magnitude, but how to reliably and automatically search for such pulses and quantify their properties ?**
- **Is there more in a “seemingly simple” pulse than the dominant single-period pulse?**
- **Are these pulses only an effect of directivity ? What other properties of earthquake rupture affect the pulse generation and pulse properties?**



from Somerville et al, 1997

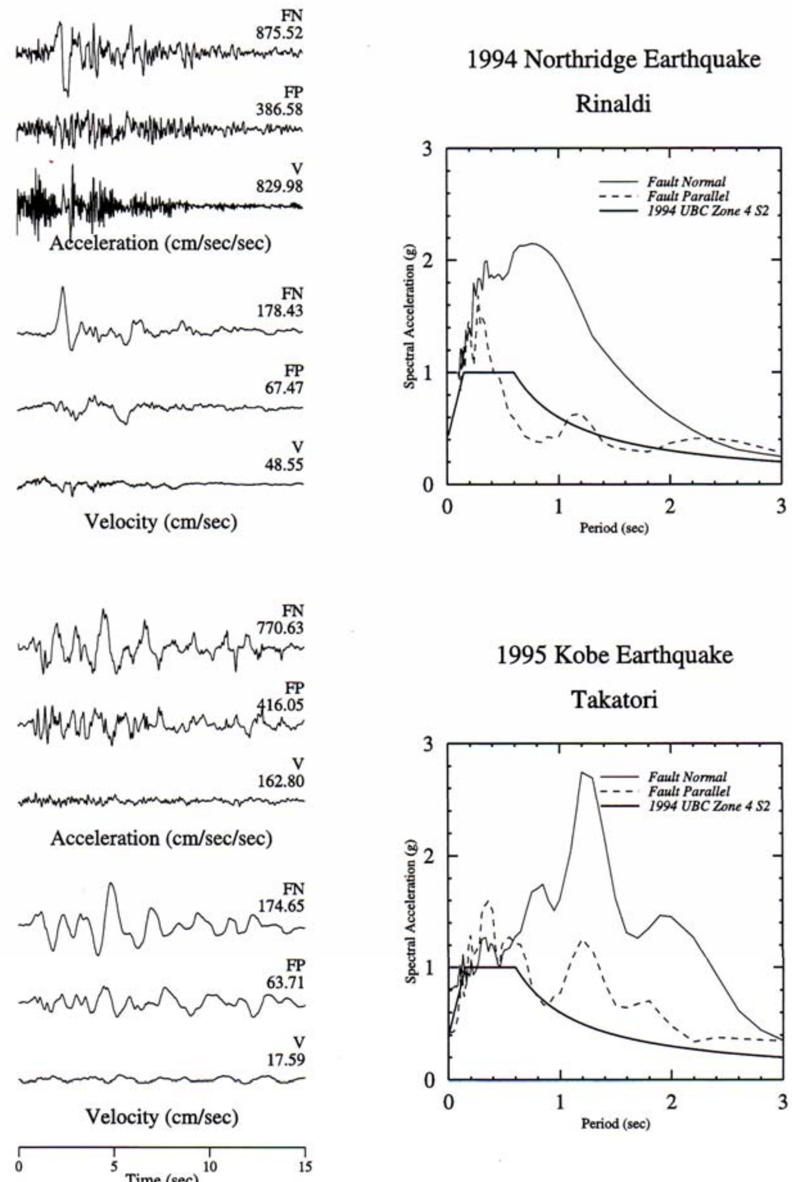
Directivity pulse measurements

► **Forward-directivity, creating large pulses on the fault-normal velocity records**

- ➢ **The pulse-period scales with magnitude, but how to reliably and automatically search for such pulses and quantify their properties ?**
- ➢ **Is there more in a "seemingly simple" pulse than the dominant single-period pulse?**
- ➢ **Are these pulses only an effect of directivity ? What other properties of earthquake rupture affect the pulse generation and pulse properties?**

Although the response spectrum provides the basis for the specification of design ground motions in all current design guidelines and code provisions, there is a growing recognition that the response spectrum is not capable of adequately describing the seismic demands presented by brief, impulsive near-fault ground motions. This indicates the need to use time histories to represent near-fault ground motions.

Somerville and Graves, 2003

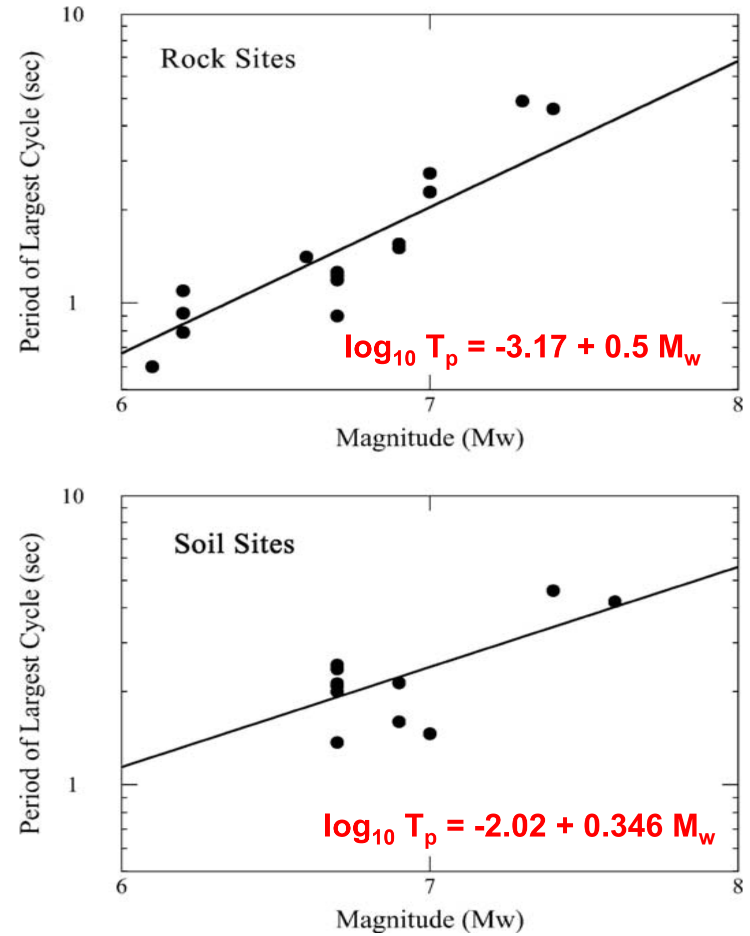


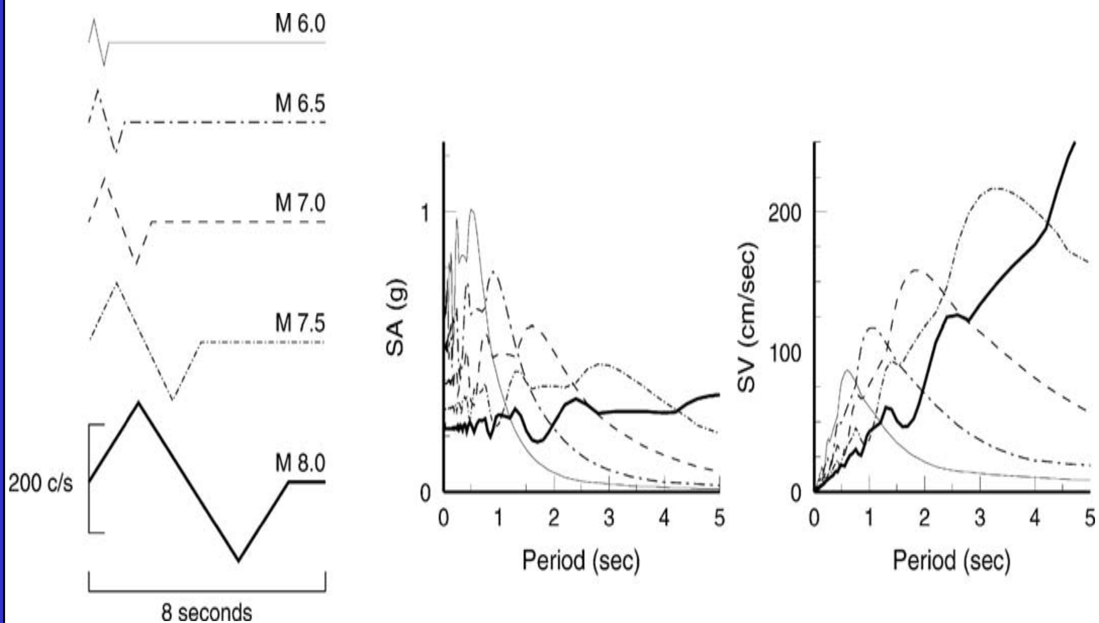
Somerville and Graves, 2003

Directivity pulse measurements

► **Forward-directivity, creating large pulses on the fault-normal velocity records**

- ➢ **The pulse-period scales with magnitude; a simple model of triangular basis functions (velocity pulses) following the scaling relations (right) reproduces the key features in response spectra (peak in SA at ~0.75 T_p, peak in SV at ~0.85 T_p)**





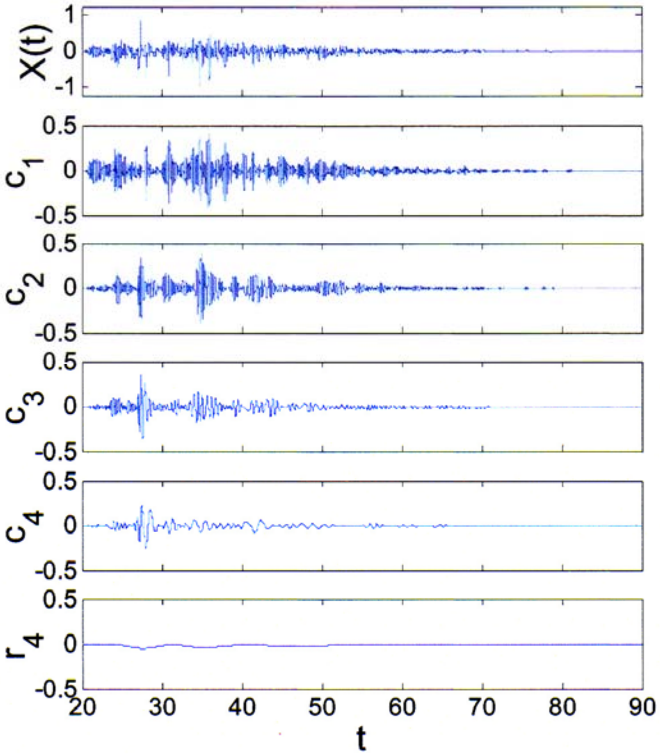
after Somerville, 2003

Automated estimates of pulses

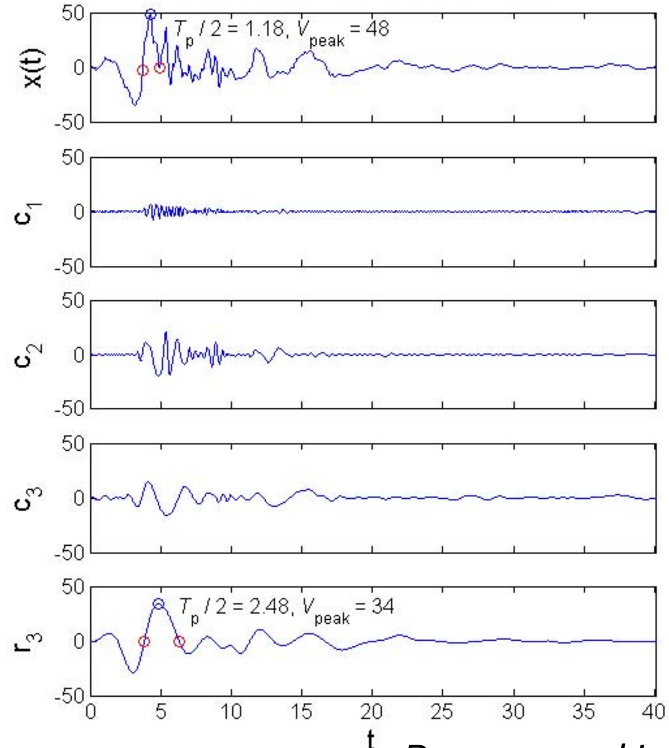
► **The question arises how to identify the pulse-like motions (without tedious visual inspection) and characterize their properties ?**

➢ **Bazzurro & Luco (2003) used an Empirical Mode Decomposition (Huang et al, 1998) to investigate time-dependent properties of near-fault motions, allowing them to measure pulse period T_P and peak-velocity V_{peak}**

Example of EMD for 1999 Taiwan record TCU129-W



Example of measuring pulse character for 1994 Northridge, record NWH-FN



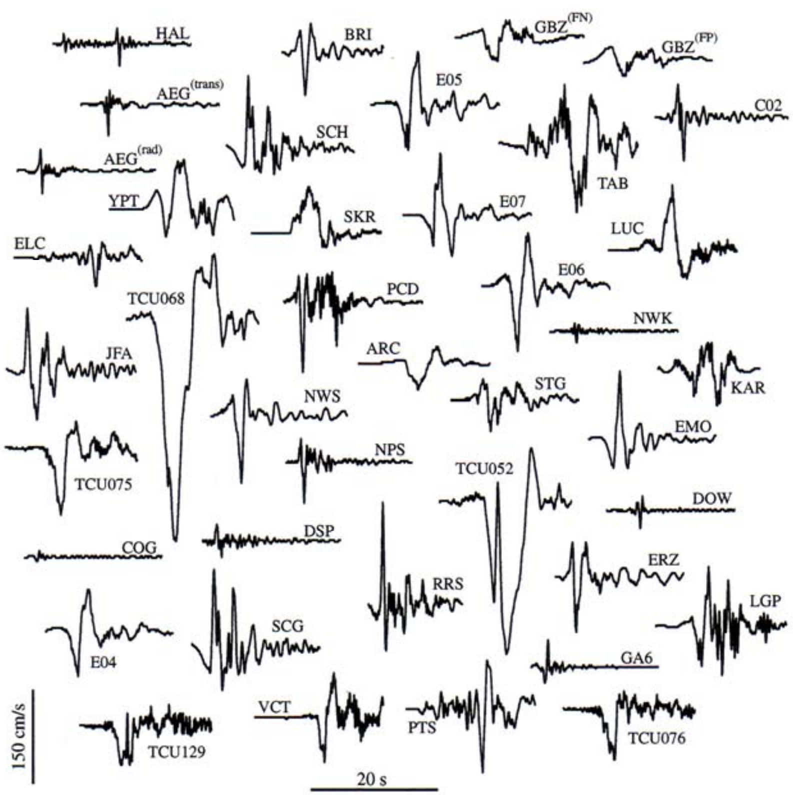
Bazzurro and Luco, 2003

Automated estimates of pulses

► **The question arises how to identify the pulse-like motions (without tedious visual inspection) and characterize their properties ?**

- **Mavroeidis et al. (2003, 2004) develop a mathematical representation of near-fault motions based on an analytical function, and relate this to the 'specific barrier model' for earthquakes (Papageorgiou and Aki, 1983, a,b)**

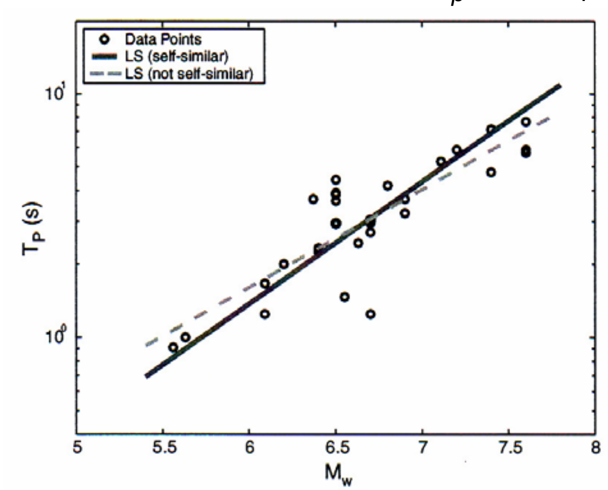
Collection of pulses, used by Mavroeides et al



Analytical signal, derived from Gabor wave-let

$$f(t) = \frac{A}{2} \cdot \left[1 + \cos\left(\frac{2\pi f_p}{\gamma} \cdot t \right) \right] \cdot \cos\left(2\pi f_p t + \nu \right)$$

Scaling of pulse-period T_p (= $1/f_P$)



$\log_{10} T_p = -2.20 + 0.4 M_w$

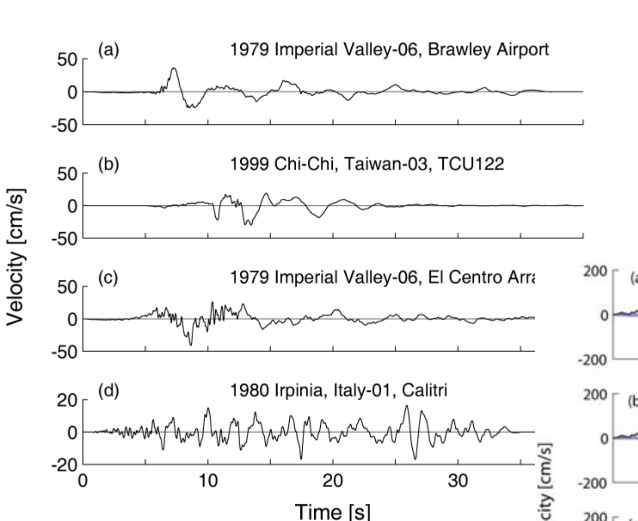
$\log_{10} T_p = -2.90 + 0.5 M_w$

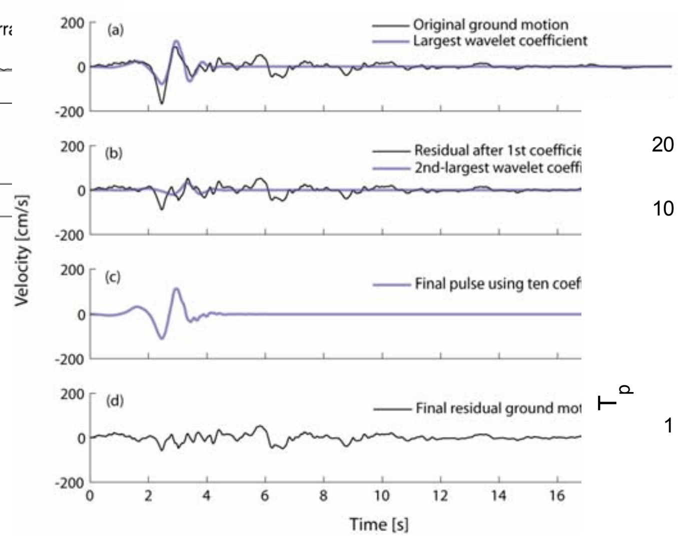
Mavroeides ans Papageorgiou, 2003

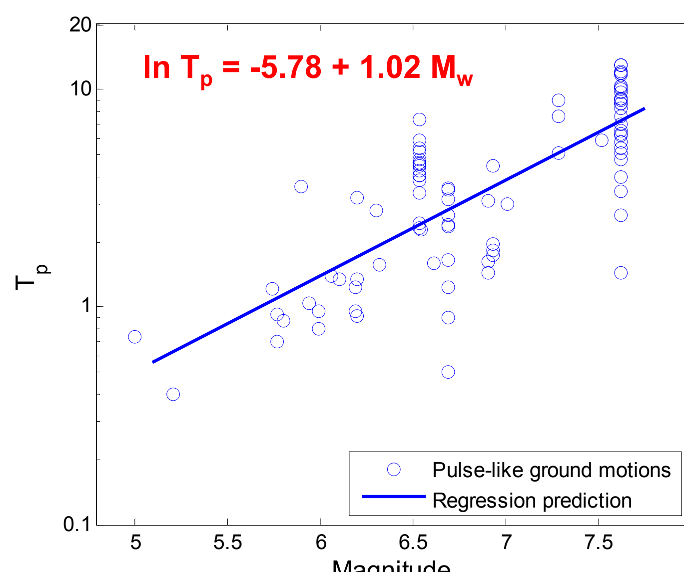
Automated estimates of pulses

► **The question arises how to identify the pulse-like motions (without tedious visual inspection) and characterize their properties ?**

➢ **Baker (2006) deploys a Discrete Wavelet Transform (DWT) to investigate the occurrence of near-fault pulses in the NGA-data set and to quantify their properties**







Courtesy Jack Baker

Ground-motion parameterization

► **These works extract the main characteristics of the dominant pulse, but do not investigate potential higher-frequency features or multiple pulses (wave trains) that could be important for structures or soils:**

- ***Does the structure care only about pulse-period or are the higher-modes of the structure affected by the secondary (high-frequency) features hidden in the pulse or later-arriving smaller pulses with different period? Is therefore the full non-linear response affected by the interplay of these different-frequency constituents?***

- ***Does the soil response, and its susceptibility for liquefaction, depend on pulse properties (in time and frequency domain)?***

► **We investigate simple automatic procedures to estimate pulse-period from a subset of NGA-records, and their respective scaling properties.**

► **We also perform time-frequency analysis of these records, to NGA-records to**
(a) quantify pulse-properties in time / frequency in an automated procedure
(b) investigate the time-dependent spectral properties of near-fault motions, and potentially relate them to earthquake rupture-model characteristics

► **Later, we will use advanced ground-motion simulation techniques (incl. source dynamics and scattering) to investigate the generation of these pulses and the dependence of their properties on source characteristics.**

1 PRINCIPLE OBJECTIVE

2 DATA SELECTION AND DATA PROCESS

3 WORK ON PULSE PERIOD

4 INITIAL CONCLUSIONS

5 FURTHER WORK

Principle Objective

- Improved parameterization for the engineering specification of near-fault ground motions
  - Classical seismic intensity measures: PGA, S_A
  - ***Waveform-based intensity measures***: pulse period, its amplitude, number of cycles

- Existence of a velocity pulse
  - FN component of near-field velocity seismograms in forward rupture directivity region
  - occurs at the beginning of the record

- Selection from a database

  1) Requires some level of judgment from the analyst
     - a visible large pulse in the velocity time history
     - source-to-site geometry suggests a pulse

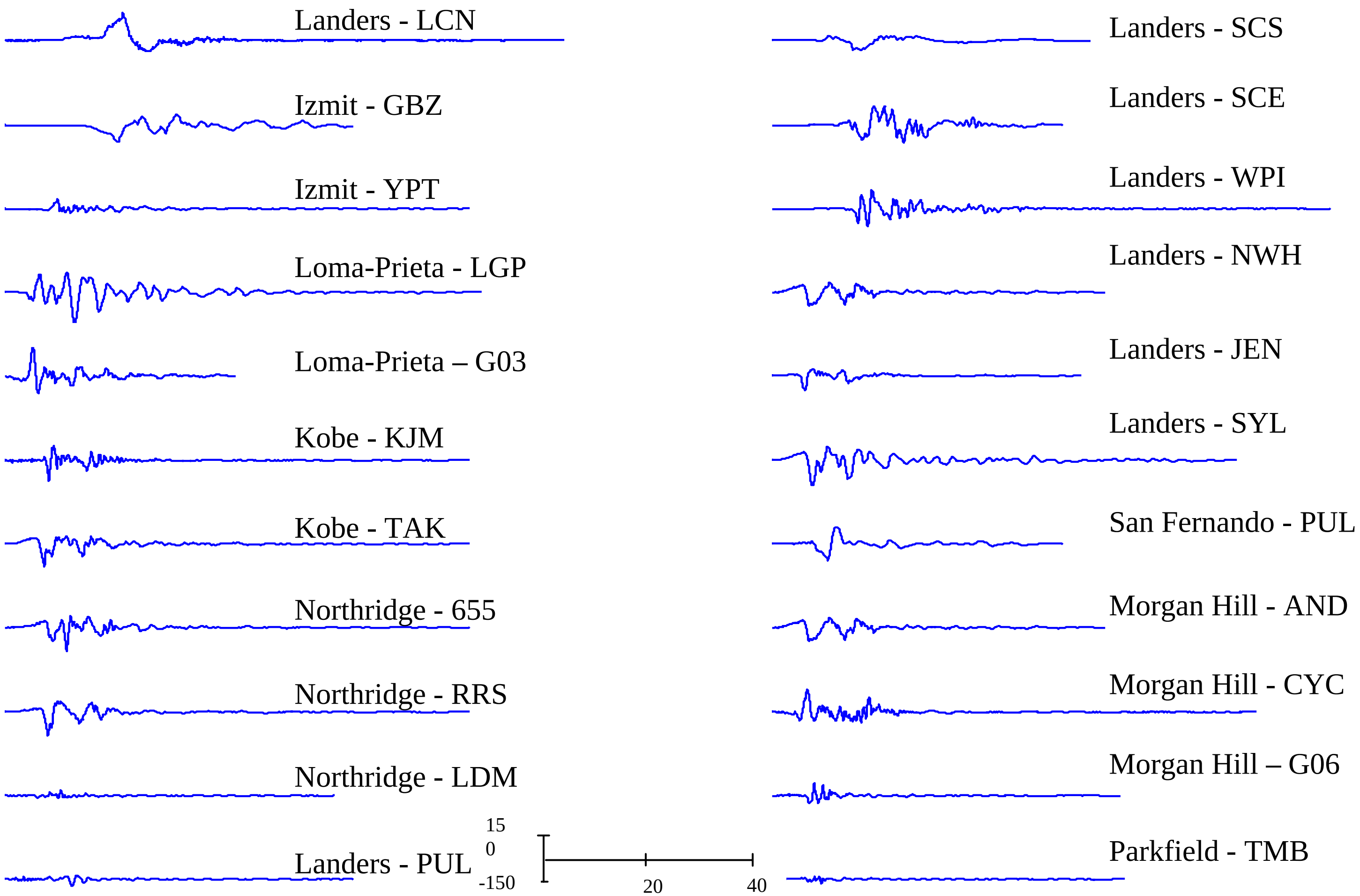
  2) An automated scheme for detecting pulses in ground motions
     - Baker, personal comm., 2006

- In this initial stage of the project, we focus on:
  - automated scheme for measurement of pulse period
  - do pulse period and amplitude differ significantly in different frequencies of the signal?
  - Is this difference, if it exists, vital for structural response?

Data selection and processing

- PEER NGA Strong Motion Database, as a “training data set”
  - 3551 records from 127 earthquakes
  - uniformly processed, well documented (including abundant meta-data) time histories
- Data selection among NGA database
  - a subset of NGA recordings, for which finite-source rupture model exists
  - the records in forward rupture directivity region (defined by Somerville et al., 1997)
  - as an initial step, the records used in Somerville, 2003 are selected
- Data Processing
  - rotation to FP and FN components
  - windowing long records
  - Cosine tapering
  - Resampling

Velocity Seismograms of FN component



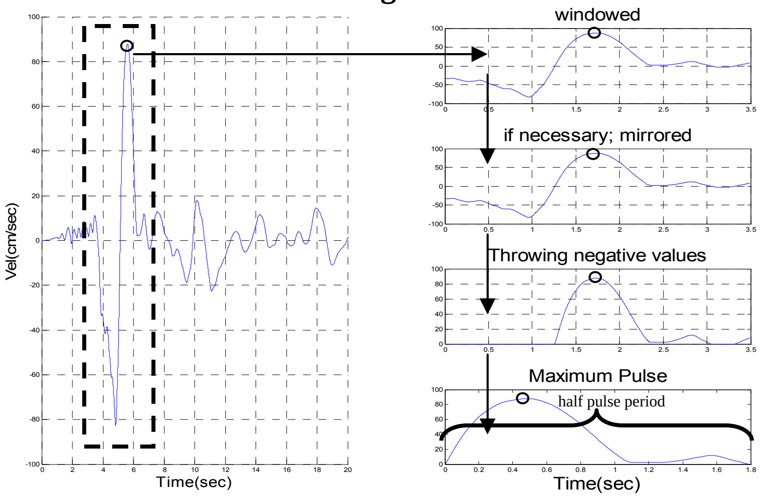
We focus on the following topics, using the above reduced data set:

1) **Finding an automated scheme to measure the pulse period**
2) **Is the pulse period frequency dependent?**

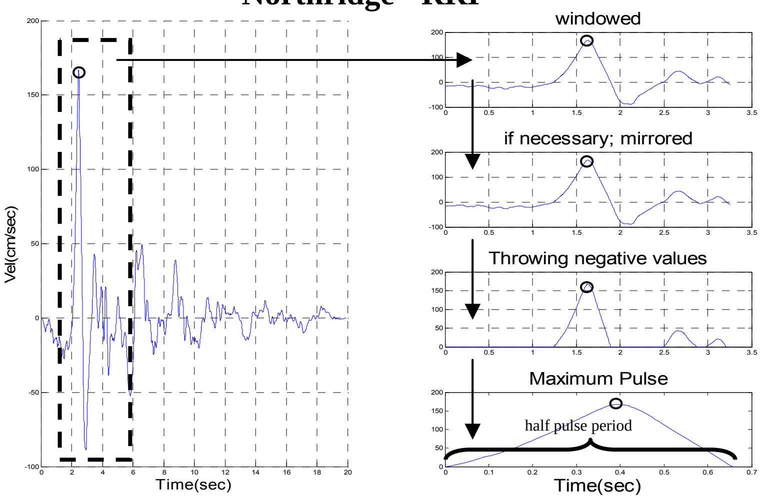
Automated Pulse-Period Estimation

- **Trial # 1: Pick up the maximum-amplitude pulse, select a magnitude-dependent time window around it, and discard the rest of the time series**

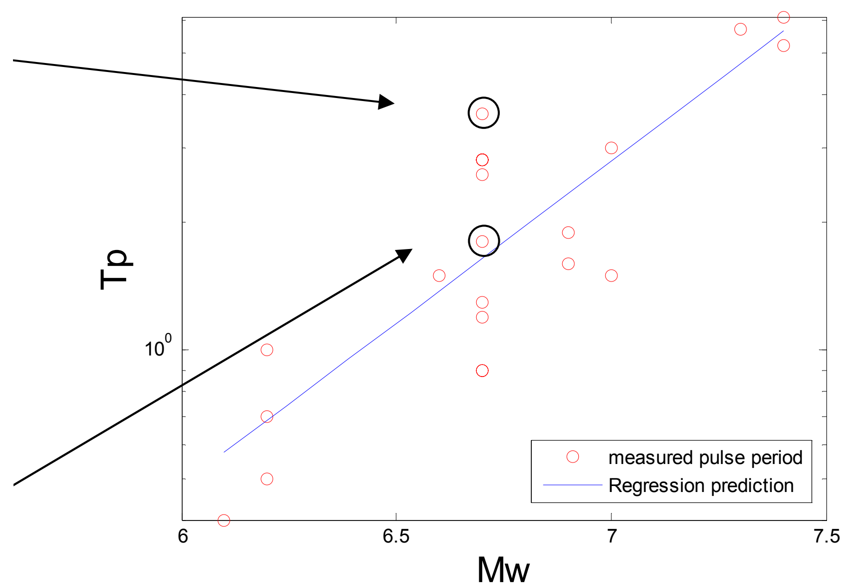
Northridge - WPI



Northridge - RRI



Pulse Period versus magnitude



scaling relation

$$\ln T_p = 1.75\, M_w - 11.25$$

$$\log_{10} T_p = 0.76\, M_w - 4.88$$

Automated Pulse-Period Estimation

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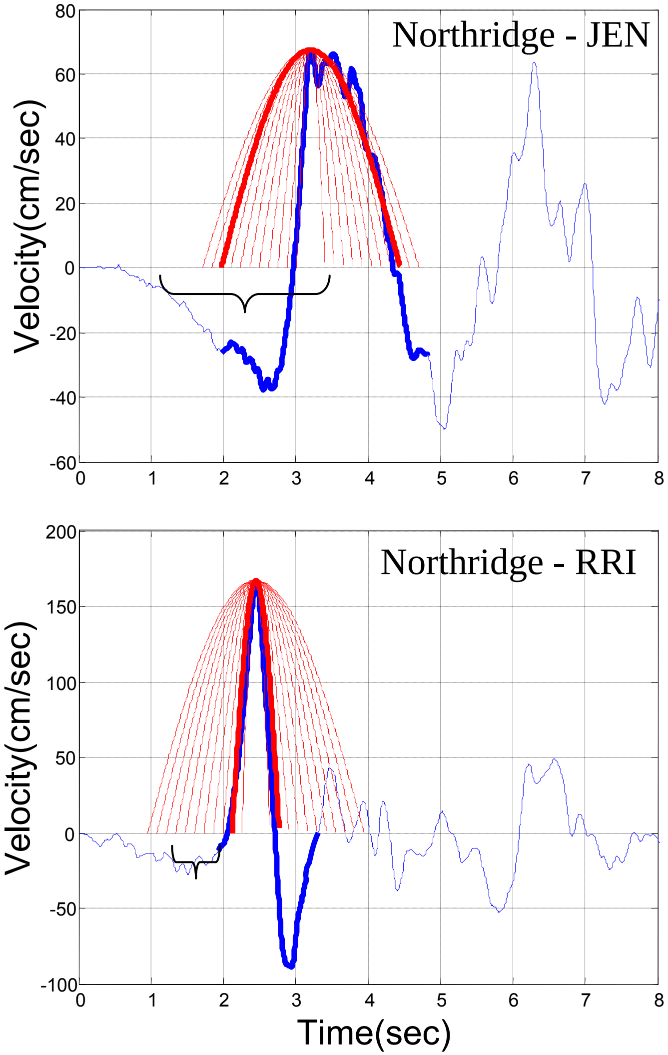
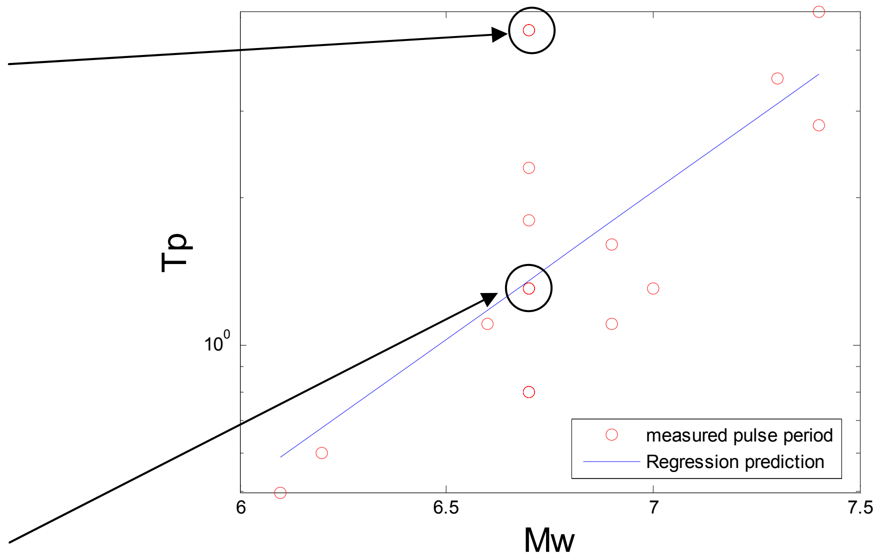
- **Trial # 2: Fitting sine waves to the velocity pulse in a least-squares sense, starting from a magnitude-dependent "initial guess", centered at the maximum-amplitude pulse**

Selection of sine wave with minimum residual:





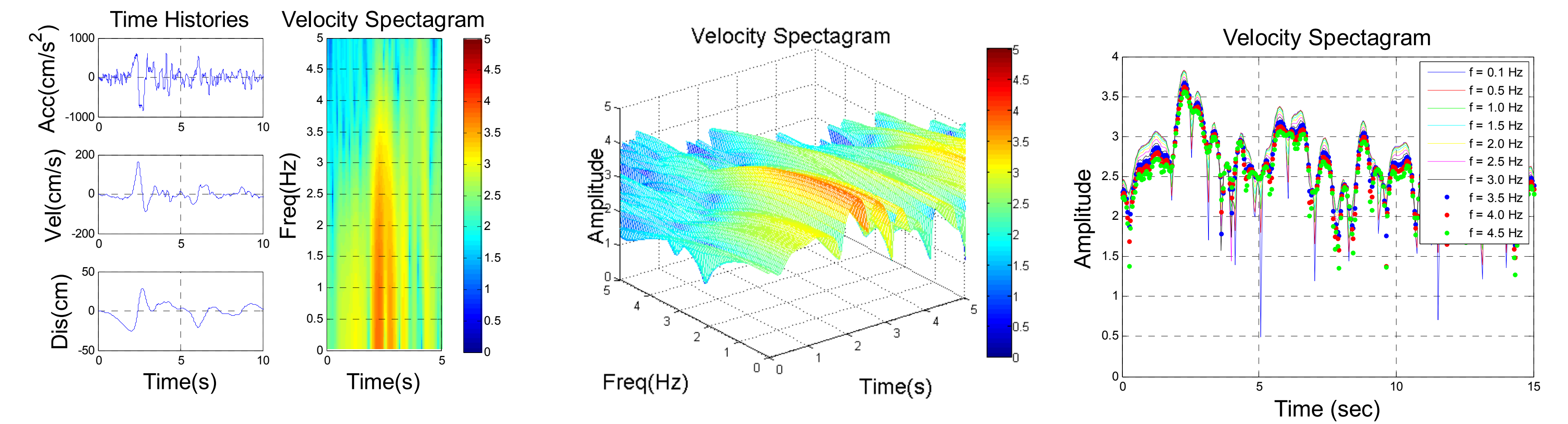
Scaling relation

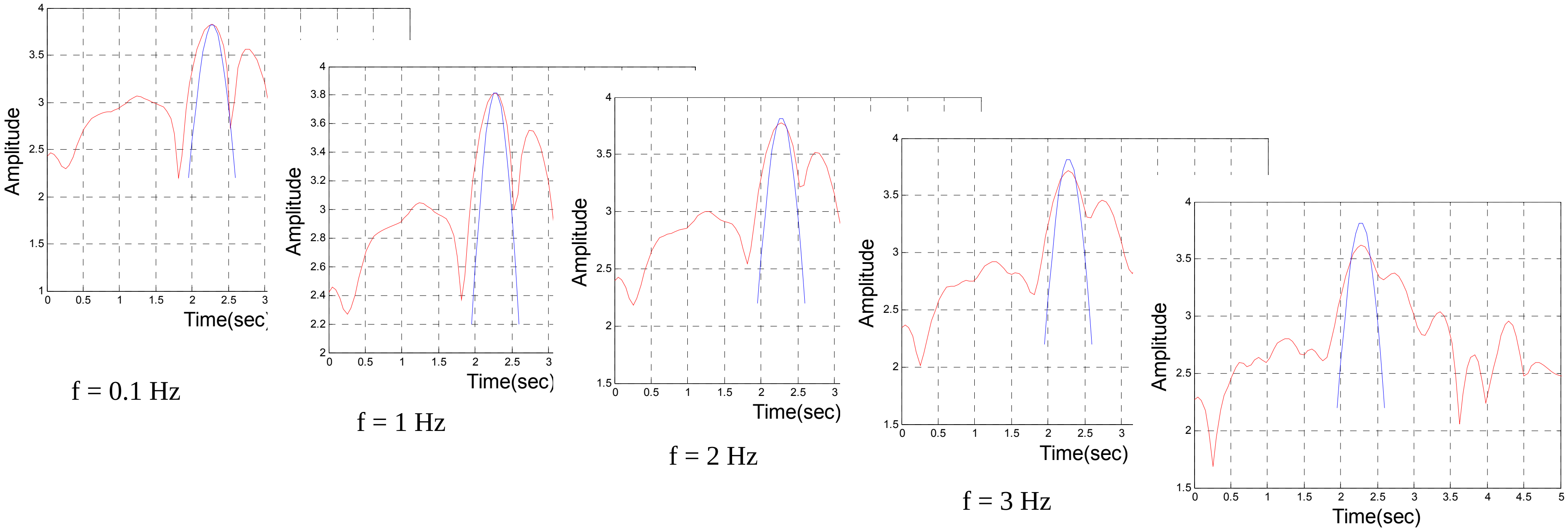
$$\ln T_p = 1.38\, M_w - 8.98$$

$$\log_{10} T_p = 0.6\, M_w - 3.9$$

Frequency dependence of T_{p} ?

- Time-frequency analysis (spectragram) of time series (Loma Prieta G03)





f = 0.1 Hz

f = 1 Hz

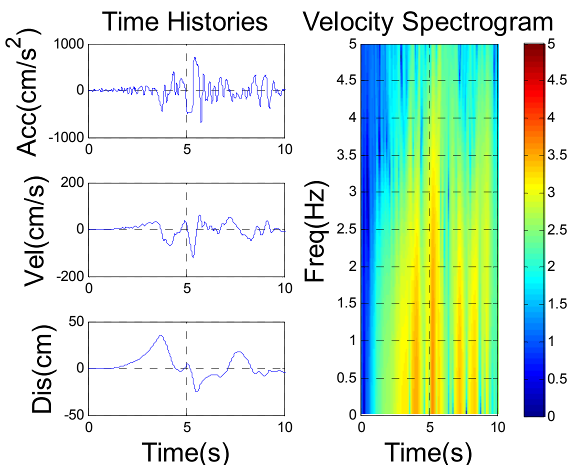
f = 2 Hz

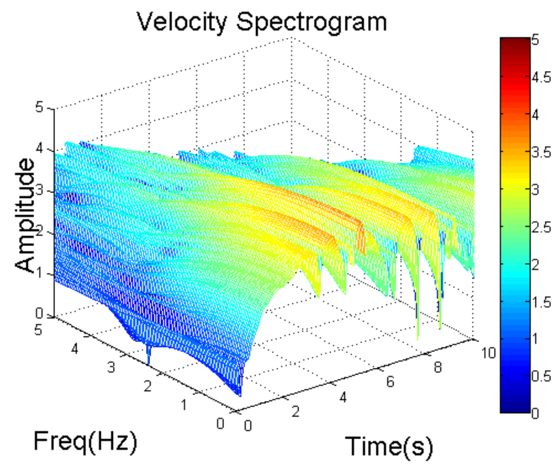
f = 3 Hz

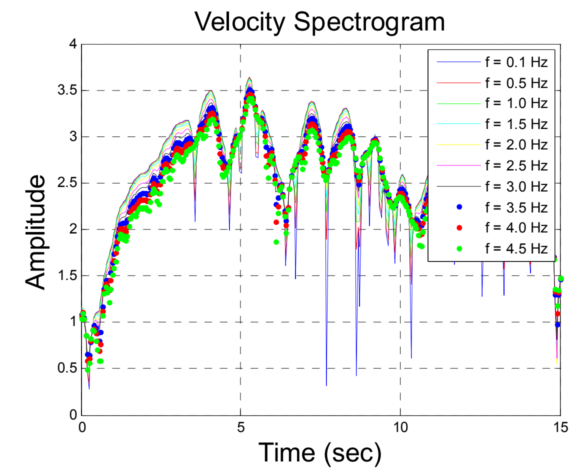
f = 4 Hz

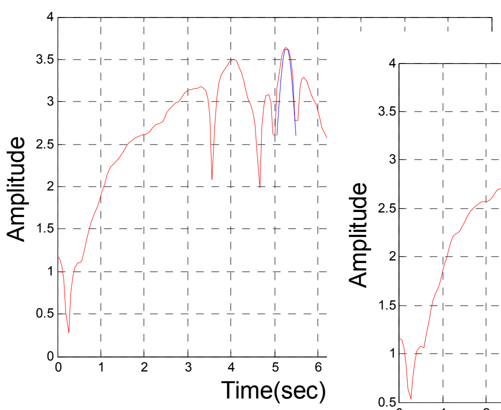
Frequency dependence of T_{p} ?

- **Time-frequency analysis (spectragram) of time series (Northridge 655)**

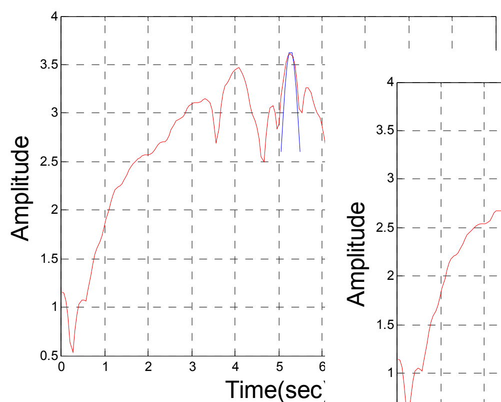




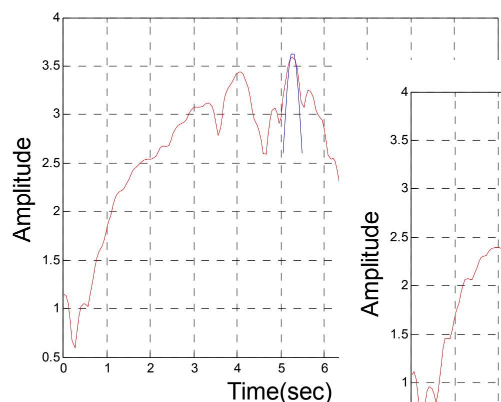




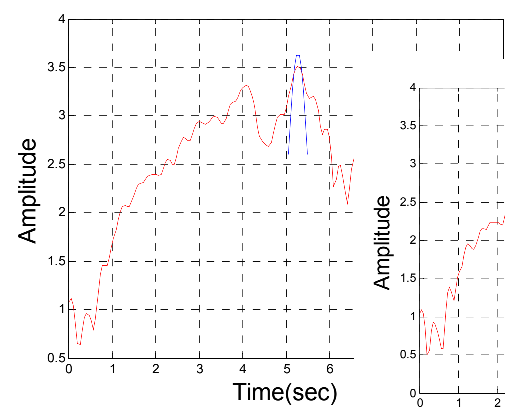
f = 0.1 Hz



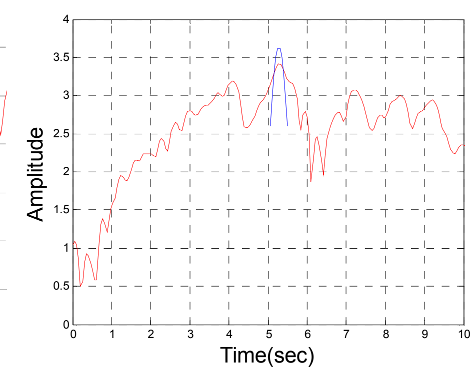
f = 1.5 Hz



f = 2.5 Hz



f = 3.5 Hz



f = 4.5 Hz

Initial Conclusions / Future Work

► Two simple procedures have been tested to automatically estimate pulse period T_p on a reduced dataset. Our measurements, and their scaling with magnitude M_w, are very similar to previous "manual" measurements, but also to the more sophisticated (and CPU-intensive) work by Baker (2006).

► The techniques will be further explored and tested, and then applied to (a) the full NGA dataset, (b) other online strong-motion datasets in order to obtain a reliable, self-consistent, and unbiased data set of T_p, allowing for more detailed work on the properties of T_p.

► We perform time-frequency analysis of a subset of NGA-records to
(a) classify records as pulse-like (in collaboration with J. Baker)
(b) quantify pulse-properties in time / frequency automatically
(c) investigate the time-dependent spectral properties of near-fault motions, and relate them to rupture-model characteristics

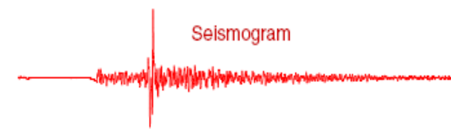
So far, we find some frequency-dependence in T_p, based on the spectragrams, but this needs further investigation.

► We plan to use advanced ground-motion simulation techniques (incl. source dynamics and scattering) to investigate the generation of these pulses and the dependence of their properties on source characteristics, allowing us to better define and quantify the relevant the condition indicators.

Additional slides

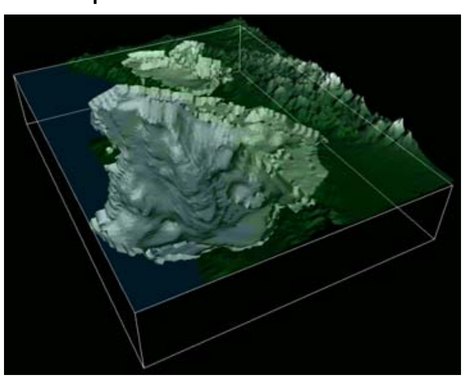
Ground-motion simulation

- ► Near-source ground-motions depend on
  SOURCE, **SITE**, and **PATH** effects
- ► Dynamic or pseudo-dynamic source models that capture the physics of earthquake rupture
- ► Consider the waves propagating in 3D-complex media (e.g. as done in various SCEC-projects)
- ► Include high-frequency scattering due to the random nature of the Earth crust at small spatial scales

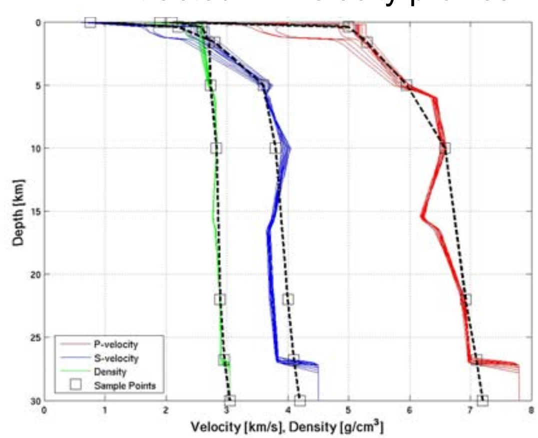


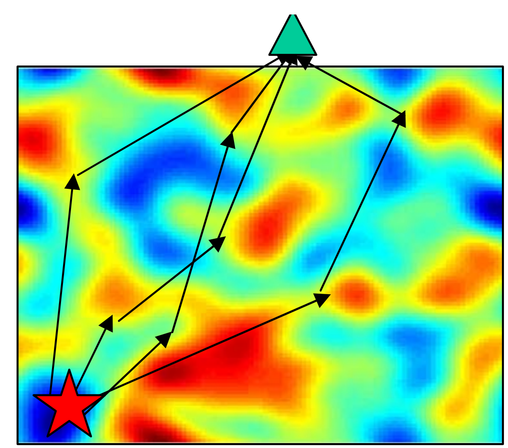
Slice of Earth' crust as "random media"

3D depth-to-bedrock view L.A. basin



Extracted 1D velocity profiles

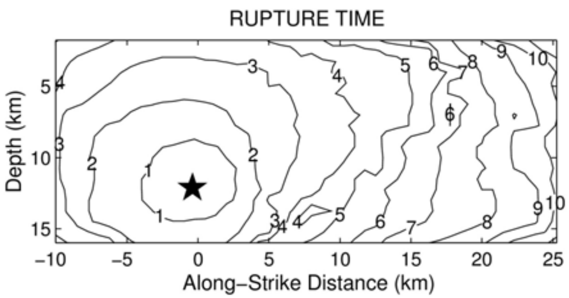


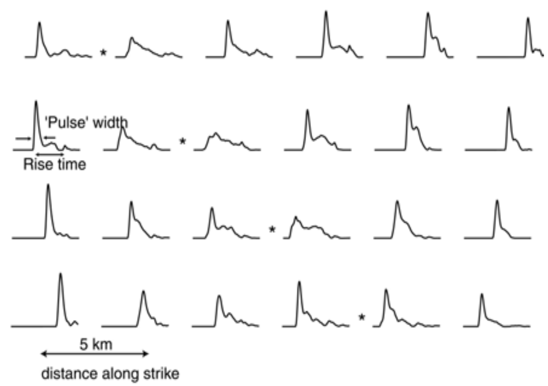


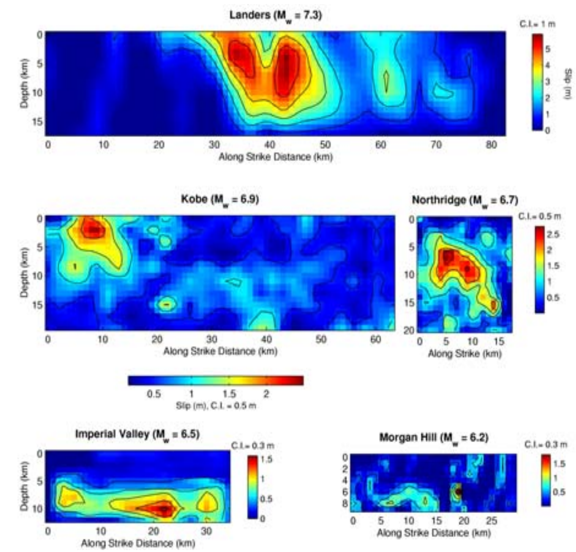
Dynamic Rupture Effects

SOURCE effects:

- heterogeneity in the slip distributions
- variability in rupture-propagation velocity
- variability in slip duration and slip function





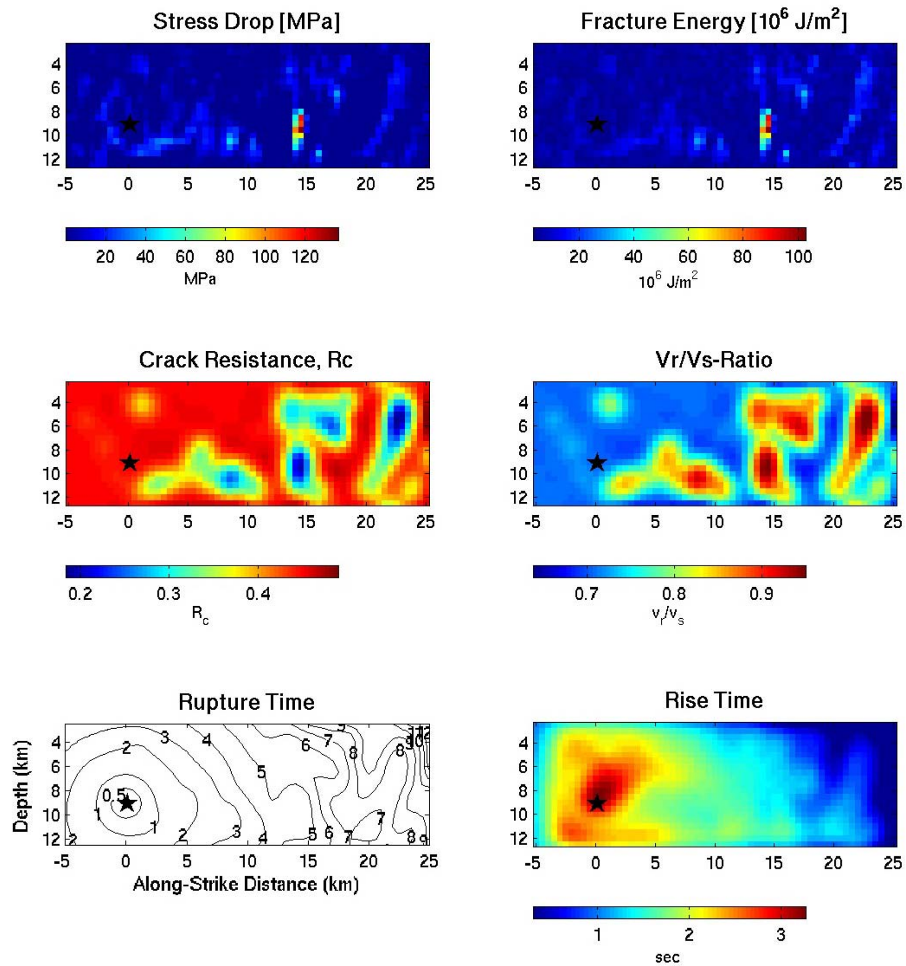


- ► Variability in slip can be modeled with spatial-random field model
- ► Need to implement dynamically consistent slip function (Kostrov, Yoffe)
- ► Include fracture-energy scaling to address difference between large surface breaking and buried events
- ► Test the influence of (locally) super-shear rupture velocity

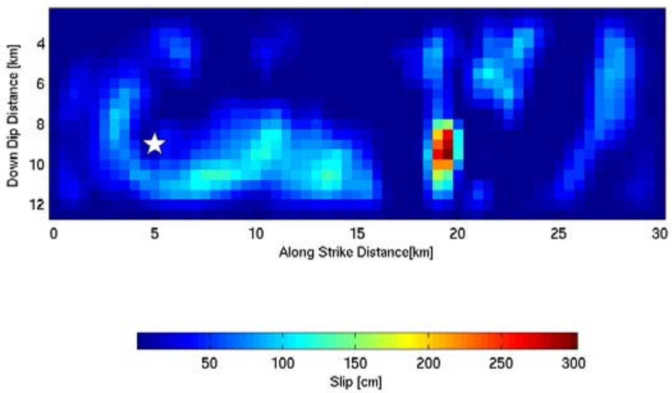
Dynamic Rupture Effects

Example for a pseudo-dynamic rupture model that contains the basic features of rupture dynamics, showing a large degree of variability in source parameters.

Pseudo-dynamic rupture model



Input slip distribution

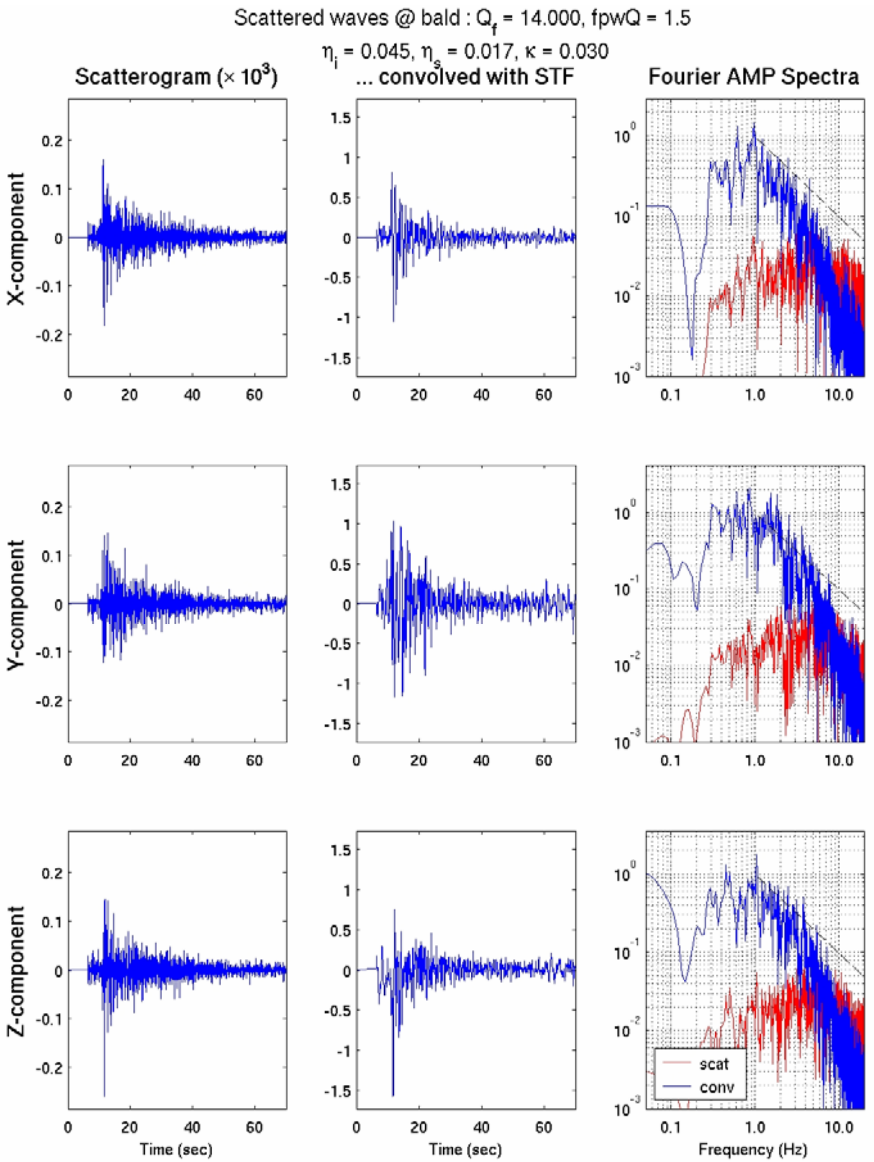


Scattering Operators

► **Site-specific scattering operators are calculated (for each component of motion) using the multiple-scattering theory by Zeng et al (1991, 1993) (and their code).**

► **Scattering parameters (scattering and attenuation coefficient, site kappa, intrinsic attenuation) are taken from the literature and are partly based on the site-specific velocity structure.**

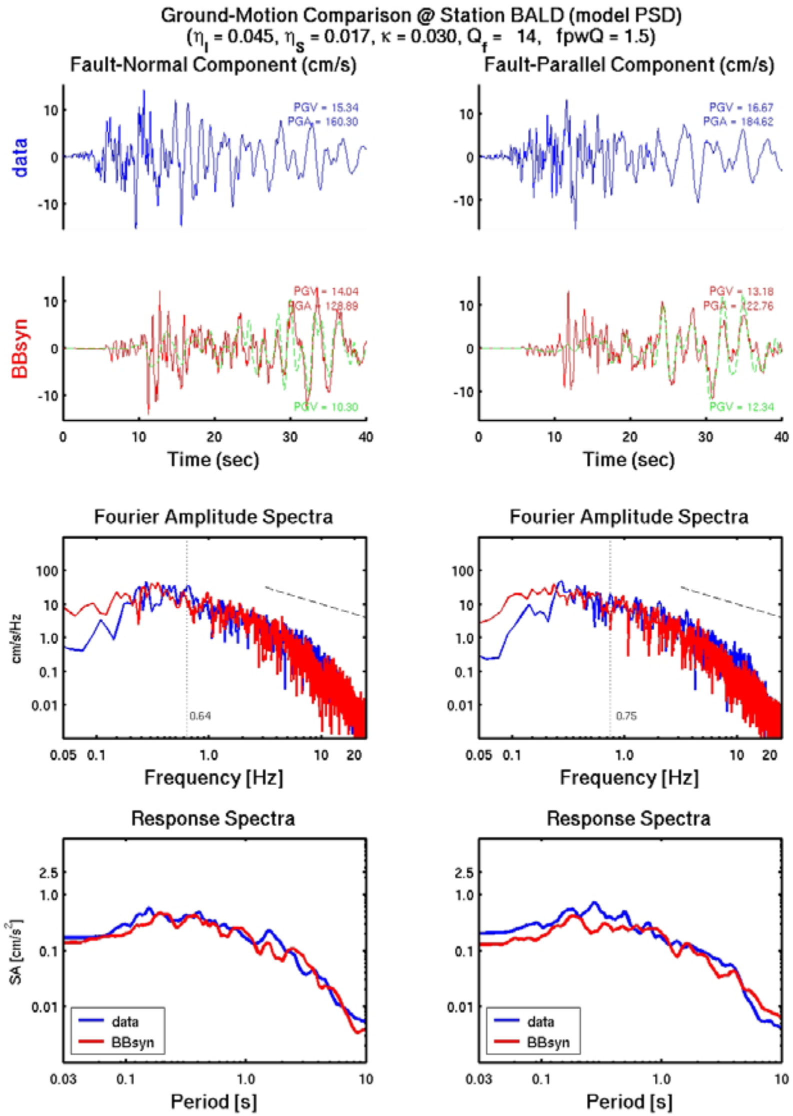
► **Currently, the site-specific scattering is computed using the distance from the hypocenter, which could strongly over-estimate its contribution for a near-fault site which is close to the area of largest seismic radiation.**

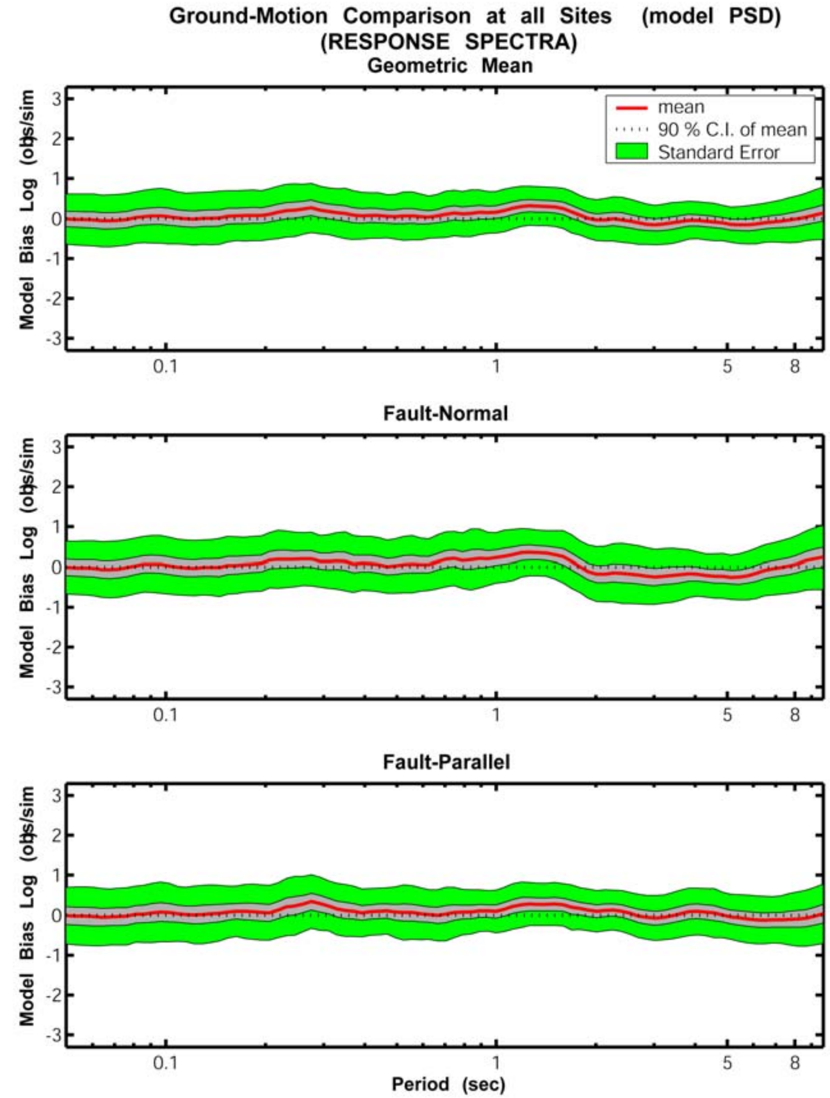


Mai and Olsen, 2005

Validation of Simulated Broadband Motions

► Ground-motion validation: single-site evaluation and ensemble average





Mai and Olsen, 2005