

# Characterization of crustal models for quantitative ground motion estimation

## A – Ground Motion Estimation

Jean Virieux

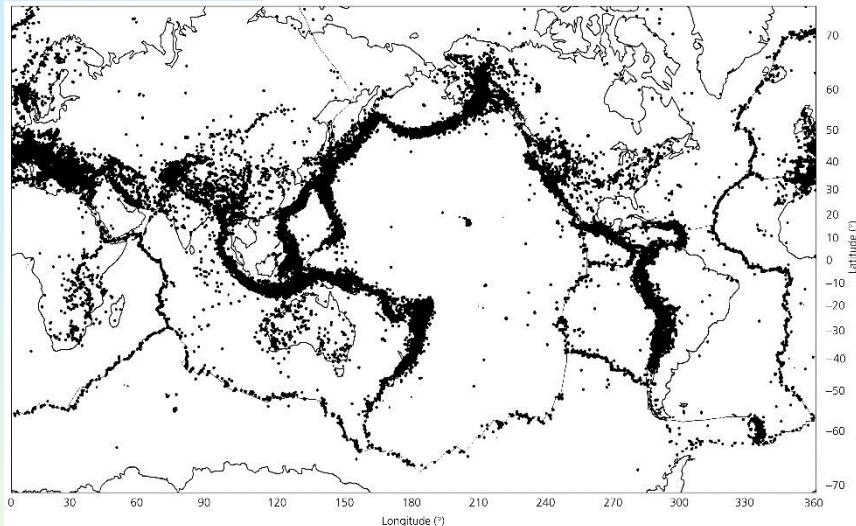
Emeritus Professor at UGA

Some slides are inspired from Dave Boore's presentation and from Arthur McGarr's presentation

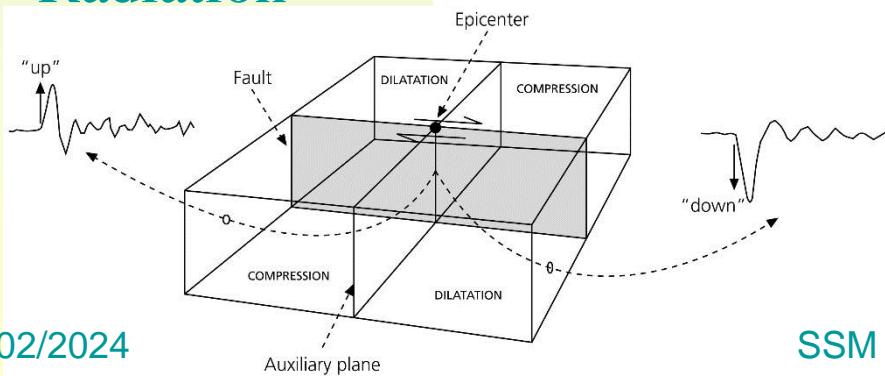
# Wave propagation in the Earth

## Natural events : earthquakes

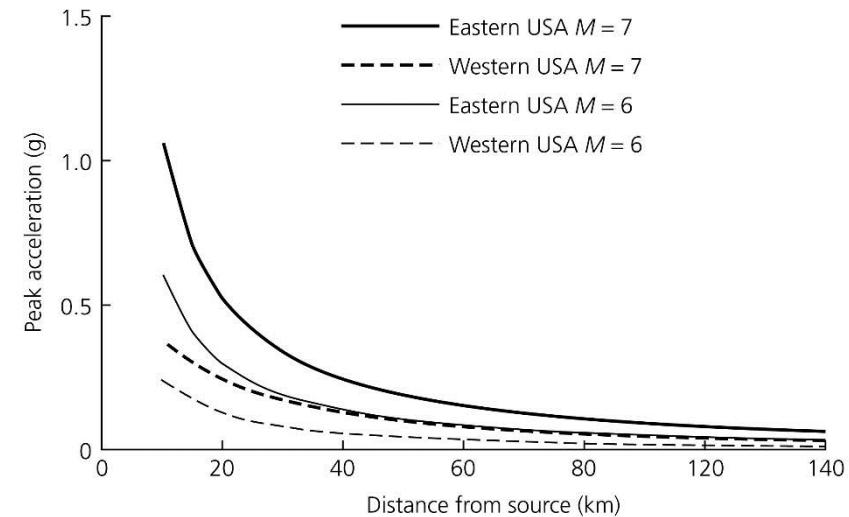
### Source



### Radiation



26/02/2024



Geometrical attenuation:  
amplitude decreases with  
distance

SSM NAPLES

# Translucent Earth



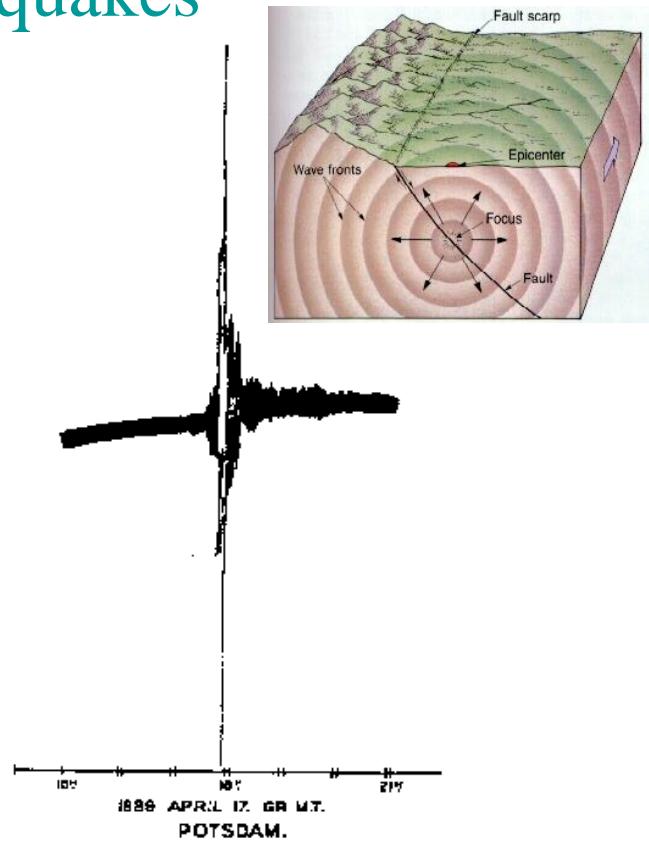
1600 years before first sensors in Europe (XIX century)

- Ground vibration away from quakes

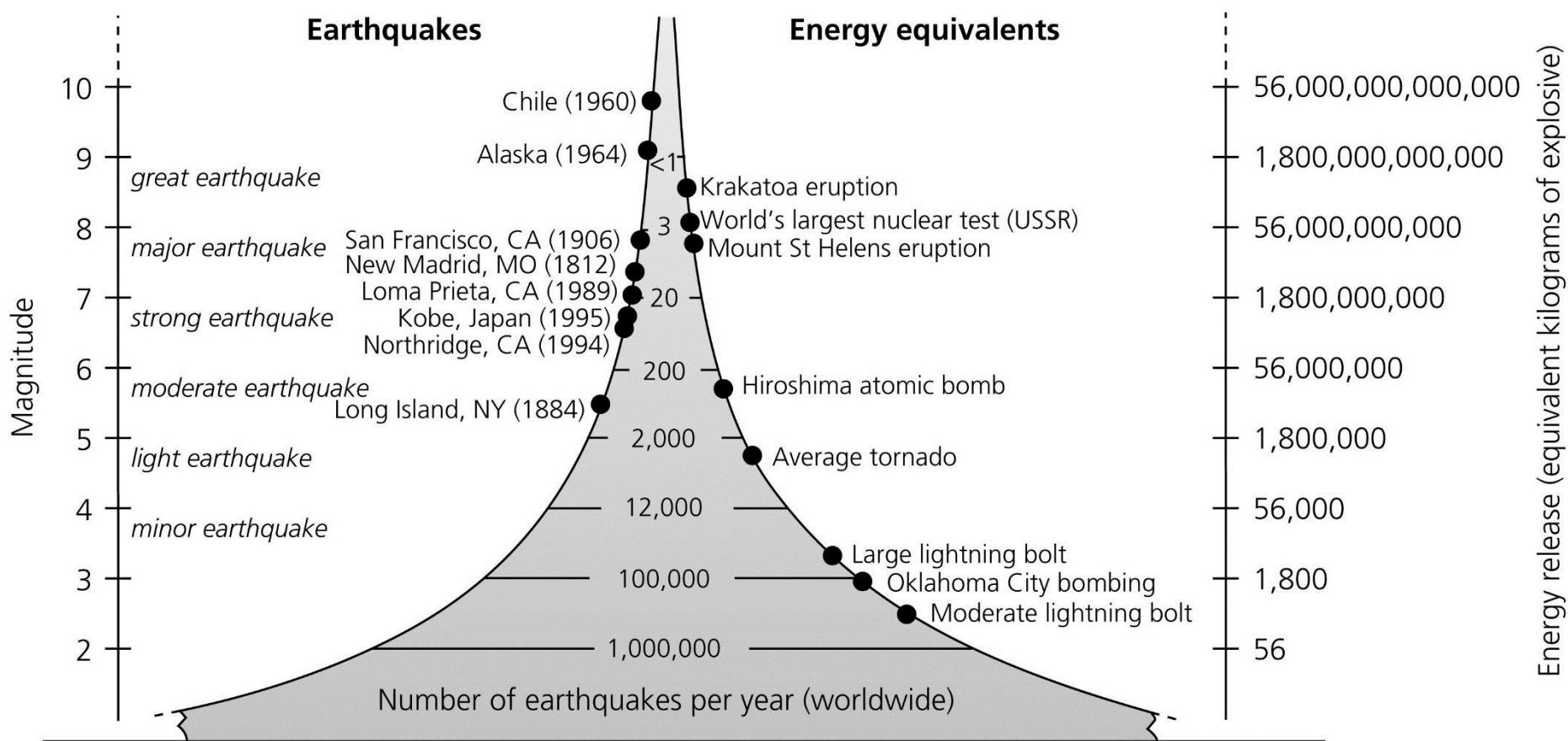
Earthquakes and local effects known for a long time

In 1889, for the first time, an earthquake in Japan has been associated with a ground motion in Germany!

The modern seismology was born



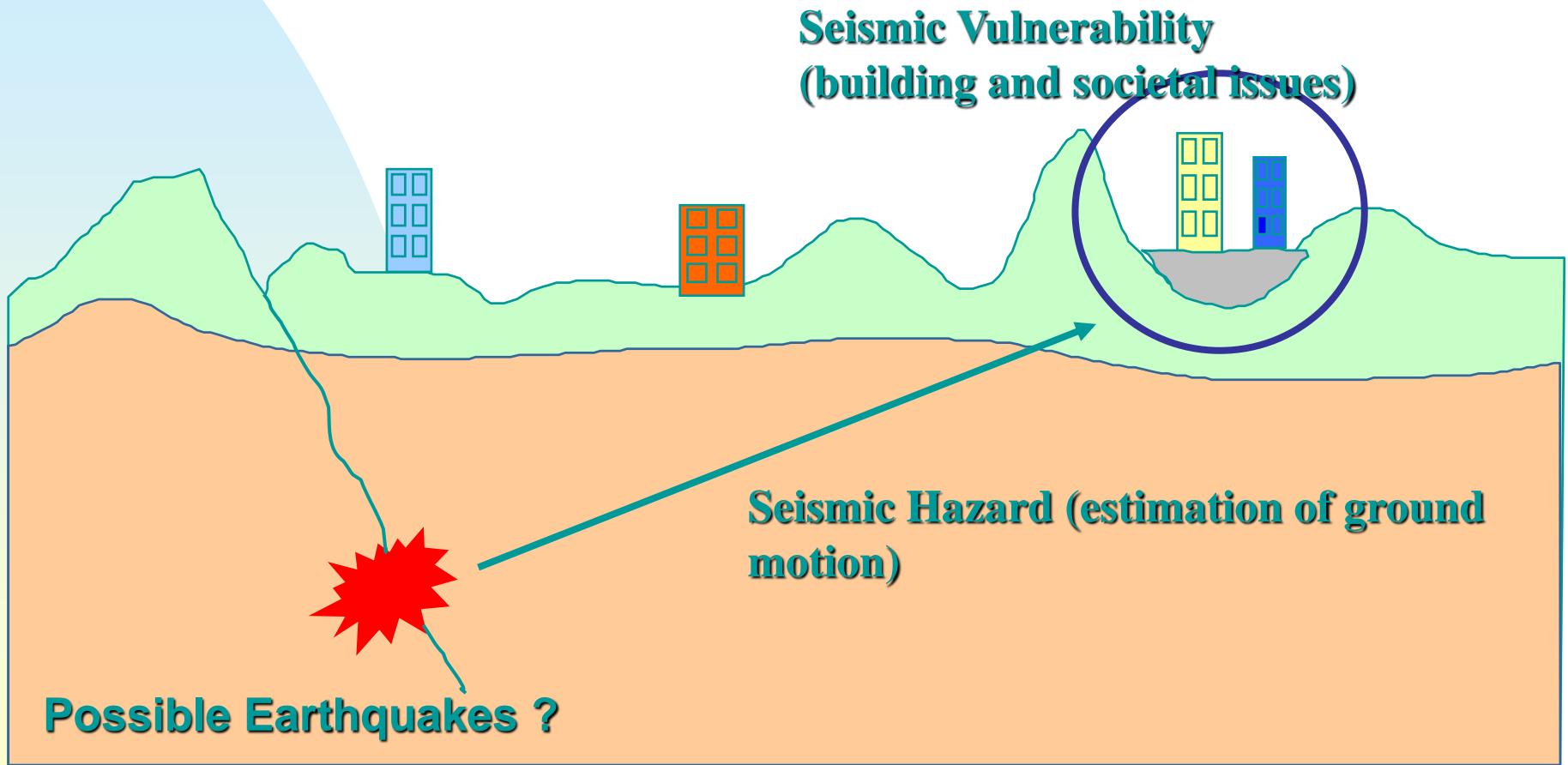
# Source energy!



Estimation of magnitude is important in the second time

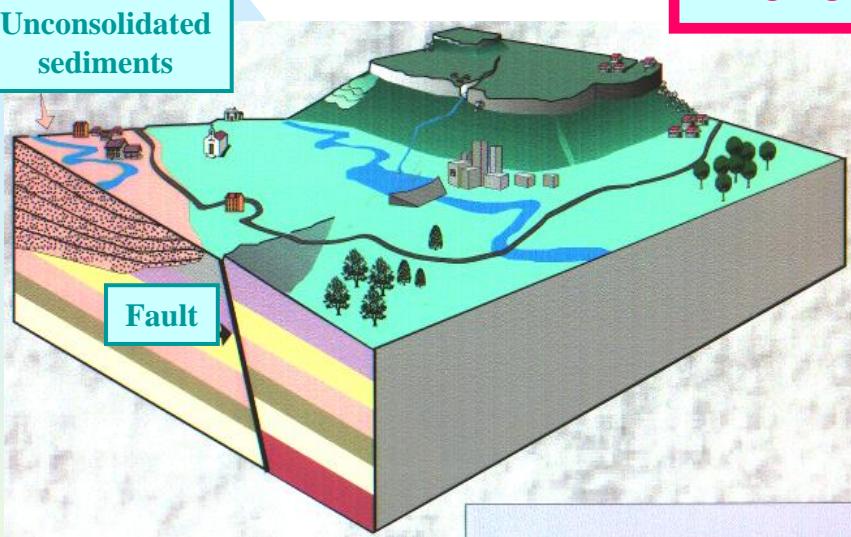
# Seismic Risk Mitigation

In the framework of mitigation, different components must be considered

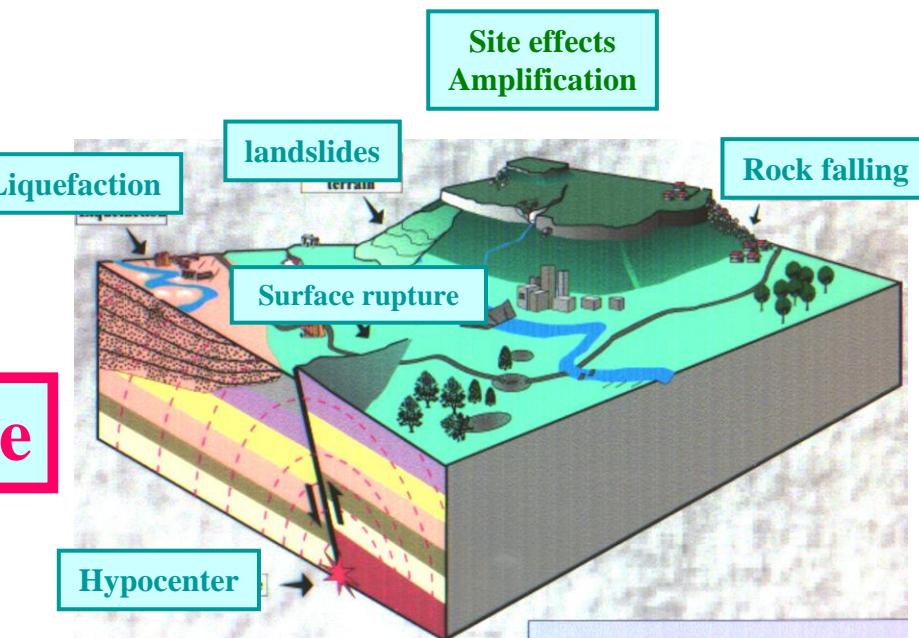


# Various impacts of seismic waves (from earthquakes)

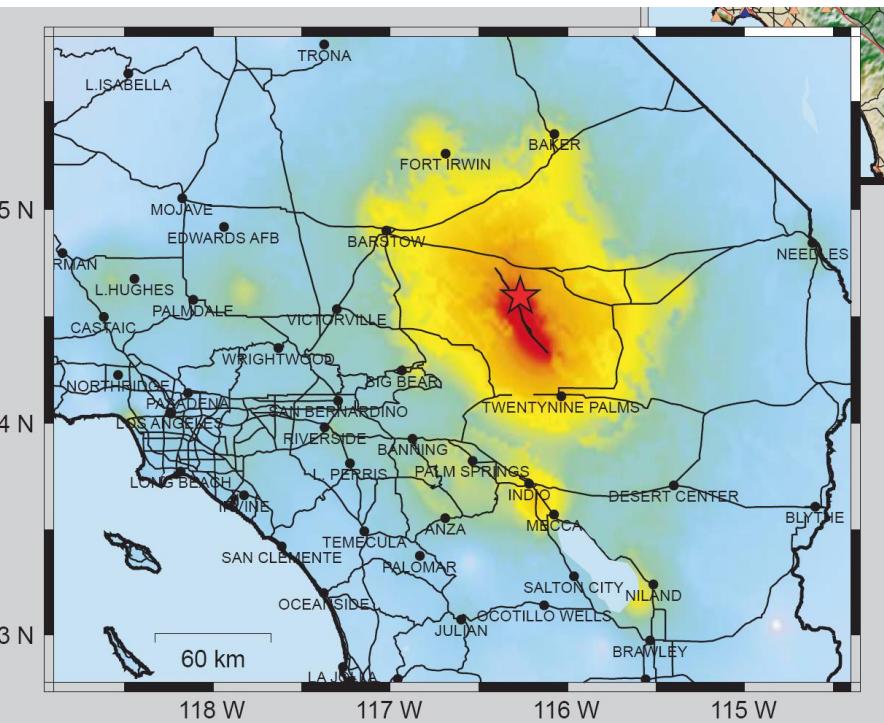
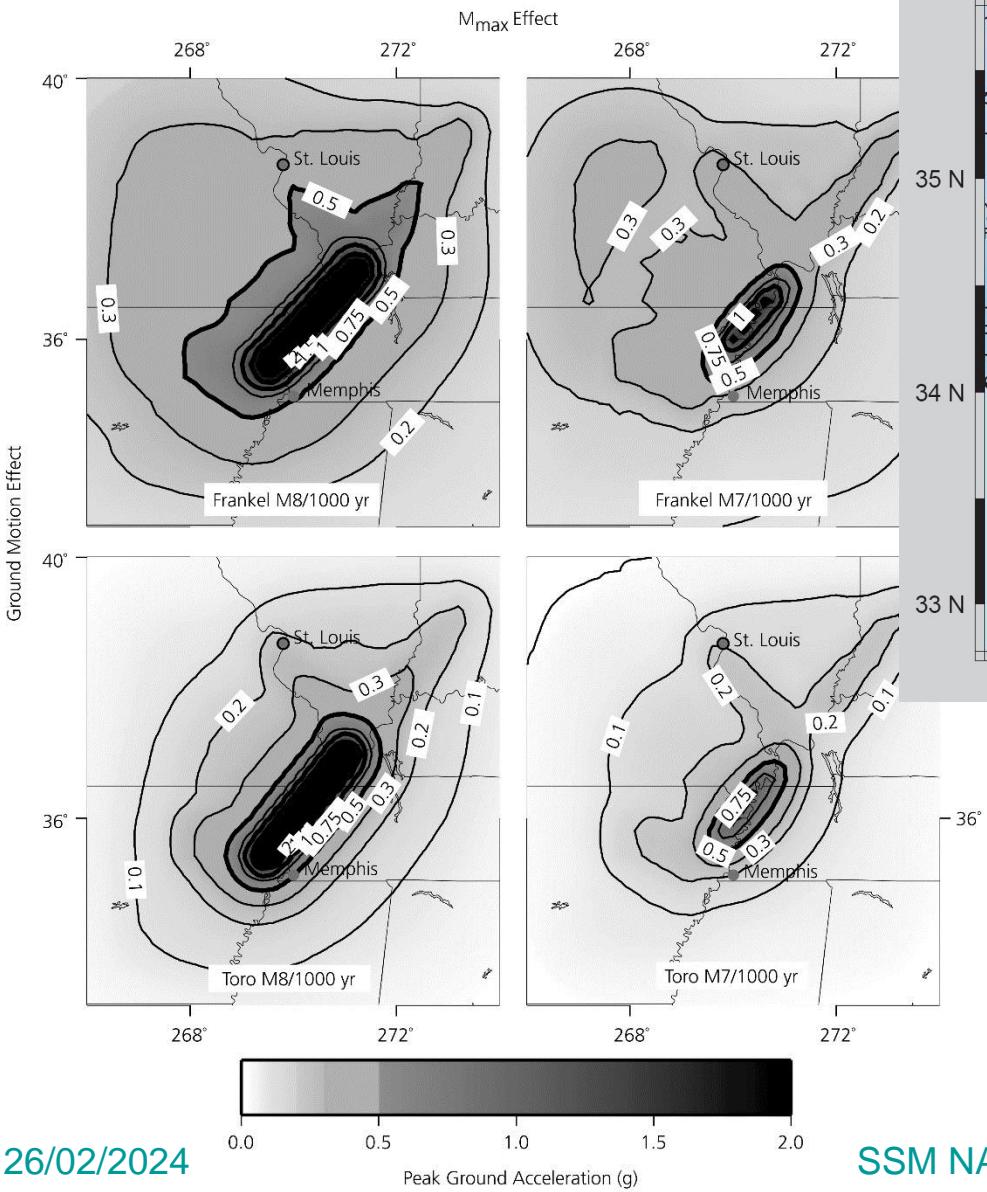
Before quake



After quake



# Seismic wave impact



Obviously, the pattern with distance is more complex than a simple decrease with distance : we must tackle this phenomenon and quantify it the best we can.

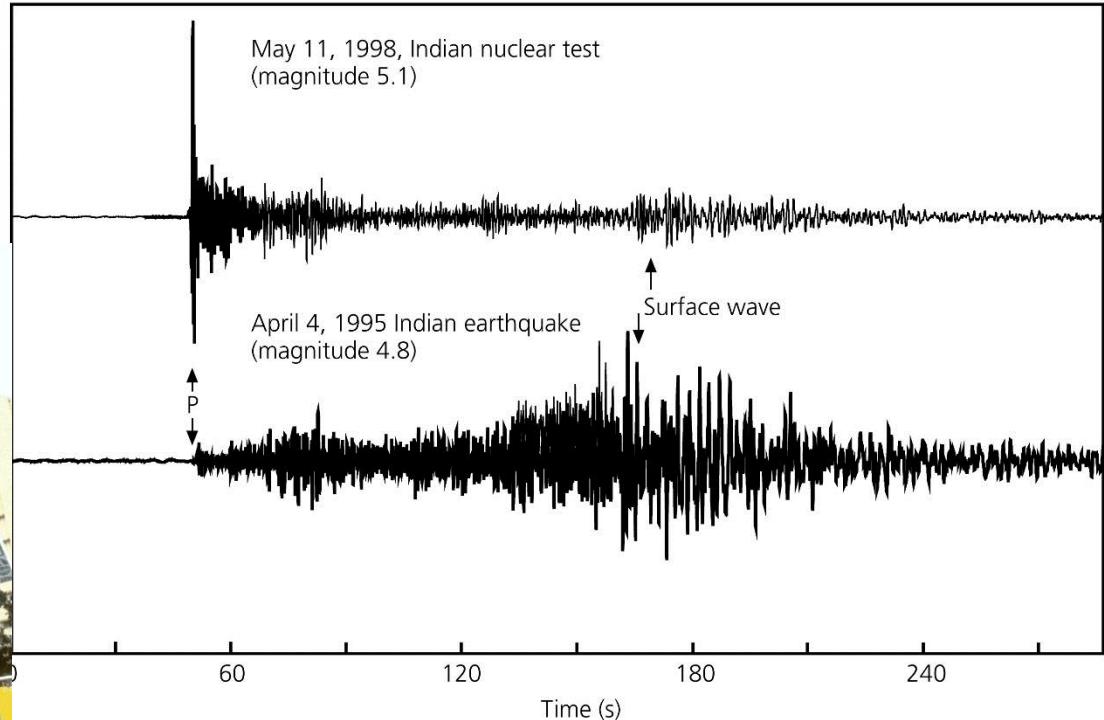
# Destruction by waves !

Importance of the radiation pattern

KOBE 1995



26/02/2024 NIIGATA JAPON (1964)



- Vulnerability through building design
- Local effects may amplify ground motion

# The Earth surface: geological risks?

But also not so far away from home

Messine earthquake 28-12-1908



(list events in Italy ...)

Understanding

Management

Warning

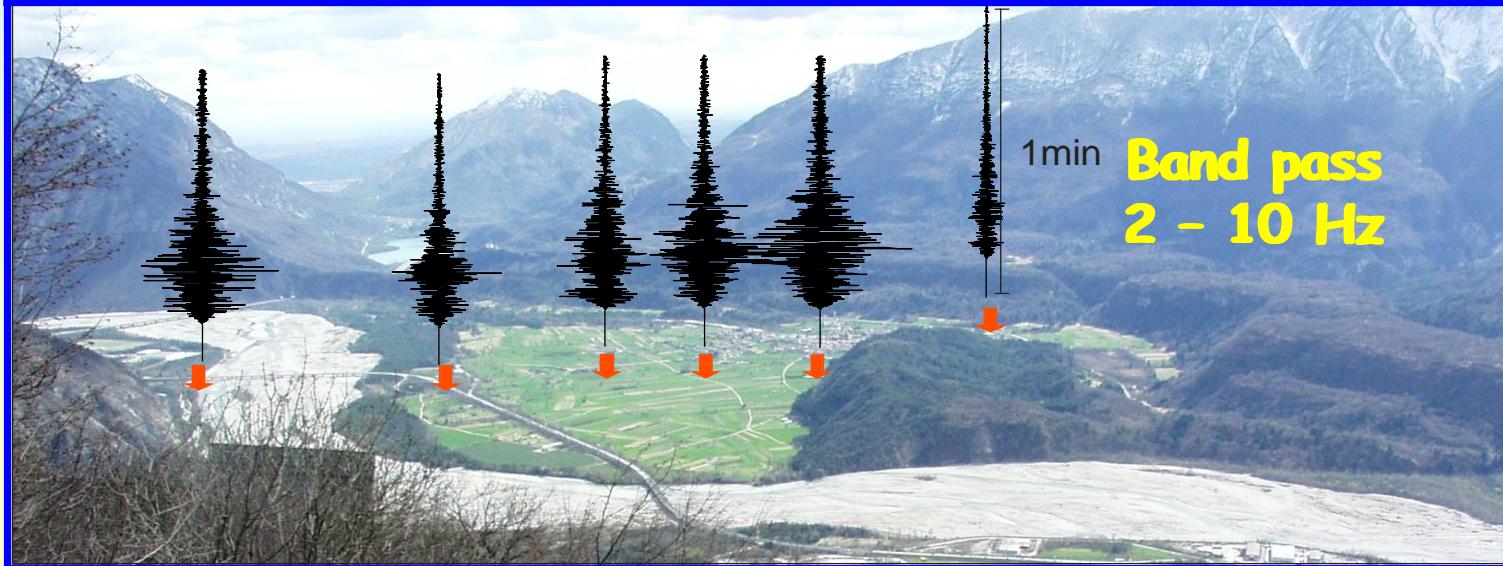
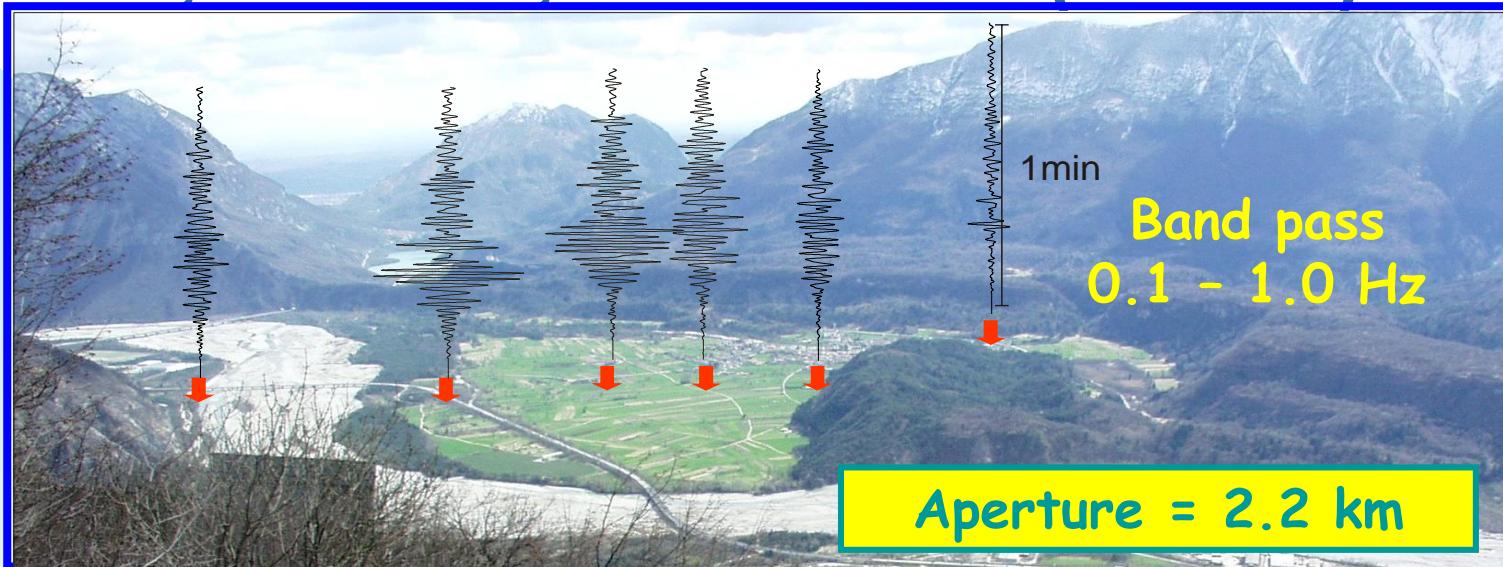
Education

Could we believe in science! How useful is it?

# **Large-scale structures**

**General subsurface structure  
... basin or valley ...**

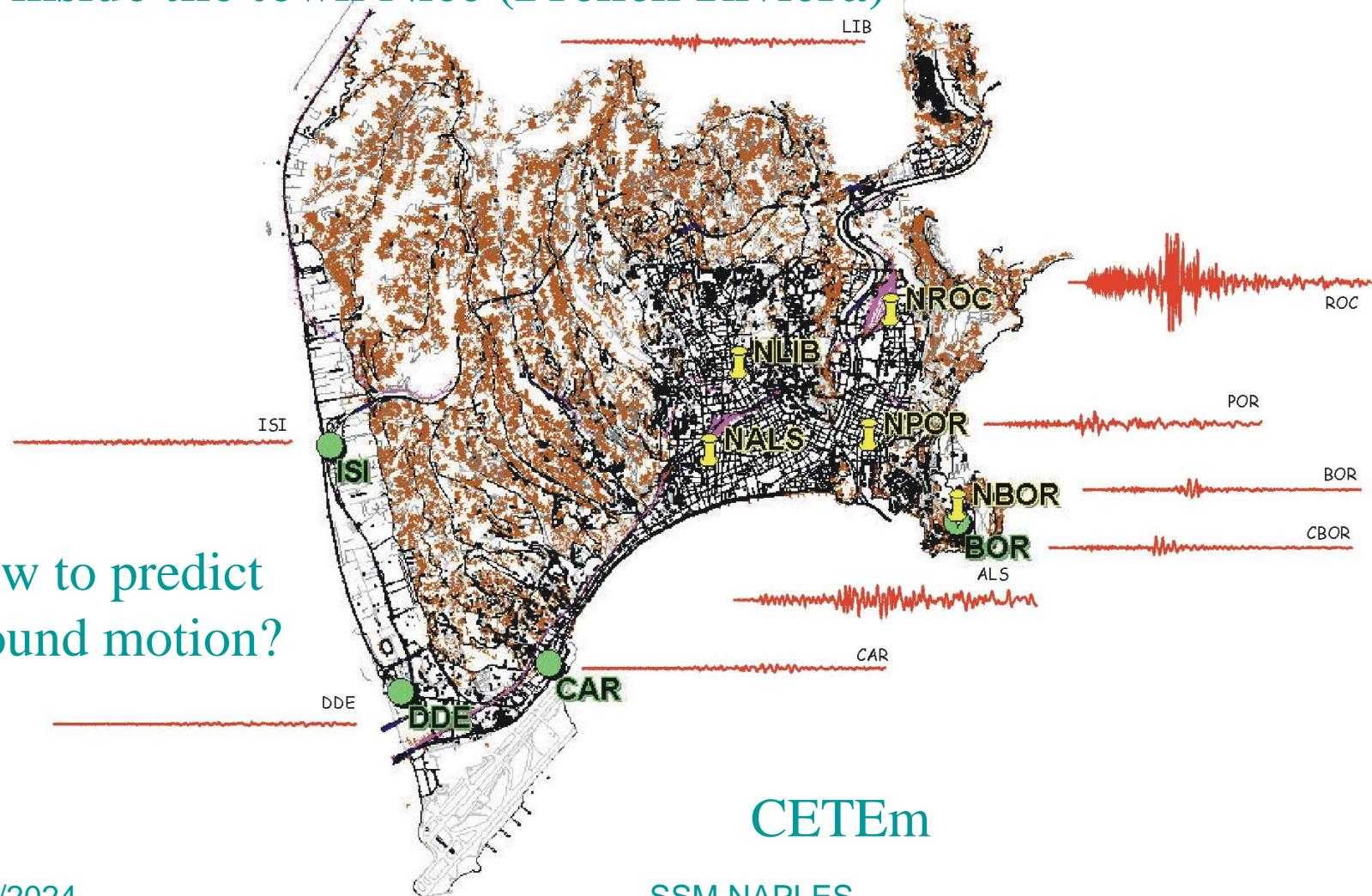
# Tagliamento Valley : seismic recording Kobarid, MD=5.1, 12.07.2004 (45 Km)



# Spatial Variability

Recorded seismograms for a small earthquake

inside the town Nice (French Riviera)



How to predict  
ground motion?

# **Short-scale structures**

## **Weathered zone!**

# Short-scale structures

# Soil amplification

Aoi et al (2004)

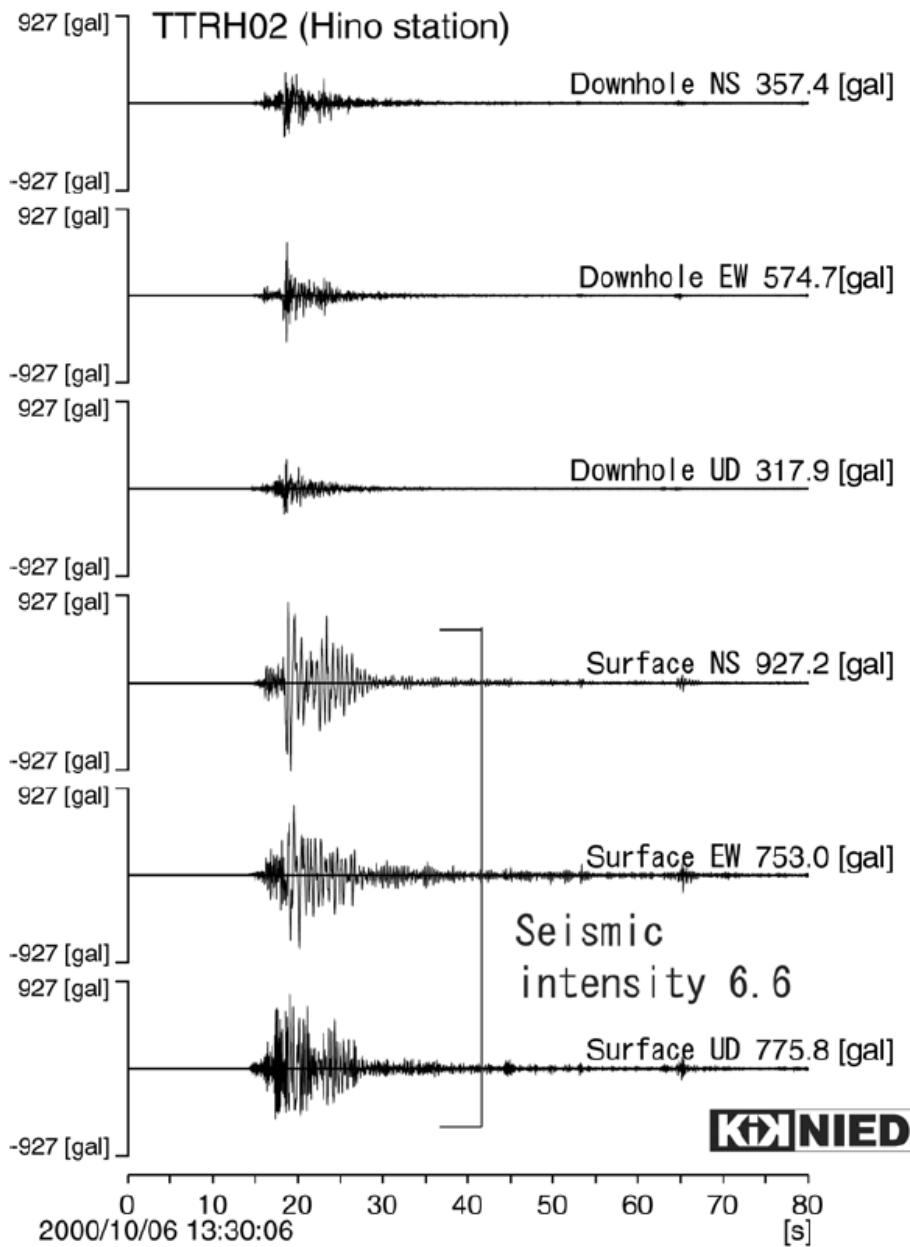
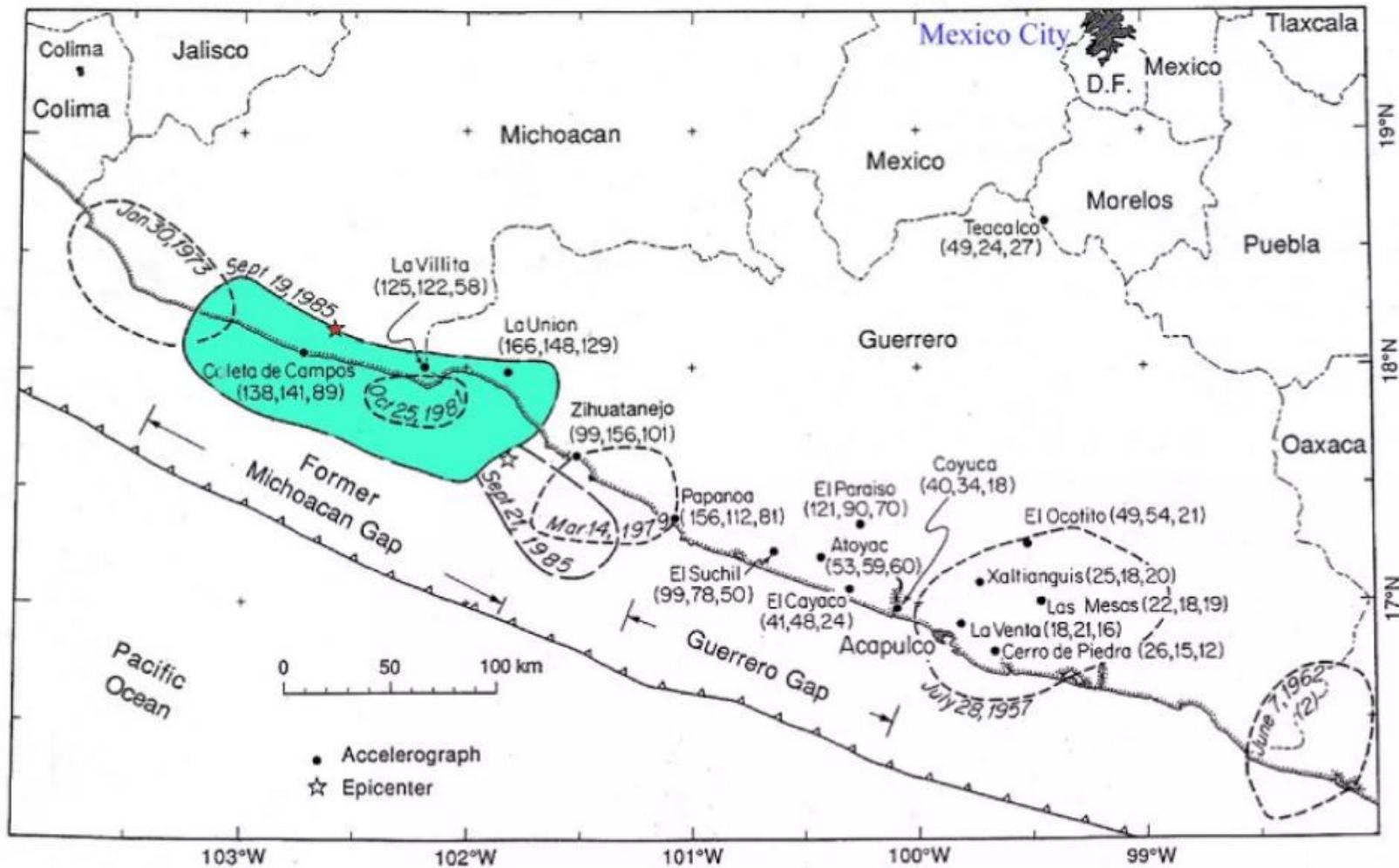


Fig. 5. Waveforms observed on the surface and the bottom of the 100 m deep borehole at Hino station (TTRH02) at 8 km away from epicenter. The maximum acceleration was 1135 gals (vector composition of three components) and the JMA seismic intensity was 6.6.

# An extreme site effect

## 1985 Michoacan, Mexico Earthquake



# Michoacan M 8.1 earthquake

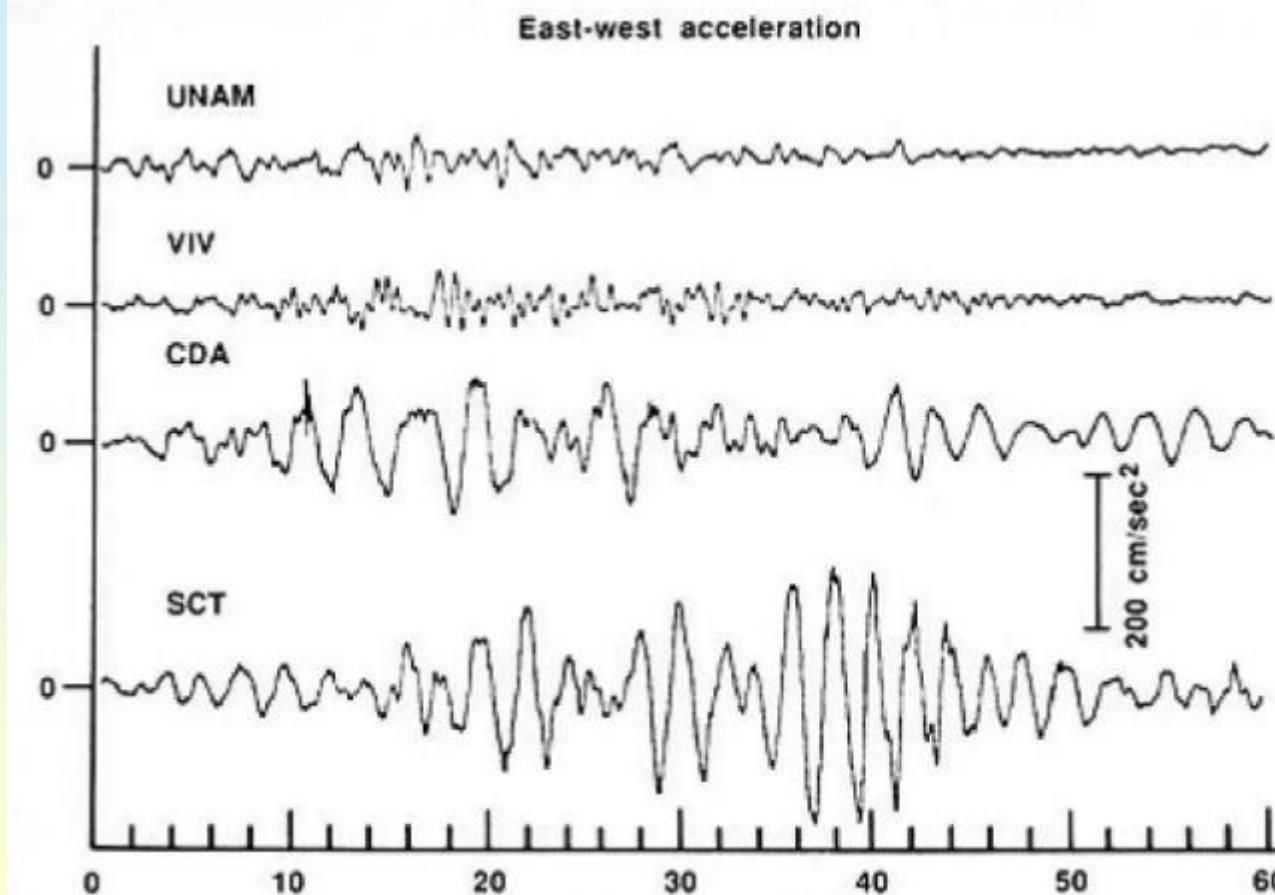
## Mexico City



- 350 km from earthquake epicenter
- 9000 deaths
- collapse of 371 high rise structures, especially 10-14 story buildings



# Strong-motion records from Mexico City



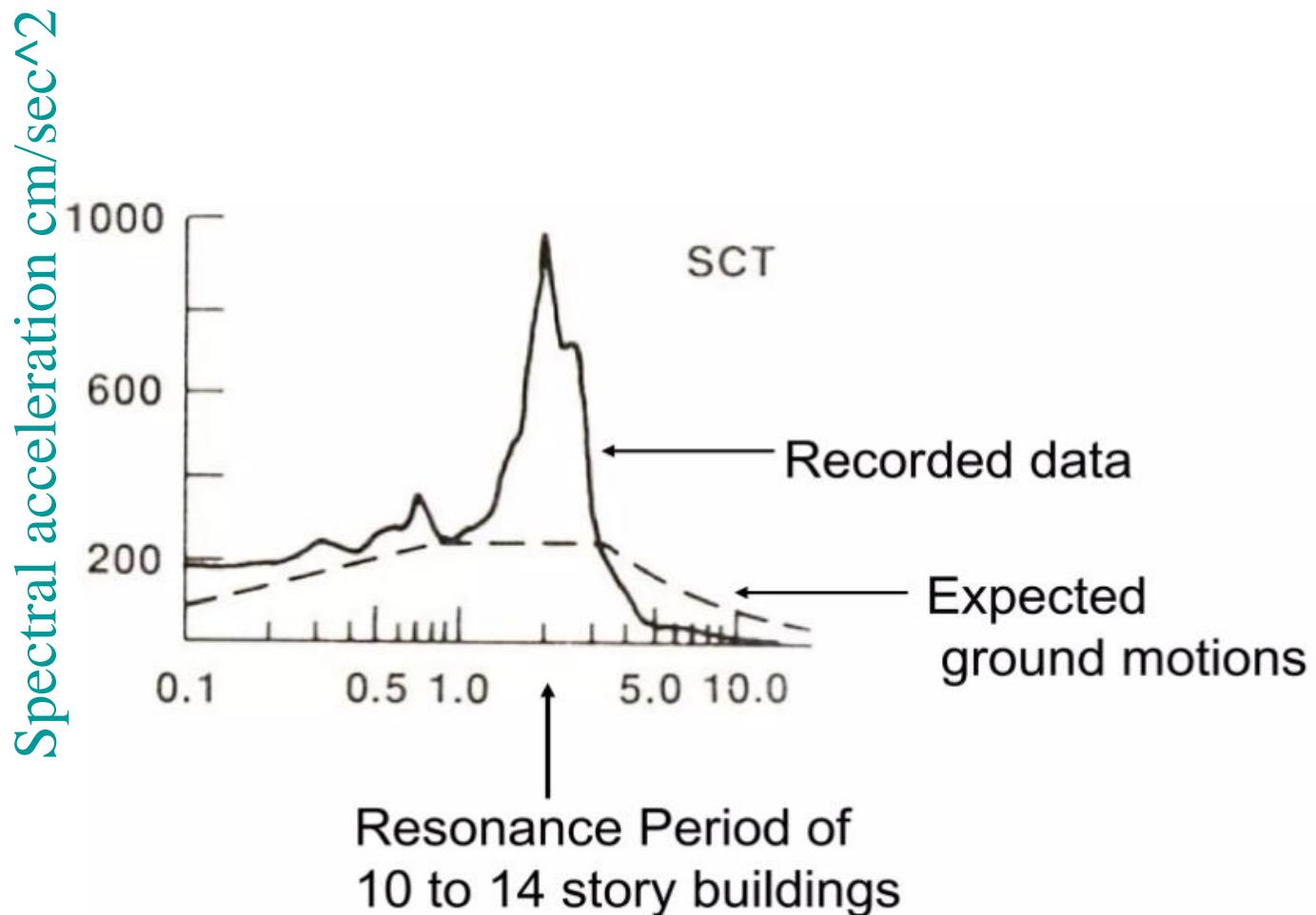
hard rock hills

Surface-wave  
amplitudes!

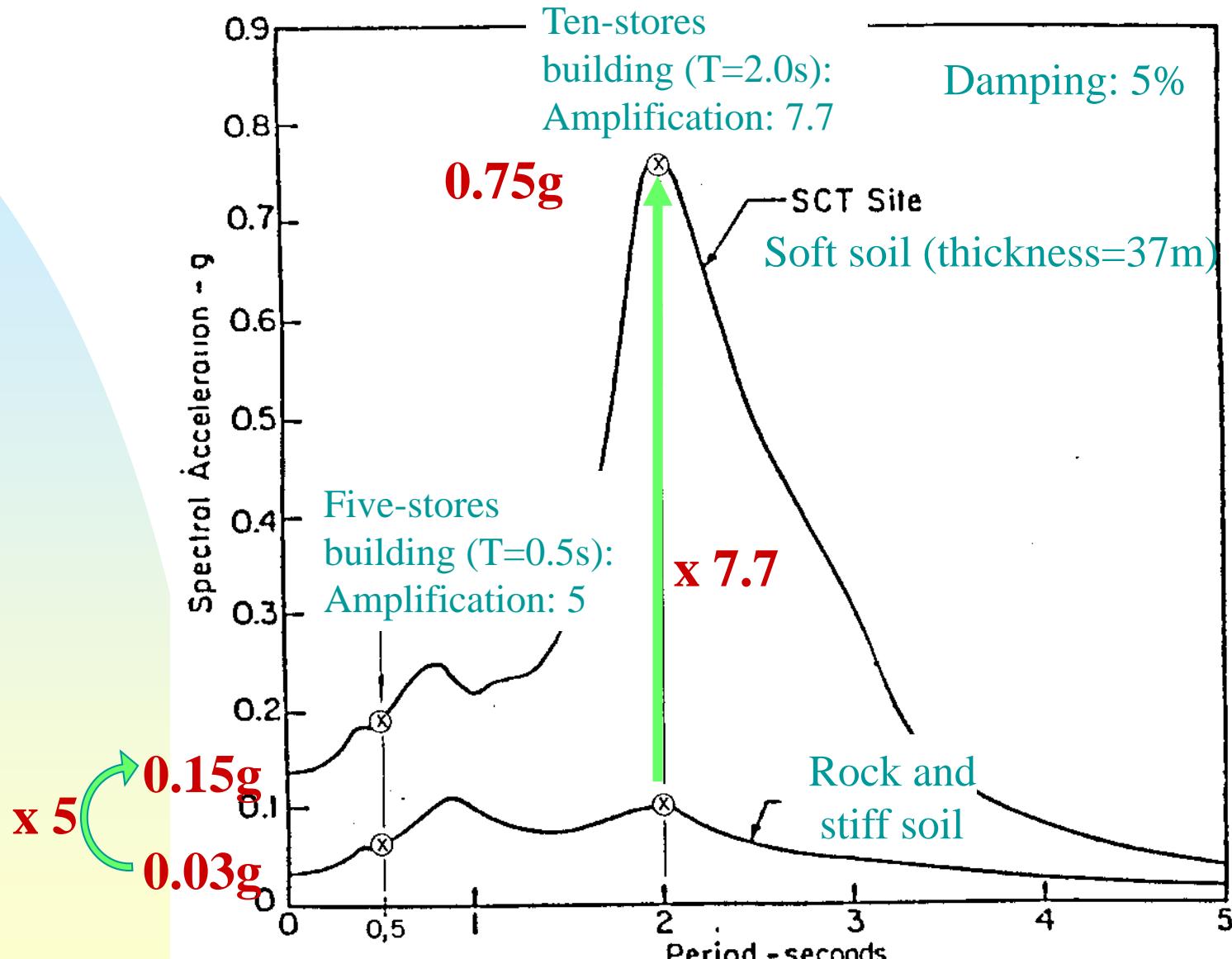
old lake bed

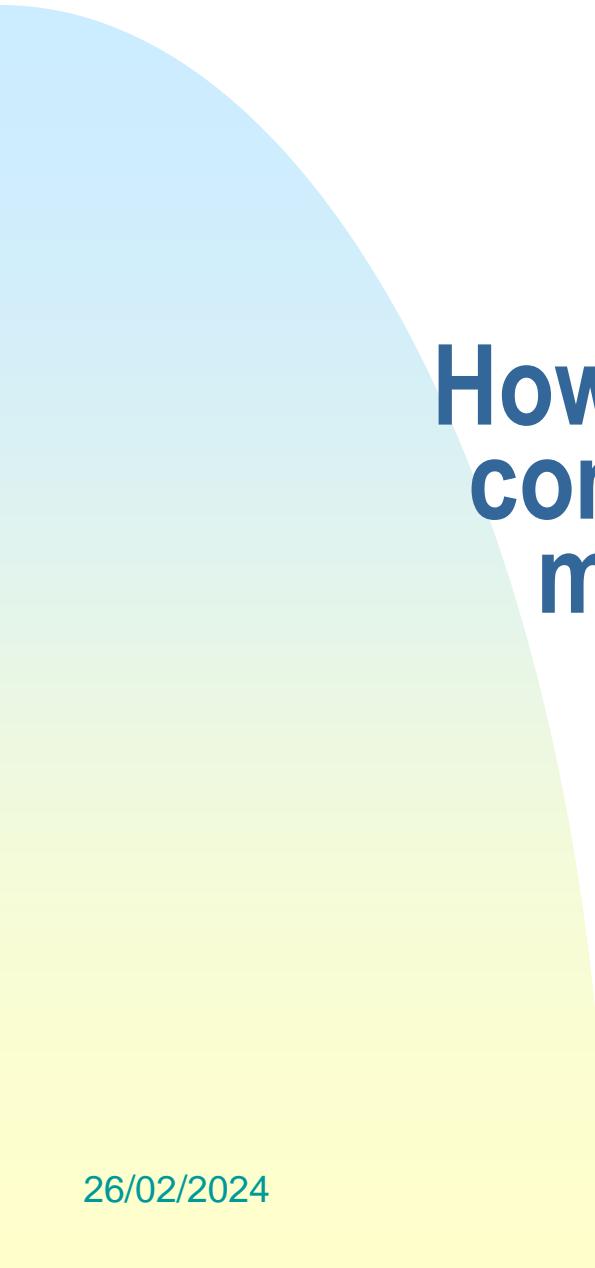
# The « 2 sec. » amplification!

## Mexico City Acceleration Response Spectrum



# The local amplification





# How to deal with such a complexity for ground motion prediction?

# Questions

- What are the most useful measures of ground motion?
- How to record these measures and predict future ones?
- What factors control the ground motion estimation?
  - ◆ Event?
  - ◆ Propagation?
  - ◆ Site?

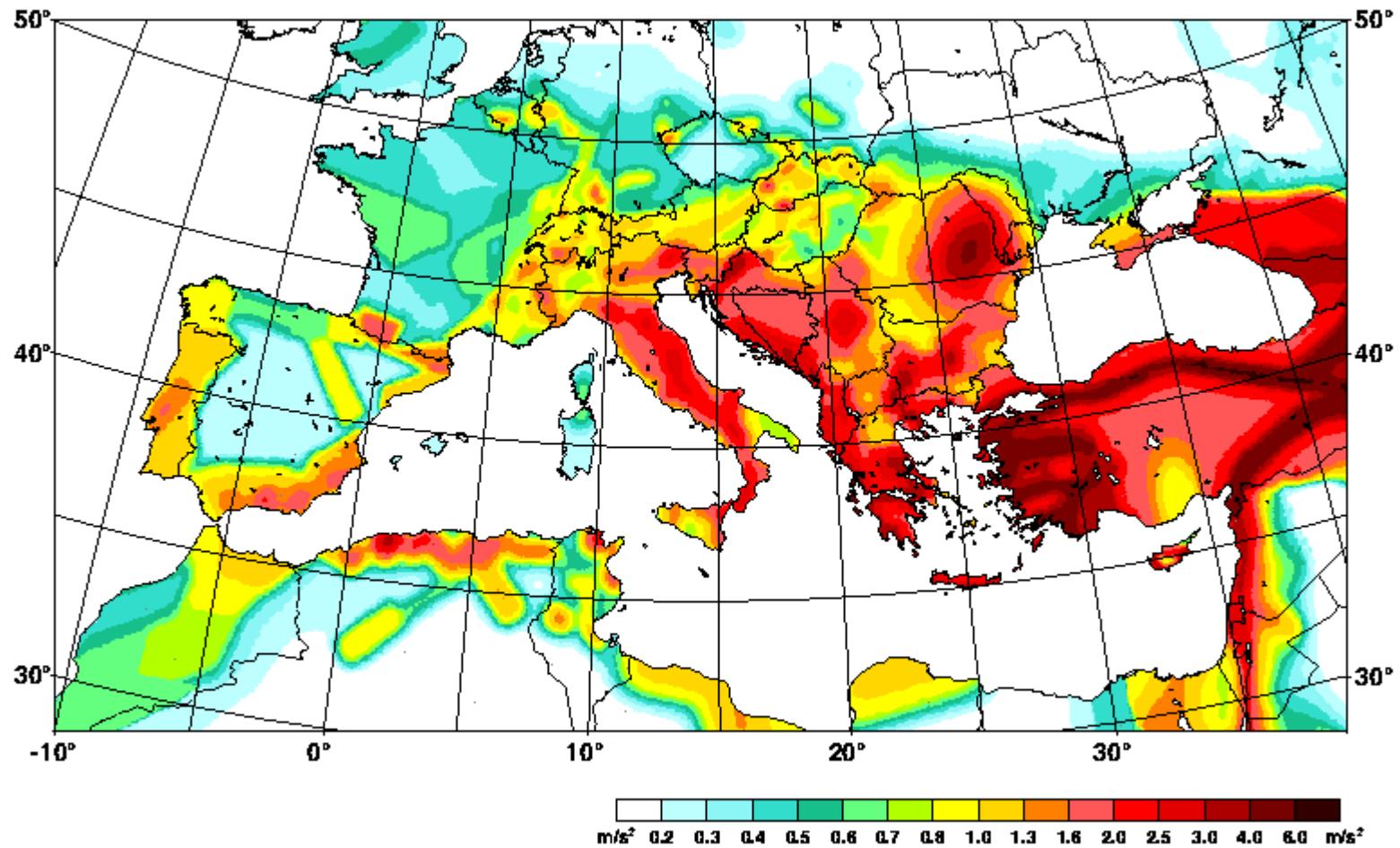
# Measures of ground-motion for engineering purposes

- PGA (peak ground acceleration)
- PGV (peak ground velocity)
- Damped response spectral acceleration at periods of engineering interest
- Intensity (can be related to PGA and PGV.)

# Peak ground acceleration (PGA)

- easy to measure because the response of most instruments is proportional to ground acceleration
- liked by many engineers because it can be related to the force on a short-period building
- convenient single number to enable rough evaluation of importance of records
- BUT it is not a measure of the force on most buildings
- and it is controlled by the high frequency content in the ground motion (i.e., it is not associated with a narrow range of frequencies); records can show isolated short-duration, high-amplitude spikes with little engineering significance

# PGA in the Mediterranean basin



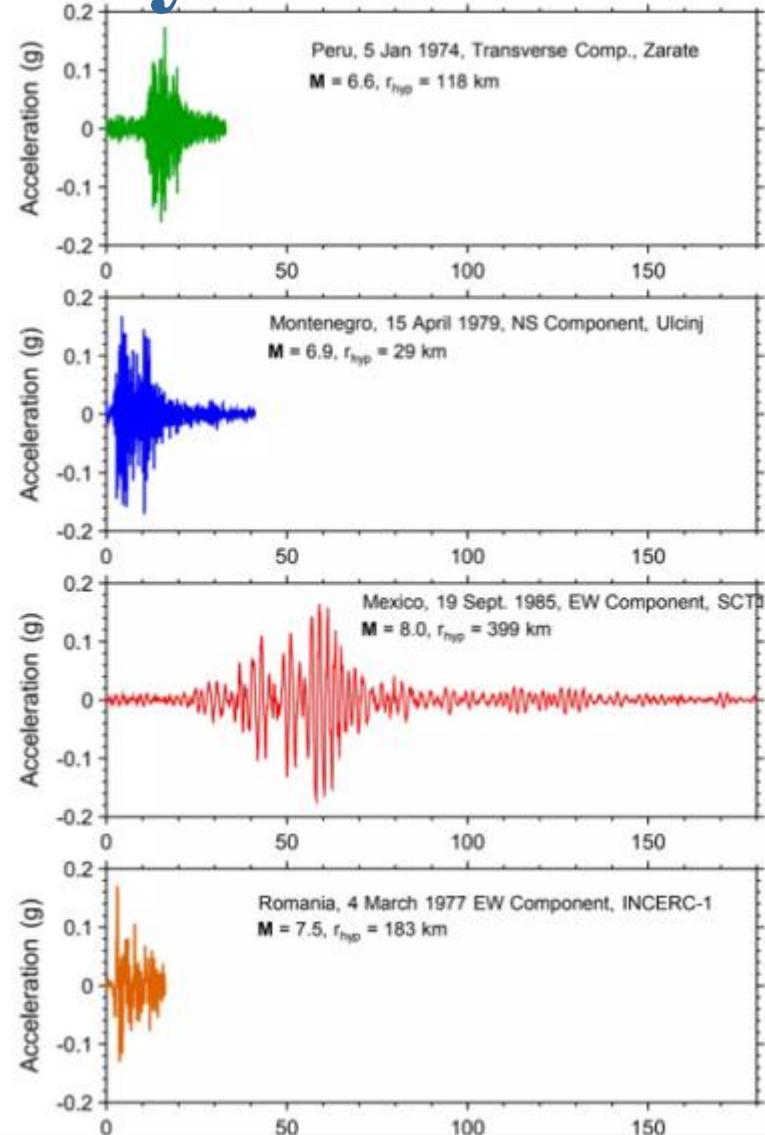
PGA = Peak Ground Acceleration

How to design these maps  
very useful for territory  
management.

# Ground-motion intensity

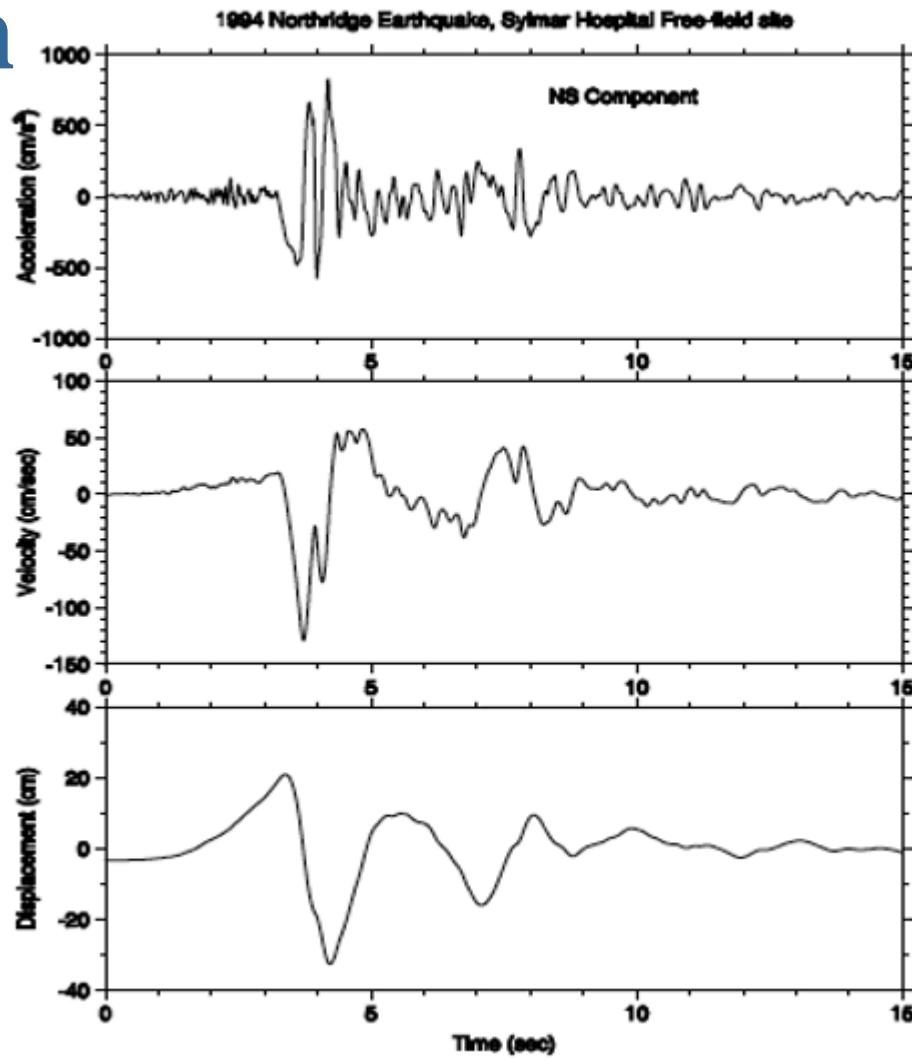
All of these time series  
have the same PGA

Peak Ground Acceleration (PGA)  
generally is a poor measure of  
ground-motion intensity



# Time integration

Digital integration of recorded acceleration for getting velocity and displacement



Acceleration, velocity and displacement time-series for the NS horizontal component of the Sylmar record

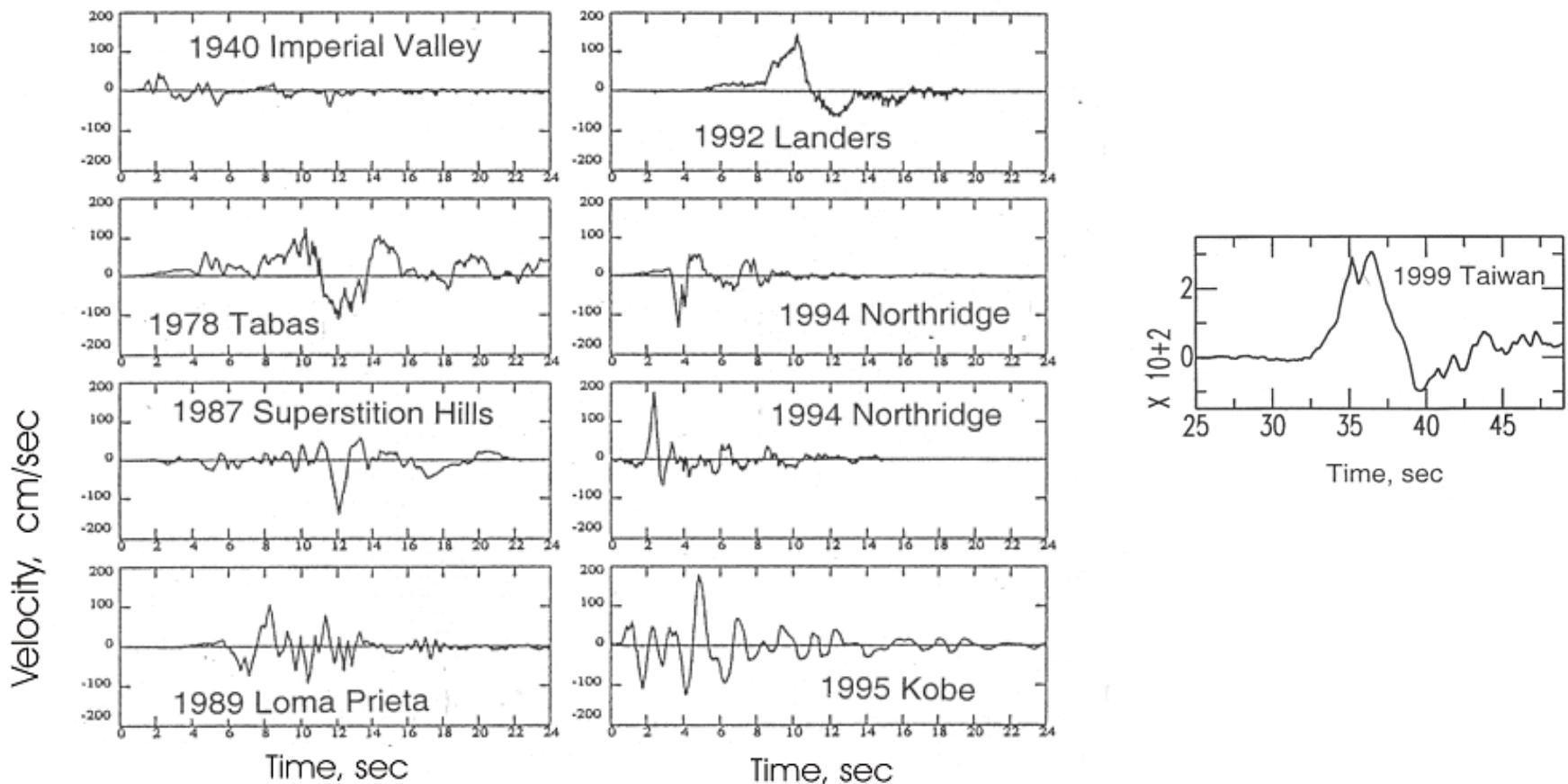
# Peak ground velocity (PGV)

- Many think it is better correlated with damage than other measures
- It is sensitive to longer periods than PGA (making it potentially more predictable using deterministic models)

Sensors can record directly particle velocity

# Peak ground velocity (PGV)

Ground-Motion Velocity from Large Earthquakes



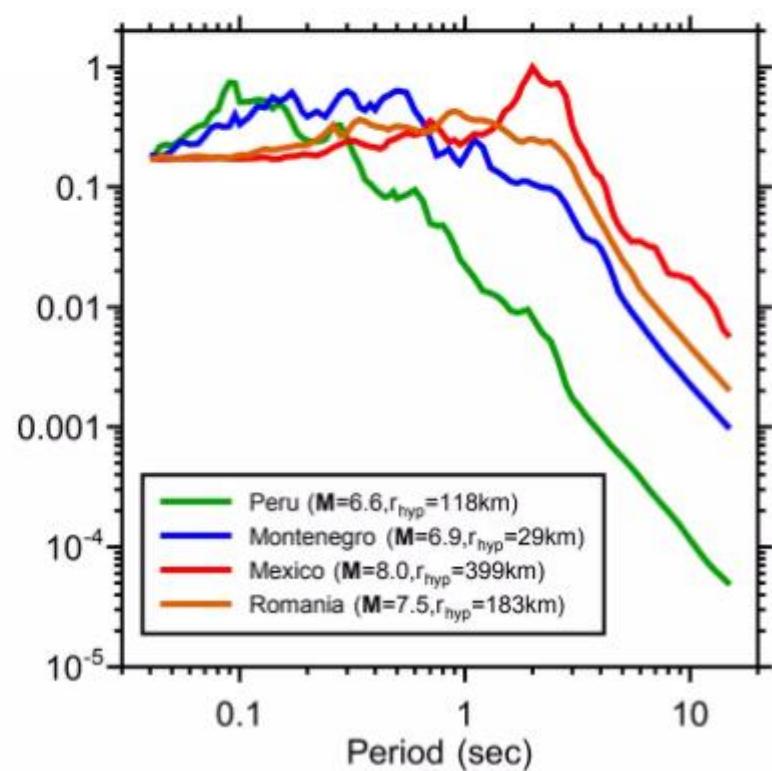
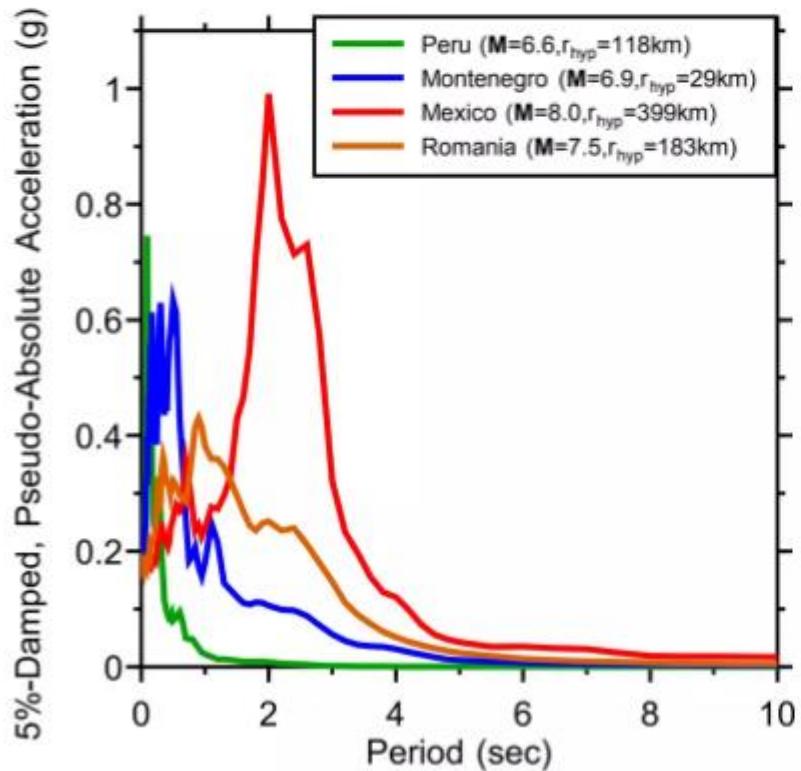
# Peak ground displacement (PGD)

- Best parameter for displacement-based design?
- Derived PGD might not represent the true PGD, unlike PGA or PGV records! (i.e. band-limited integration)
- Possible use of GPS data?

not recommended by David Boore

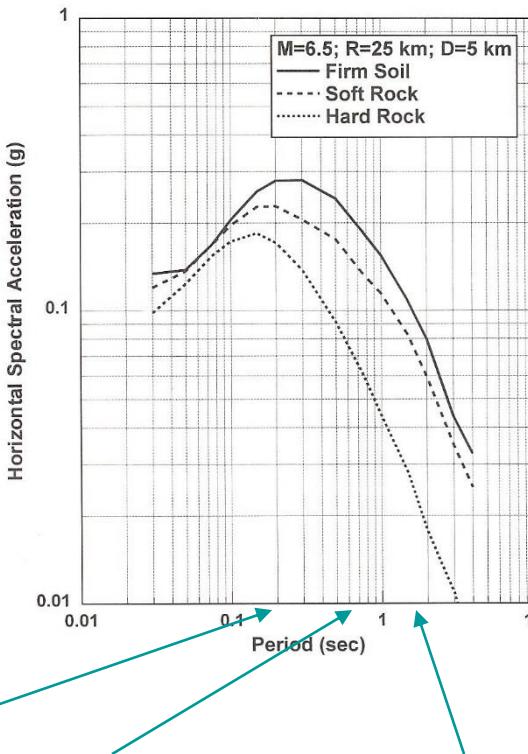
# Pseudo Spectral Acceleration (PSA)

But the response spectra (and consequences for structures) are quite different (lin-lin and log-log plots to emphasize different periods of motion):



File: D:\encyclopedia\_bommer\psa\_same\_psa.draw; Date: 2005-04-20; Time: 19:34:16

# Frequency response of structures



Unexplored topic!



2023 Turkish quake



# What ground motion estimation for seismic hazard assessment?

- Unknown sources? Site variability? Propagation complexity?
- Empirical relation often used for ground motion estimation (real-time computation)
- More & more quantitative modeling based on the physics of wave propagation (intense computation)

R: for early warning issues, source estimation crucial!

# Ground motion estimation

## Source effects

Moment/magnitude  $M_w$

Rupture directivity

Asperities

## Path effects

Spreading (geometrical decrease) (Body vs Surface)

Scattering (extrinsic attenuation)

Damping (intrinsic attenuation)

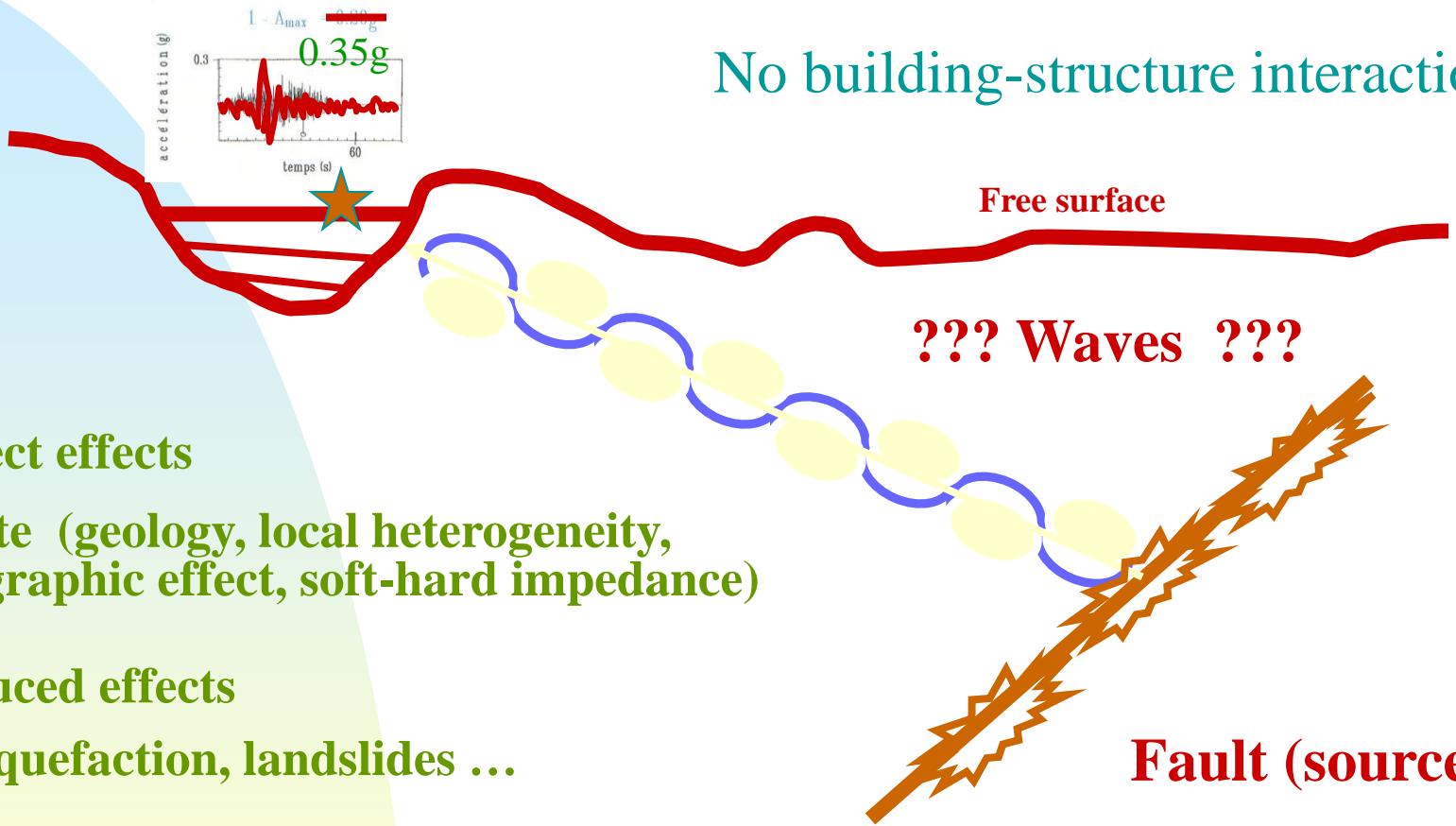


(global attenuation)

## Site effects

Local amplification

# Seismic Hazard Mitigation



\*Direct effects

+ Site (geology, local heterogeneity, topographic effect, soft-hard impedance)

\*Induced effects

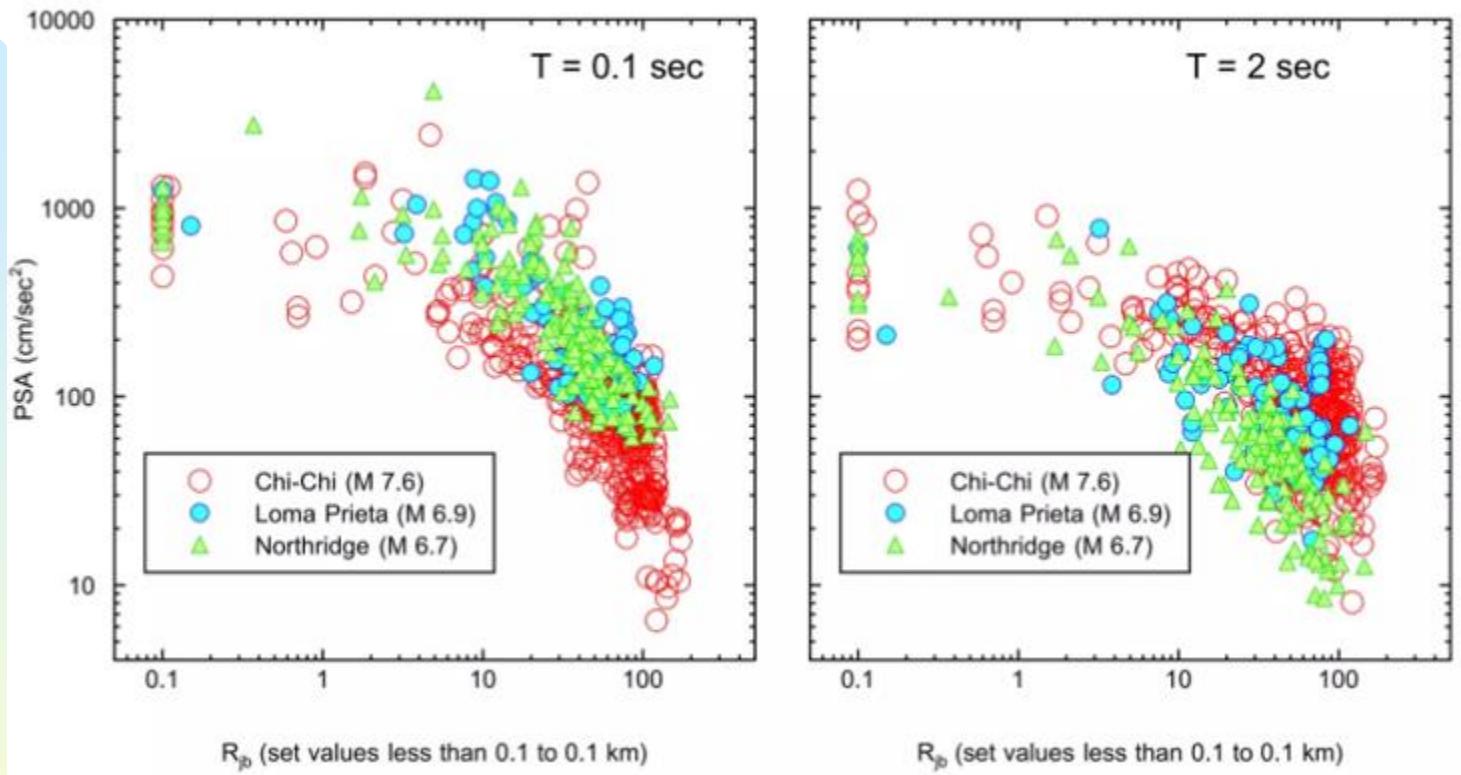
+ liquefaction, landslides ...

\*Near-source effects

+ breaking free surface

Improvement goes through better estimations of these components and the **wave propagation factor** is one factor with strong simplifications

# Distance and magnitude dependence



Chi-chi data are low at short periods (note also scattered distribution)

# Source effects

How does the motion depend on magnitude?

Source scaling theory predicts a general increase with magnitude for a fixed distance, with more sensitivity to magnitude for long periods and possible nonlinear dependence on magnitude

## Seismic Moment

$$M_0 \equiv \mu S A$$

$\mu$  = modulus of rigidity

$S$  = slip over fault area

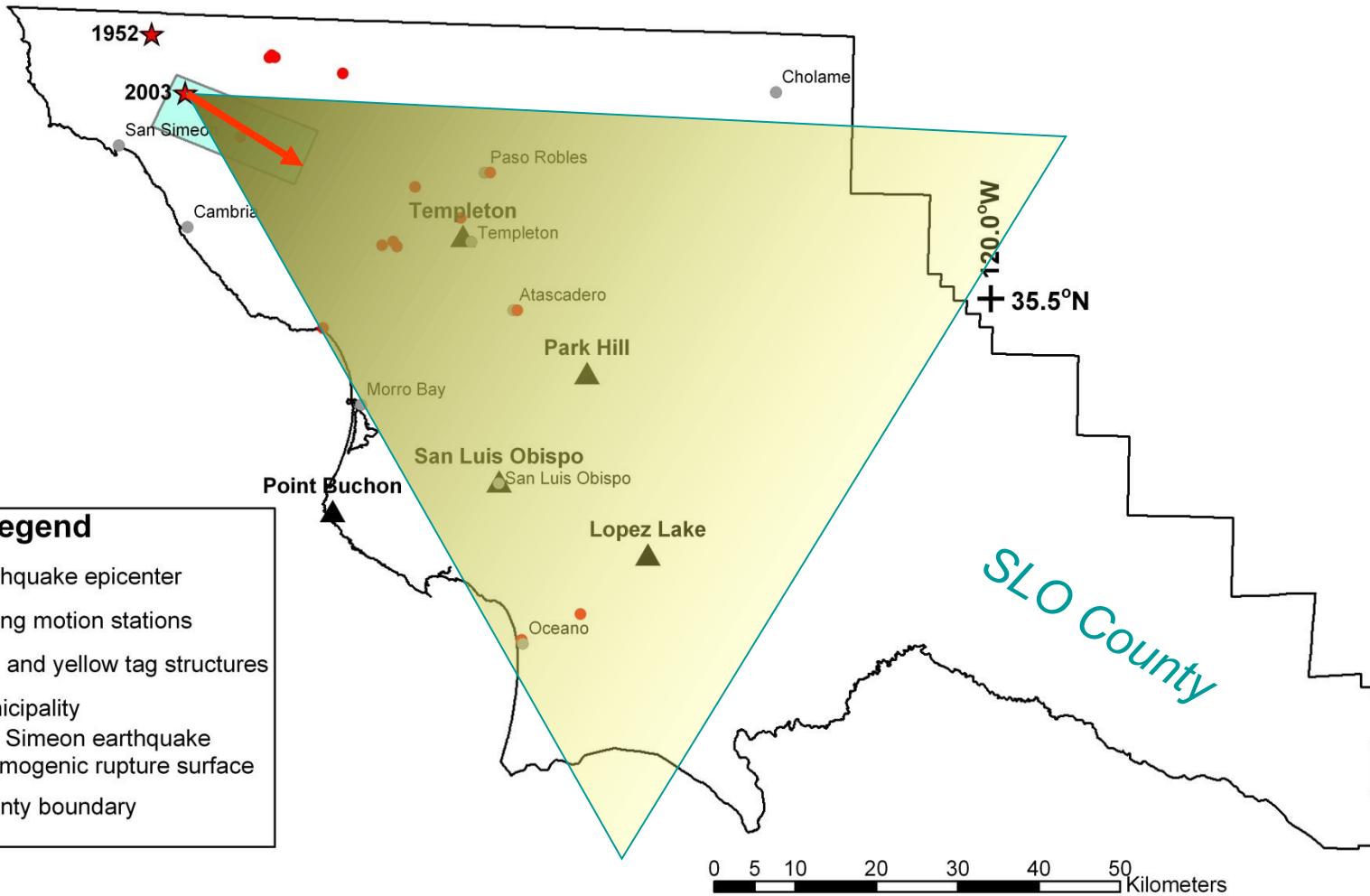
$A$  = area of fault

## Moment Magnitude

$$M \equiv \frac{2}{3} \log M_0 - 10.7$$

# Source effects

## Rupture Directivity



# *Damage in Oceano*

## *2003 San Simeon Earthquake*



# Path effects

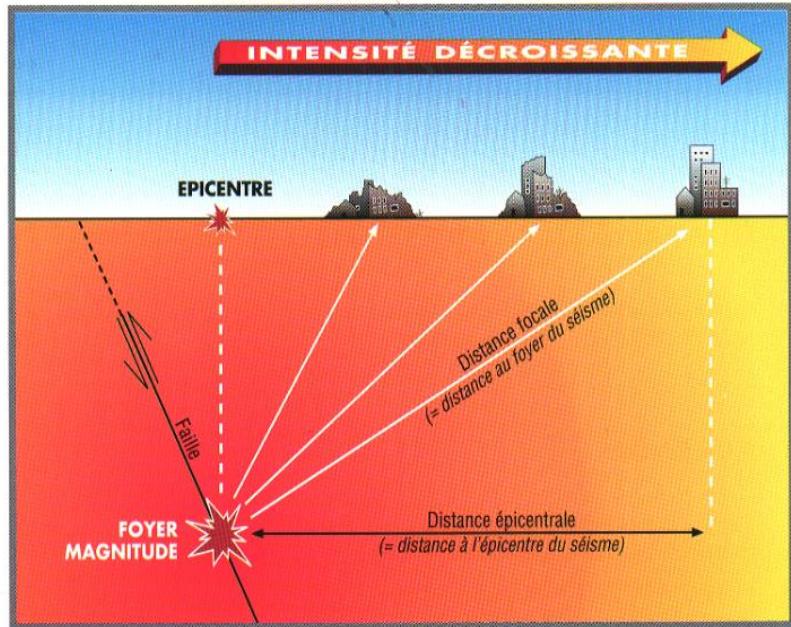
How does the motion depend on distance?

- Generally, it will decrease (attenuation) with distance
- But wave propagation may predict more complicated behavior (topography influence, Moho-bounced phases, lens effects ...)
- Ground motion prediction equations assume average over various crustal structures
- Influence of distances between finite source and station

# Geometrical attenuation

# Geometrical spreading

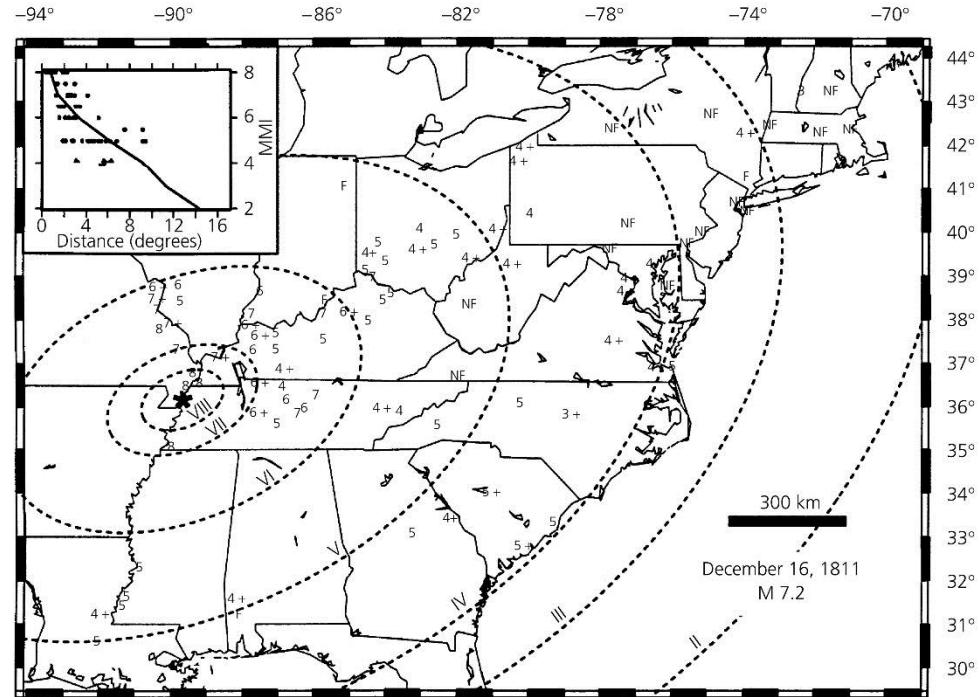
Intensité décroissante en l'absence d'amplification locale.



Magnitude = énergie libérée par le séisme.

Intensité = effets ressentis en surface, en un lieu donné.

Destruction decreases with distance (not included in seismic hazard estimation)



Intensity scale # Magnitude scale  
making difficult discrimination  
between ground motion and destruction

# Heterogeneous propagation

Layered model?  
efficient modeling

Regional scale (1 Hz)?  
high-frequency modeling (20 Hz?)

Local scale?  
challenging modeling (?)

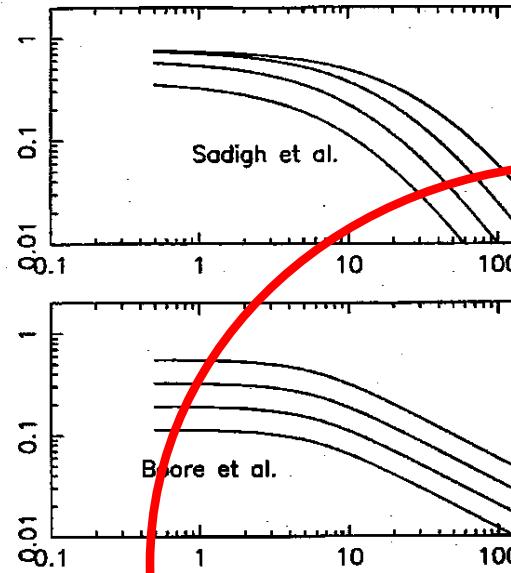
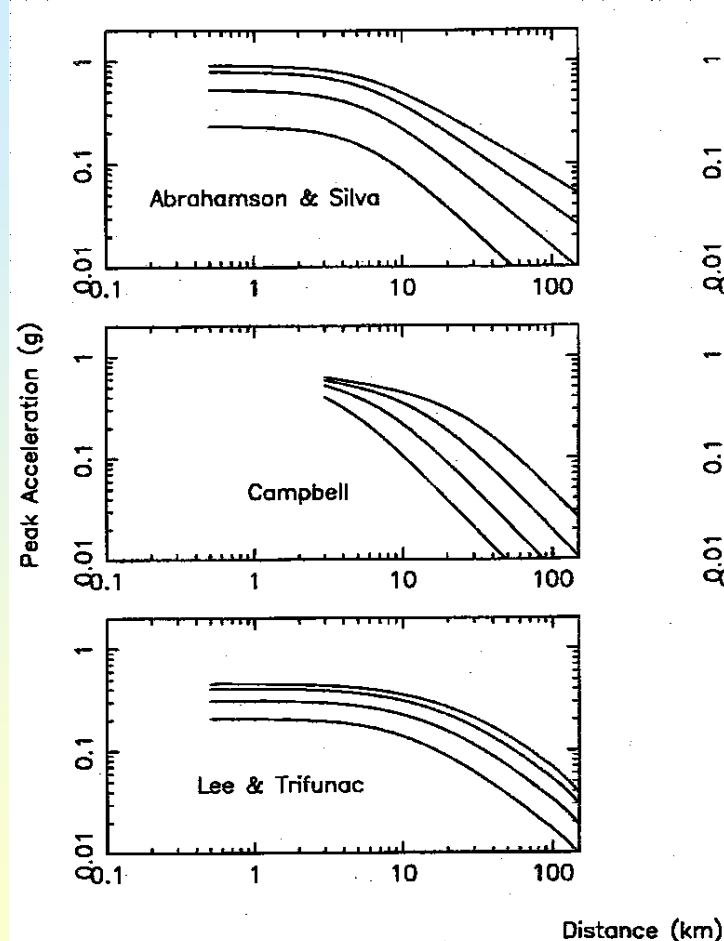
# Site effects

- ✓ Rock
- ✓ Stiff soil
- ✓ Soft soil
- ✓ Vs30
- ✓ Slope (topography)
- ✓ Other effects?

# Ground Motion Prediction Equations (GMPE)

- Empirical regressions of recorded data
- Estimate ground shaking parameter (PGA, PGV, PSA, PSV) as a function of
  - ✓ Magnitude, depth, directivity(?) ...
  - ✓ Distance
  - ✓ Site (rock, soft, Vs30, slope)
- Possible fault parameters (directivity, area, strike-slip, normal, reverse...)

# Efficient and widely used for PSHA (Probabilistic Seismic Hazard Assessment)



Ambraseys et al., 1996  
Sabetta and Pugliese, 1996  
Berge-Thierry et al., 2003  
Marin et al., 2004

# "Simple" functional form of ground motion model

$$\log(PSA(f)) = \boxed{a(f) \cdot M} + \boxed{b(f) \cdot R - \log(R)} + \boxed{c(i, f)}$$

Source

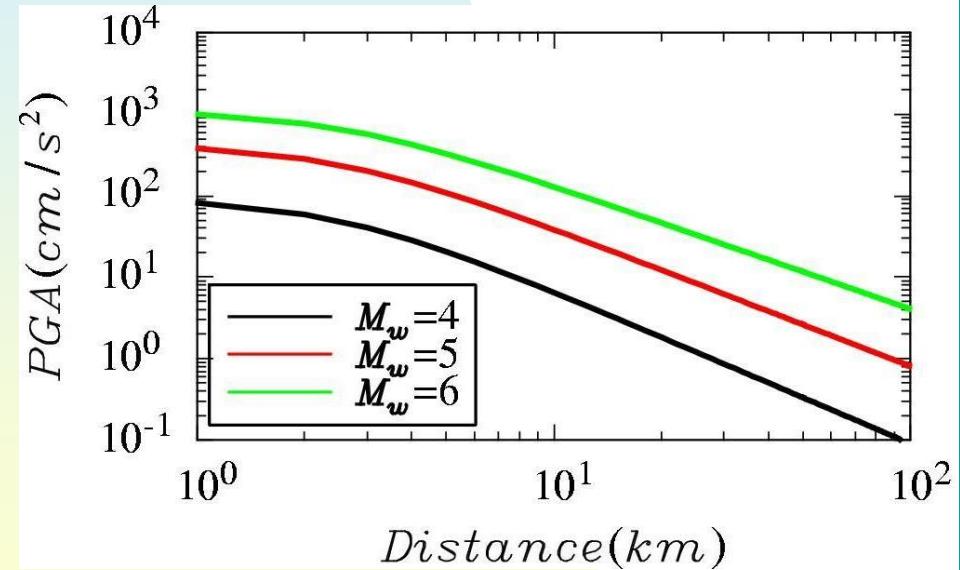
Distance

Site

- Pseudo response Spectrum Acceleration (PSA)
- The magnitude scaling of ground motion decay does not depend on magnitude
- The ground motion decay does not depend on magnitude

# Magnitude/distance dependence

$$\log(PSA(f)) = a_1(f) \cdot M + a_2(f) \cdot (8.5 - M)^2 \\ + [b(f) + c(f) \cdot M] \log(\sqrt{R^2 + h^2}) + d(f)$$



Fall-off faster  
for small earthquakes  
than for important ones

Courtesy of Fabian Bonilla

# GMPEs for PGA

Many GMPEs are proposed (Esteva & Rosenblueth, 1964; Ambraseys & Douglas, 2000; Ulutas & Ozer, 2010; ...)

An endless quest !!!

Ground-motion model is:

$$\log y = b_1 + b_2 M_s + b_3 d + b_A S_A + b_S S_S$$

where  $y$  is in  $\text{m/s}^2$ , for horizontal PGA  $b_1 = -0.659$ ,  $b_2 = 0.202$ ,  $b_3 = -0.0238$ ,  $b_A = 0.020$ ,  $b_S = 0.029$  and  $\sigma = 0.214$  and for vertical PGA  $b_1 = -0.959$ ,  $b_2 = 0.226$ ,  $b_3 = -0.0312$ ,  $b_A = 0.024$ ,  $b_S = 0.075$  and  $\sigma = 0.270$ .

Assume decay associated with anelastic effects due to large strains and cannot use both  $\log d$  and  $d$  because highly correlated in near field.

Extended report from Douglas (2011)

# Diverse GMPEs for PGA (data-driven)

Use four site categories (often use shear-wave velocity profiles):

- L Very soft soil: approximately  $V_{s,30} < 180$  m/s, (combine with category S)  $\Rightarrow S_A = 0, S_S = 1, 4$  records.
- S Soft soil: approximately  $180 \leq V_{s,30} < 360$  m/s  $\Rightarrow S_A = 0, S_S = 1, 87$  records.
- A Stiff soil: approximately  $360 \leq V_{s,30} < 750$  m/s  $\Rightarrow S_A = 1, S_S = 0, 68$  records.
- R Rock: approximately  $V_{s,30} > 750$  m/s  $\Rightarrow S_A = 0, S_S = 0, 23$  records.

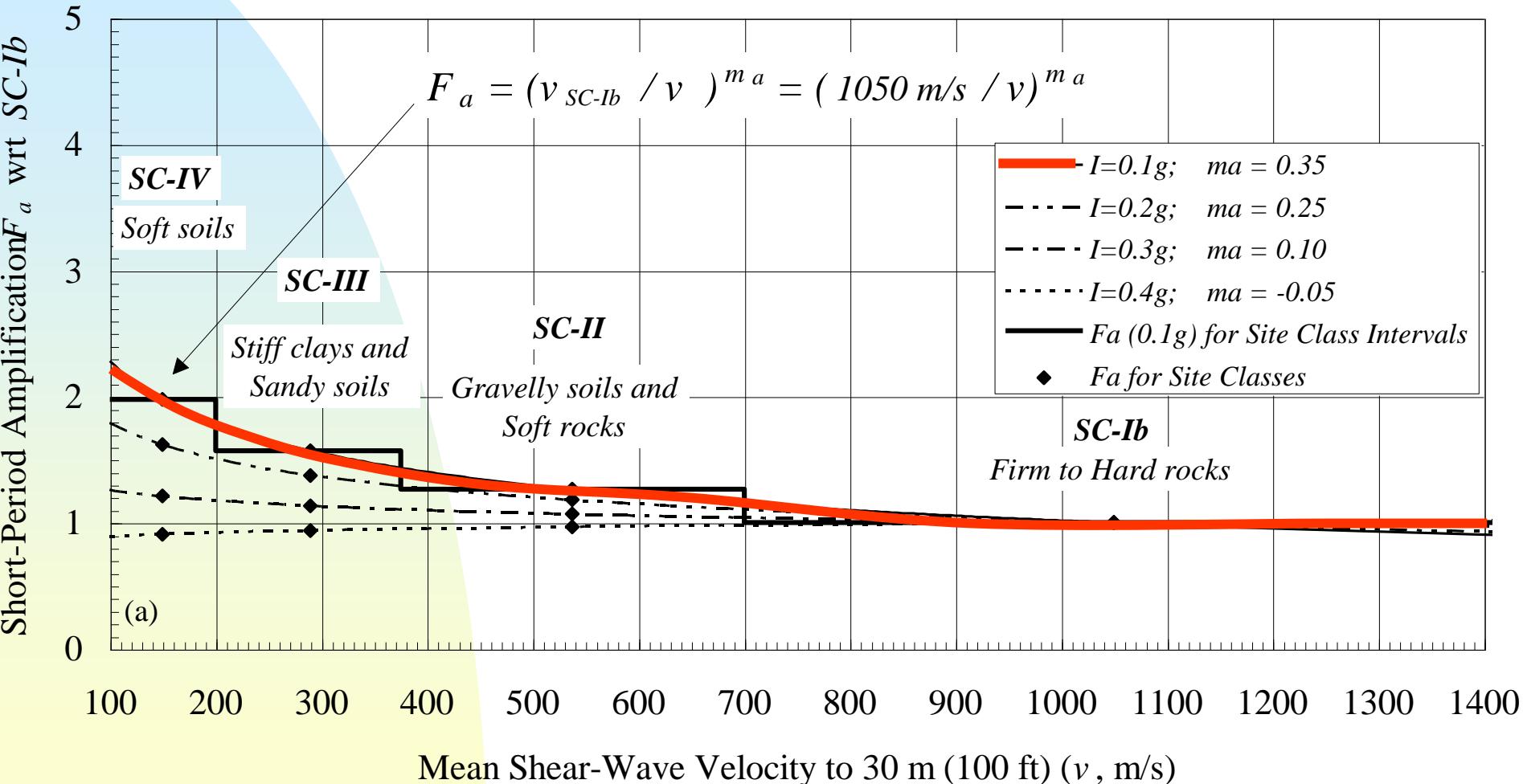
where  $V_{s,30}$  is average shear-wave velocity to 30 m. Know no site category for 14 records.



This report summarizes, in total, the characteristics of 289 empirical GMPEs for the prediction of PGA and 188 empirical models for the prediction of elastic response spectral ordinates. In addition, many dozens of simulation-based models to estimate PGA and elastic response spectral ordinates are listed but no details are given.

(Douglas, 2011)

# Amplification of PGA as a function of Vs30



# Available tools:

<https://platform.openquake.org>

THE OPENQUAKE PLATFORM

Welcome to the OpenQuake Platform, by the GEM Foundation. This web-based platform offers an interactive environment in which users can access, manipulate, share and add data, and explore models and tools for integrated assessment of earthquake risk.

QUICK ACCESS

- ❖ Risk Input Preparation Toolkit  
Tools used to create exposure, fragility and vulnerability risk input models.
- ❖ The Building Classification Survey Tool  
Allows users to share information regarding the building stock of a given region.
- ❖ TaxTweb  
Graphical tool for editing GEM Taxonomy strings, web version.
- ❖ The Physical Vulnerability Suite View  
Allows users to explore and contribute to a comprehensive global vulnerability database that includes fragility, vulnerability, damage-to-loss functions and capacity curves for different types of structure.

Maps

Layers

Documents

OPENQUAKE  
calculate share explore

Earthquake engineering

# Available tools: openquake description

<https://docs.openquake.org/oq-engine/master/manual/>

## General overview

The OpenQuake Engine software provides calculation and assessment of seismic hazard, risk and decision-making tools via the data, methods and standards that are being developed by [Global Earthquake Model \(GEM\) Foundation](#) and its collaborators.



[Getting Started](#)



[User Guide](#)



[API Reference](#)



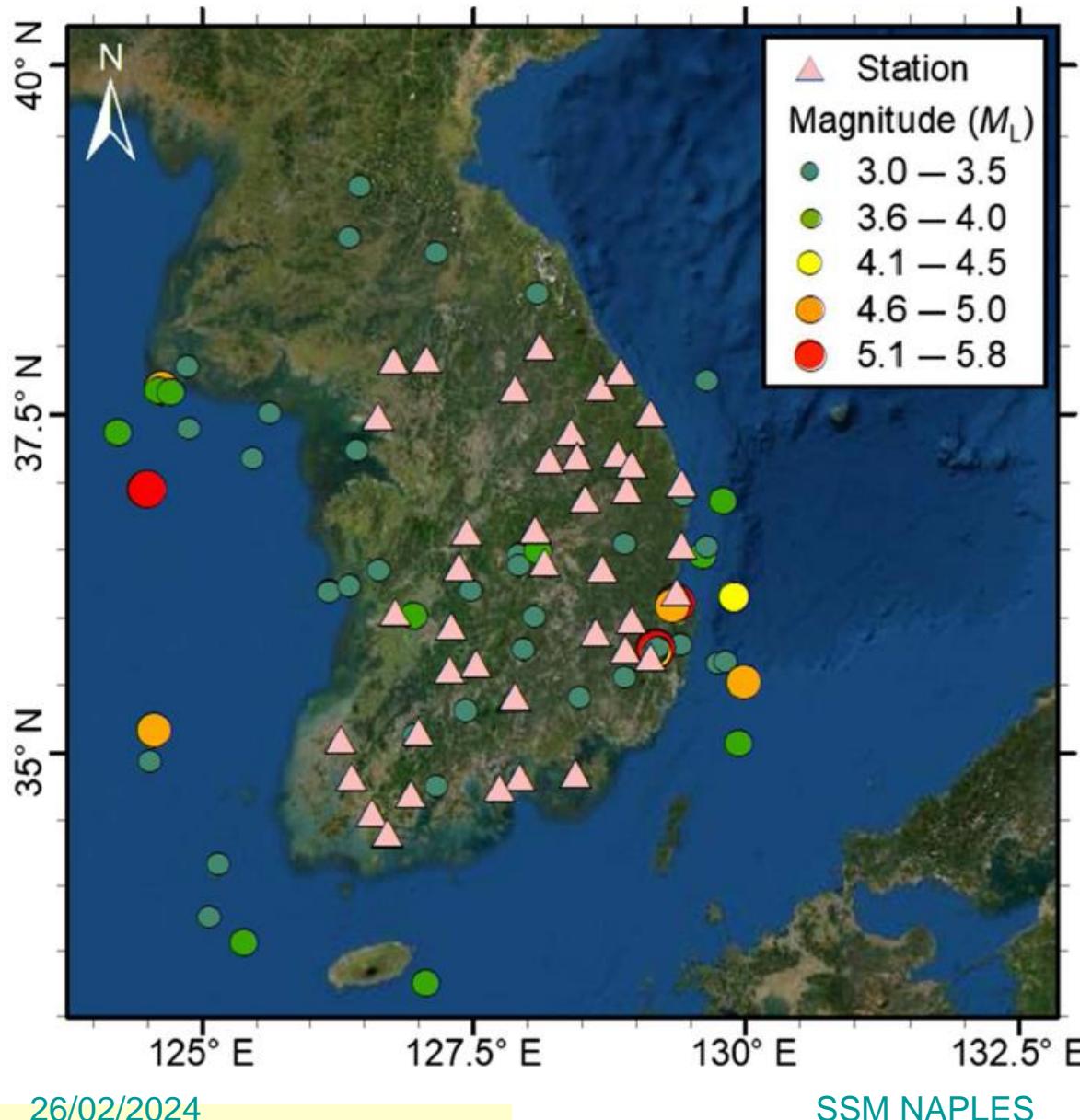
[Underlying Science](#)

# Game-changers

- ❖ Dense seismic networks
- ❖ Machine-learning approaches
- ❖ Seismic propagation tools

missing or poorly described: velocity structures!

# Machine-learning-based PSA

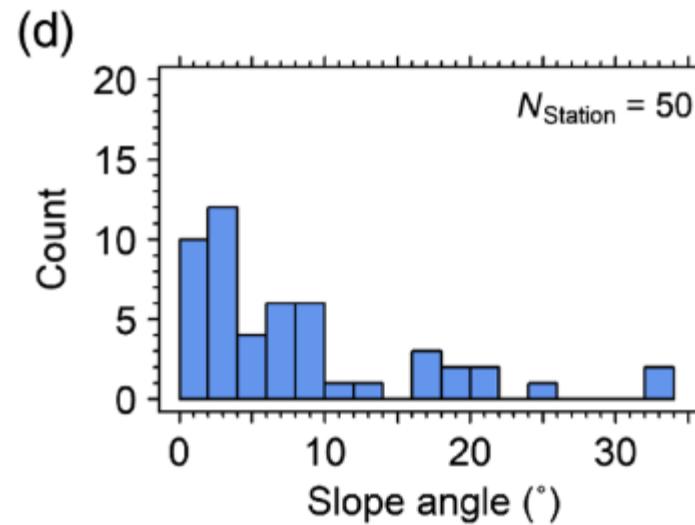
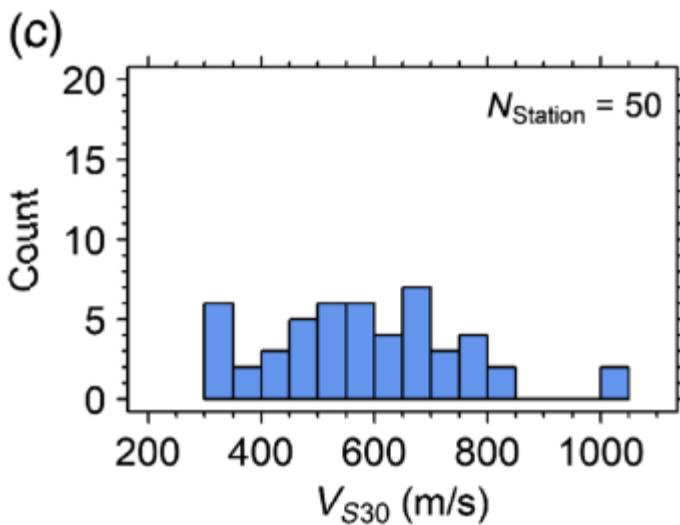
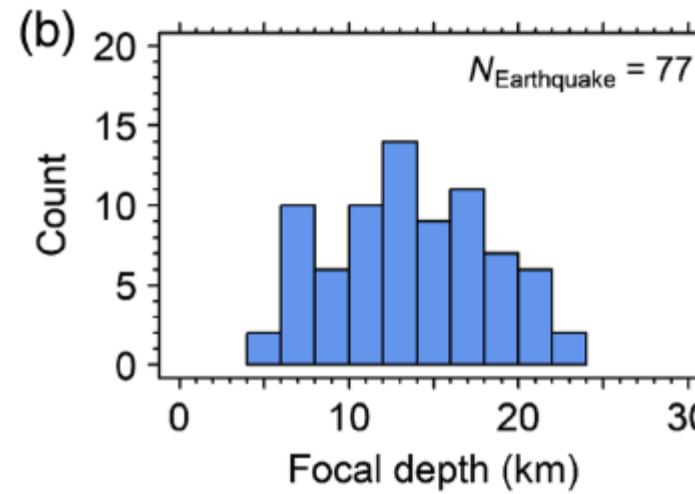
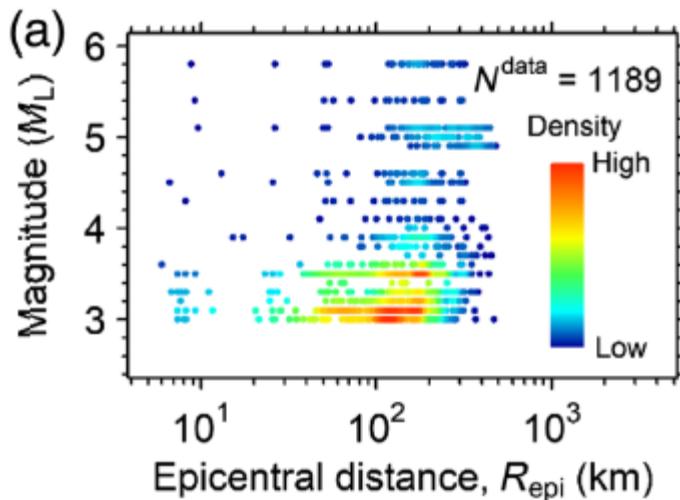


Low-to-Moderate  
seismicity

Seo et al. (2021)

# Database

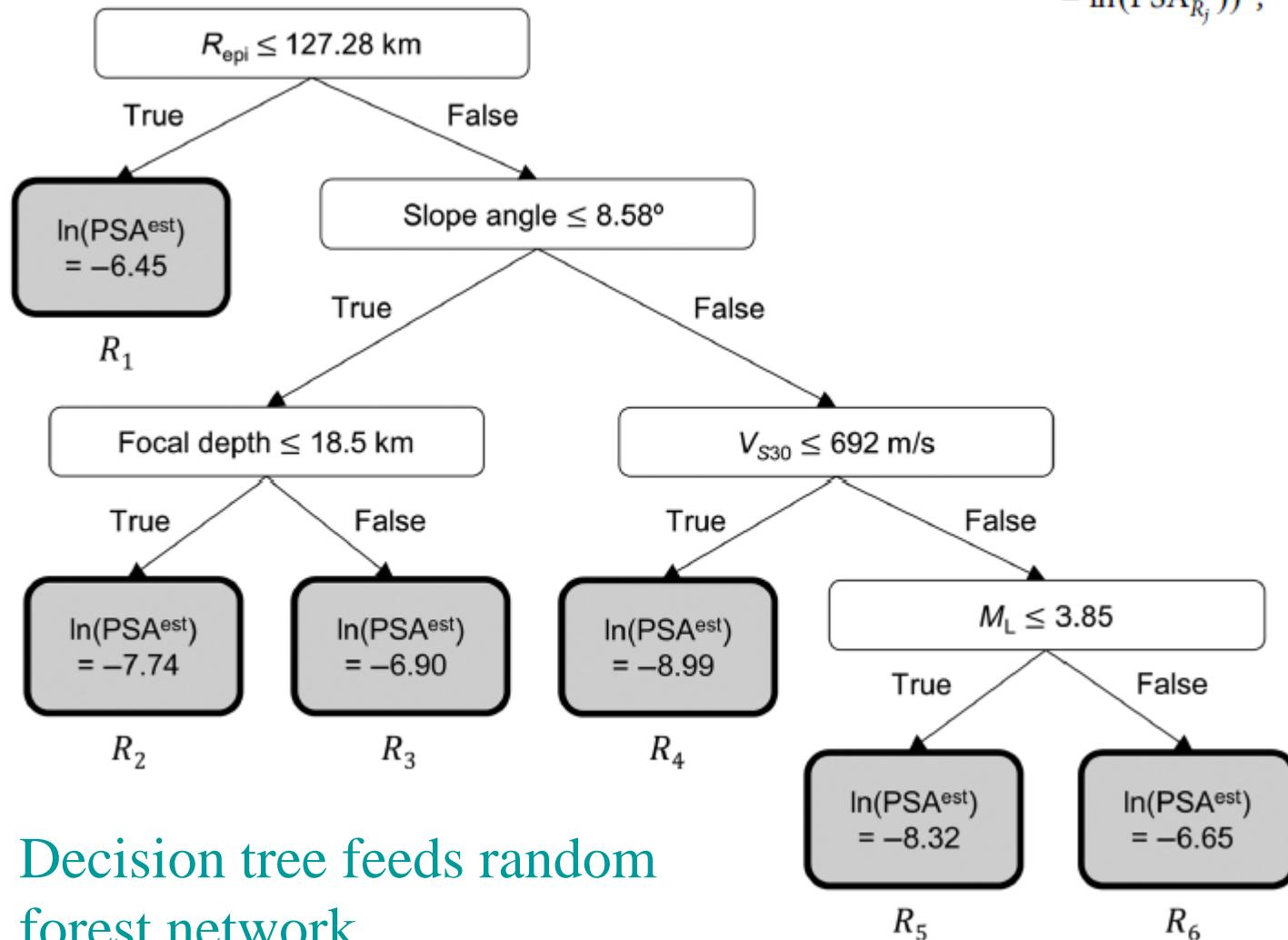
50 KMA stations: EW & NS records for 77 events, with two recent events.



Two moderate events:  
Gyeongju 2016 M 5.8  
Pohang 2017 M 5.4

# Logic-tree approach

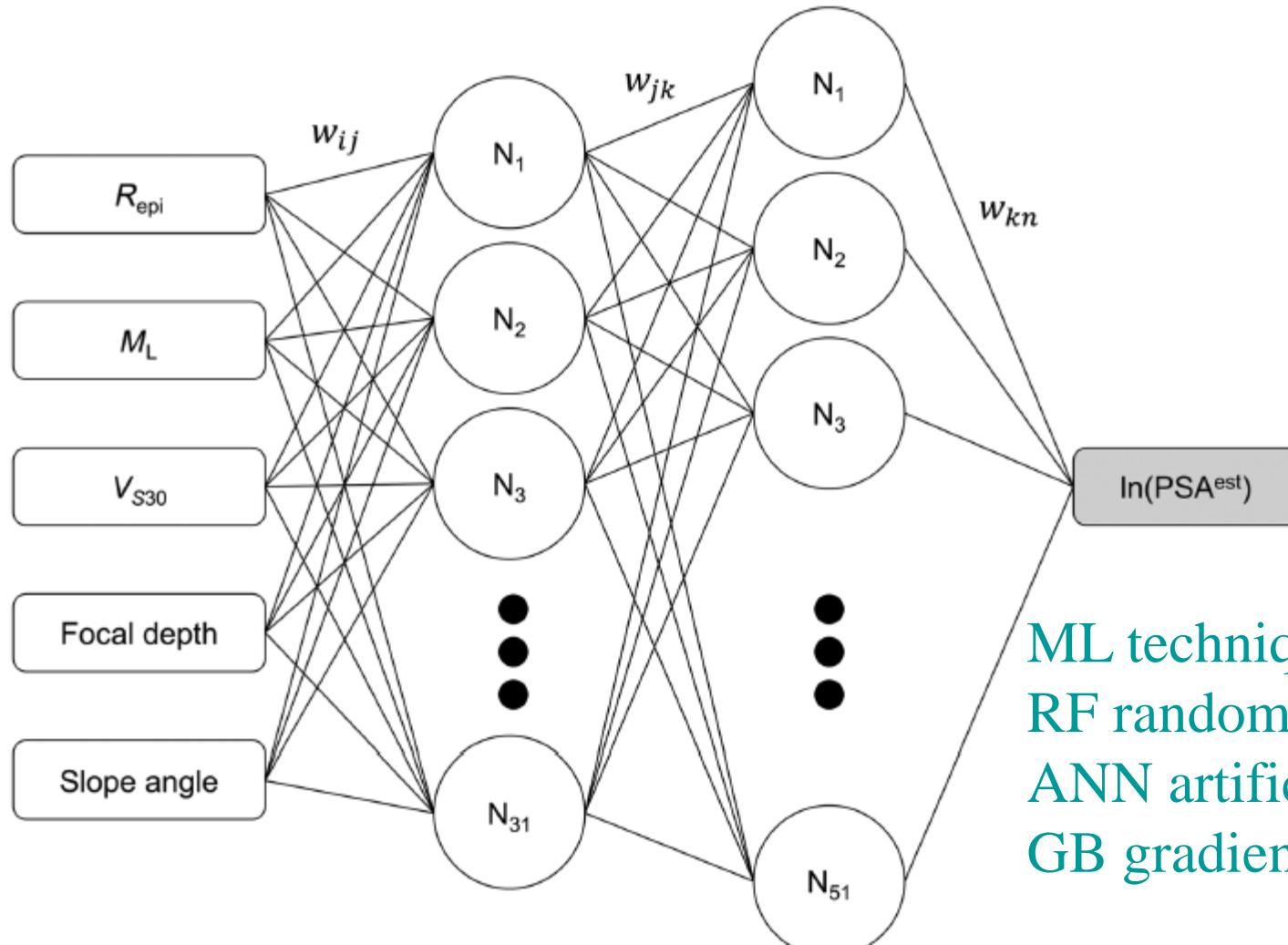
$$\text{MSE} = \frac{1}{n} \sum_{j=1}^J \sum_{i \in R_j} ((\ln(\text{PSA}_i^{\text{mea}}) - \ln(\text{PSA}_{R_j}^{\text{est}}))^2,$$



Decision tree feeds random forest network

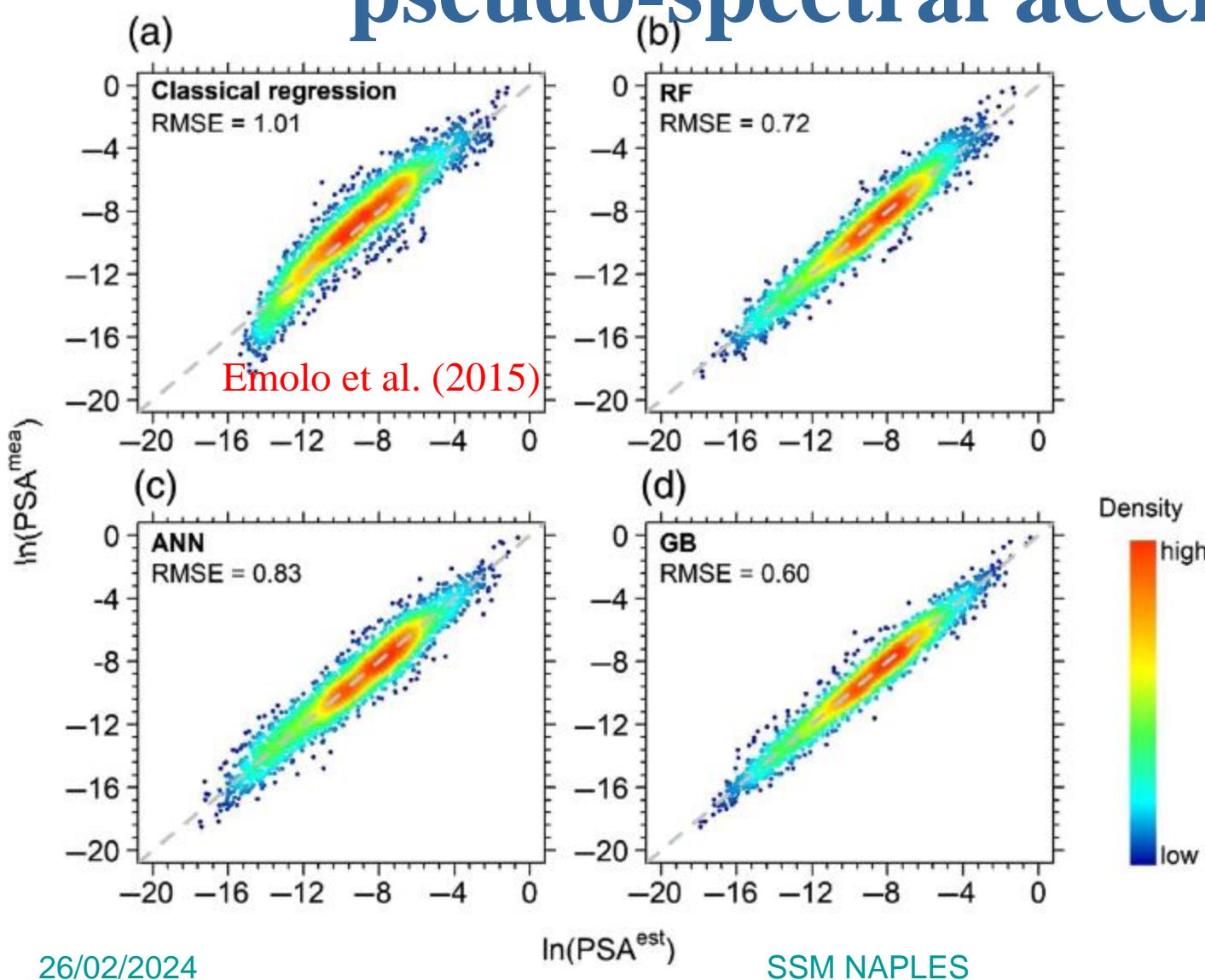
# Machine-learning techniques

Input layer	Hidden layer 1	Hidden layer 2	Output layer
5 input nodes	31 hidden nodes	51 hidden nodes	1 output node

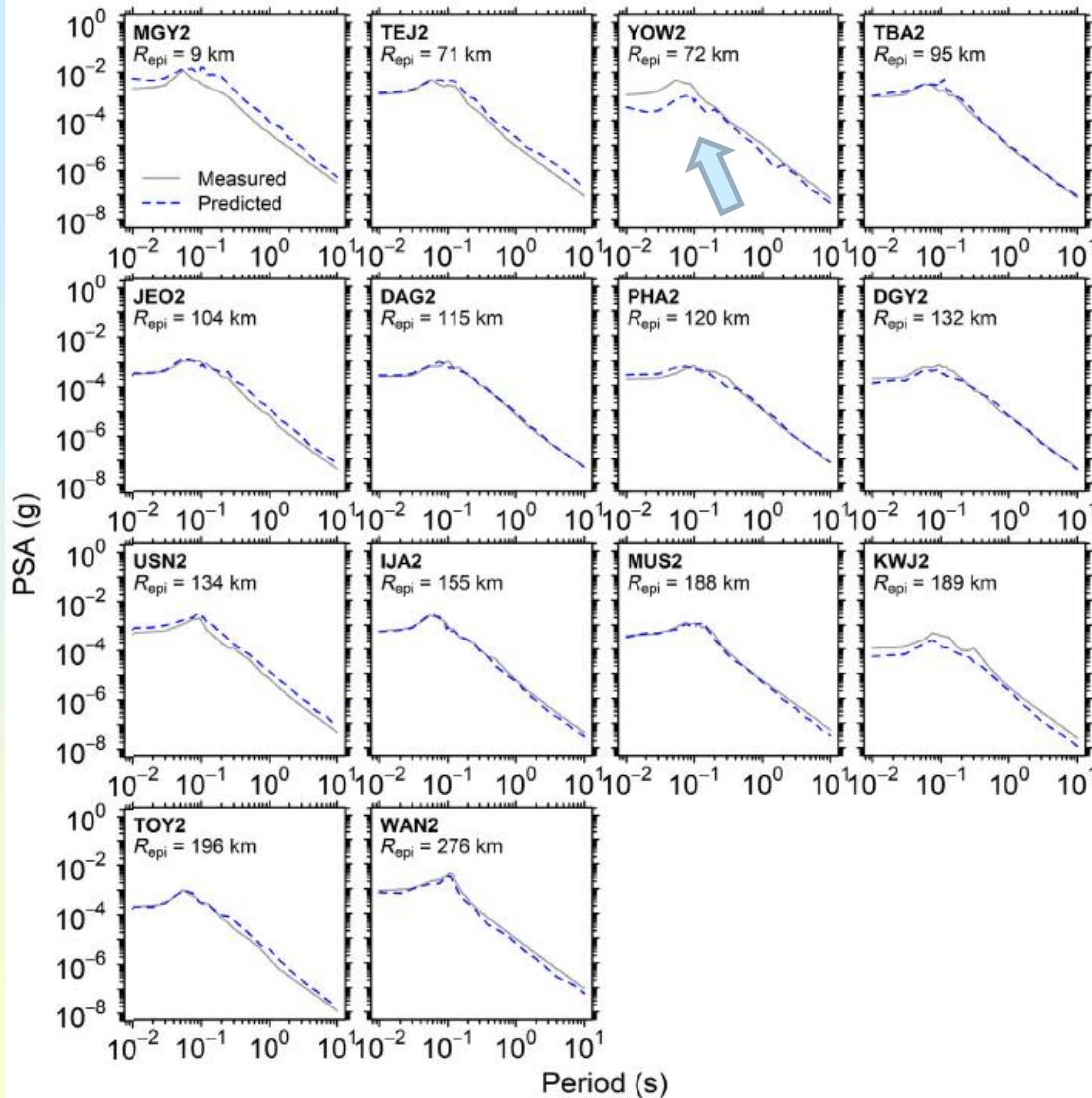


ML techniques  
RF random forest  
ANN artificial NN  
GB gradient boosting

# Measured versus estimated pseudo-spectral accelerations



# Application to real quakes (2020)



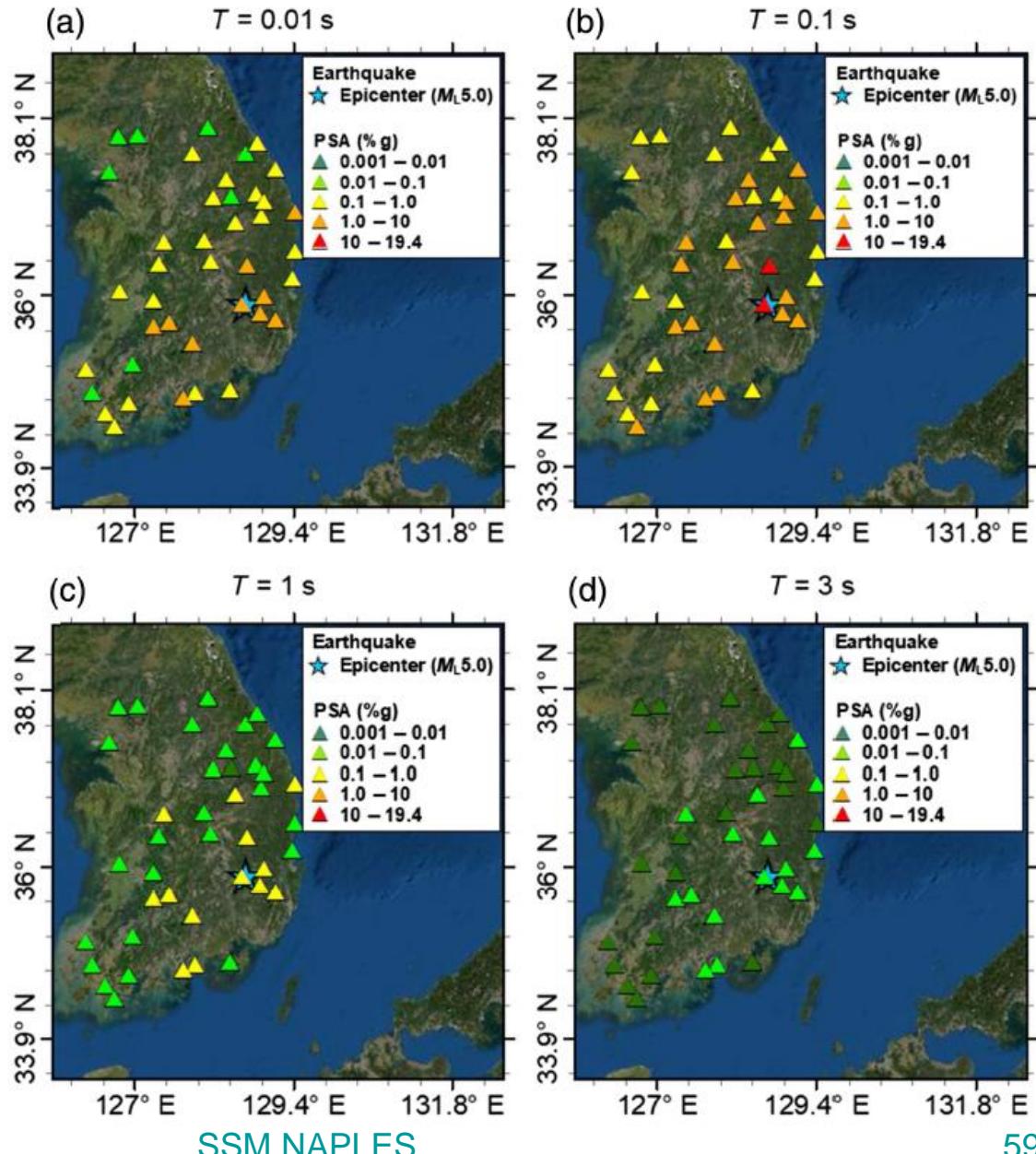
Machine-learning strategies often overcome standard regression analysis for a M<sub>l</sub>=3.2 earthquake 30/01/2020.

Other (3) events have been predicted as well.

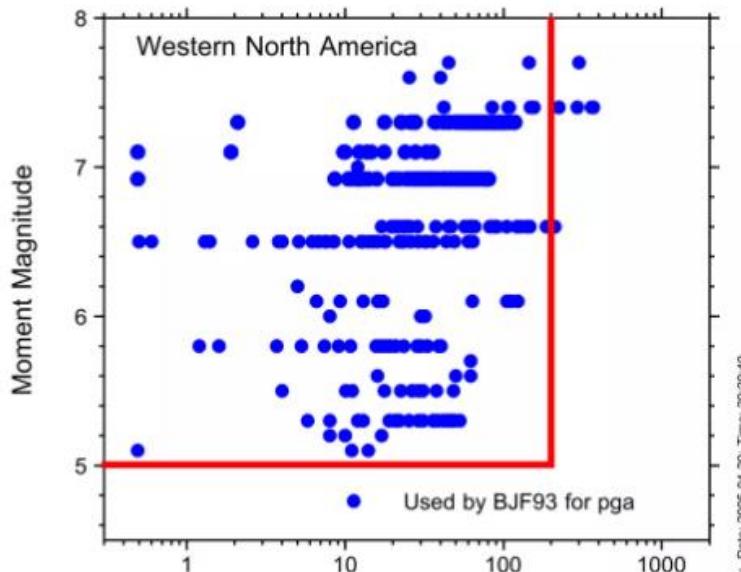
# Earthquake scenario

Influence of the period!  
(see # with Mexico basin)

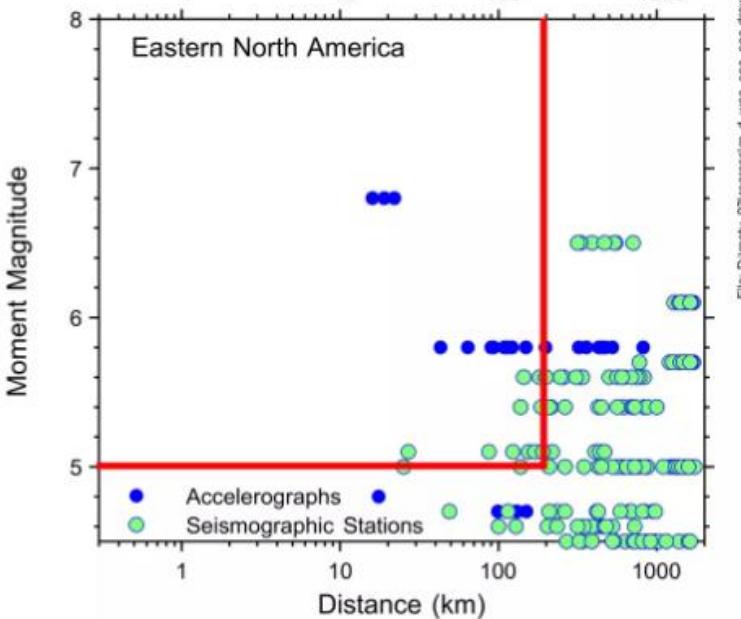
Meaning of T=0.01s!



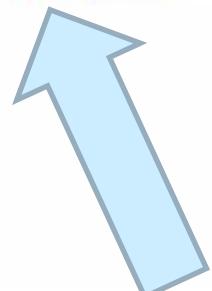
# Adequate databases



Observed data adequate  
for regression except  
close to large 'quakes



Observed data not  
adequate for regression,  
use simulated data



# Summary

GMPE

When have data (rare for most of the world):

- Regression analysis of observed data using specific equations
- Machine-learning approaches (new!)

When adequate data are lacking:

- Regression analysis of simulating data (PDE or PDE-Empirical Green function) and ML option (new!)
- Hybrid methods capturing complex source effects from observed data.

# Difficulties

- 1) Consistent differences and larger variabilities in ground motions for small earthquakes
- 2) Decreasing increments at higher magnitudes
- 3) Amplitudes from small-magnitude events decay more rapidly with distance
- 4) Overestimation of « local » ground motion when using GMM derived from larger events « abroad »
- 5) Influence of the style-of-faulting adjustments

# Simulation-based Ground Motion Estimation?

Deterministic and stochastic models

Generic site conditions and generic crustal model

To be consistent with strong motion data used in the empirical regressions

not a new idea but increased interest nowadays, thanks to more realistic crustal models and computer-simulation tools.

# Focusing interest for realistic wave propagation

Ad.

## Physics-Based Ground Motion Modeling

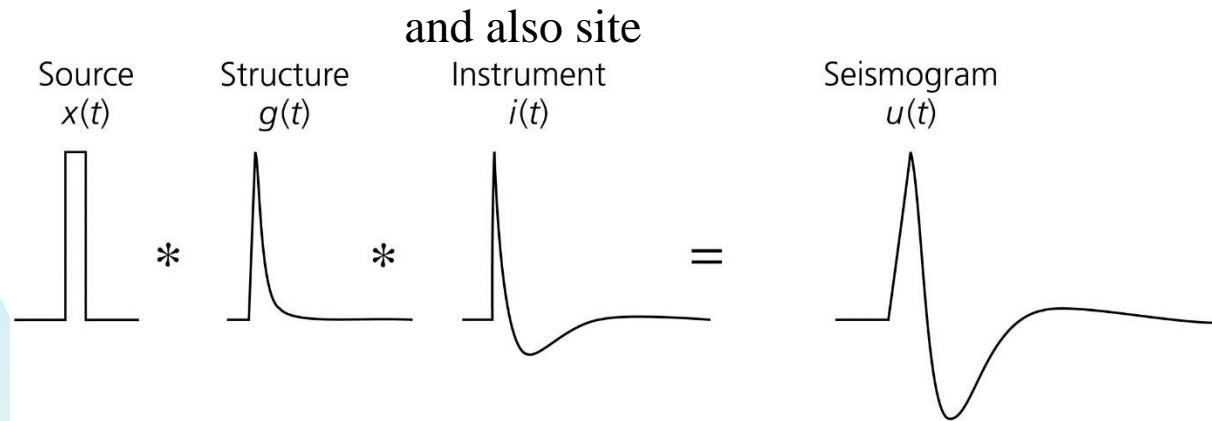
Join us in Vancouver in 10-13 October 2023 for a new SSA conference on regionalized, empirical and physics-based ground motion modeling, co-sponsored with the Seismological Society of Japan.

We're looking forward to sharing new research and fostering a lively discussion about the ways the field is expanding.

## Format:

Modern ground-motion modeling for improved source physics and hazard uses both simulations and empirical data for quantitative prediction of ground motions. Ergodic models that grouped similar tectonic regions around the world to make use of large data sets now share the field with spatially varying models which harness the knowledge from ergodic models but are specific to a region. At the same time, physics-based simulations that have often focused on a single region, fault or earthquake are now broadening their application to regions or faults not previously considered.

# Ground motion: three contributions



$$u(r, t) = i(t) * \iint G(r - r'; t - t') x(r', t') dt' dV'$$

How to estimate the Green function (propagation component)?

# How to estimate more accurately the propagation effect

- Ad hoc « simple » analytical formulae
  - ◆ Used in PSHA (probabilistic seismic hazard assessment)
- Deterministic simulations
  - ◆ Valid for low frequency for known models!  
(Quantitative seismic hazard assessment-QSHA)
- Empirical Green Function (EGF)
  - ◆ Valid where small-event data are available
- Mixed strategy
  - ◆ Combining both EGF and QSHA

# Deterministic approach

## Wave propagation simulation

Ingredients :

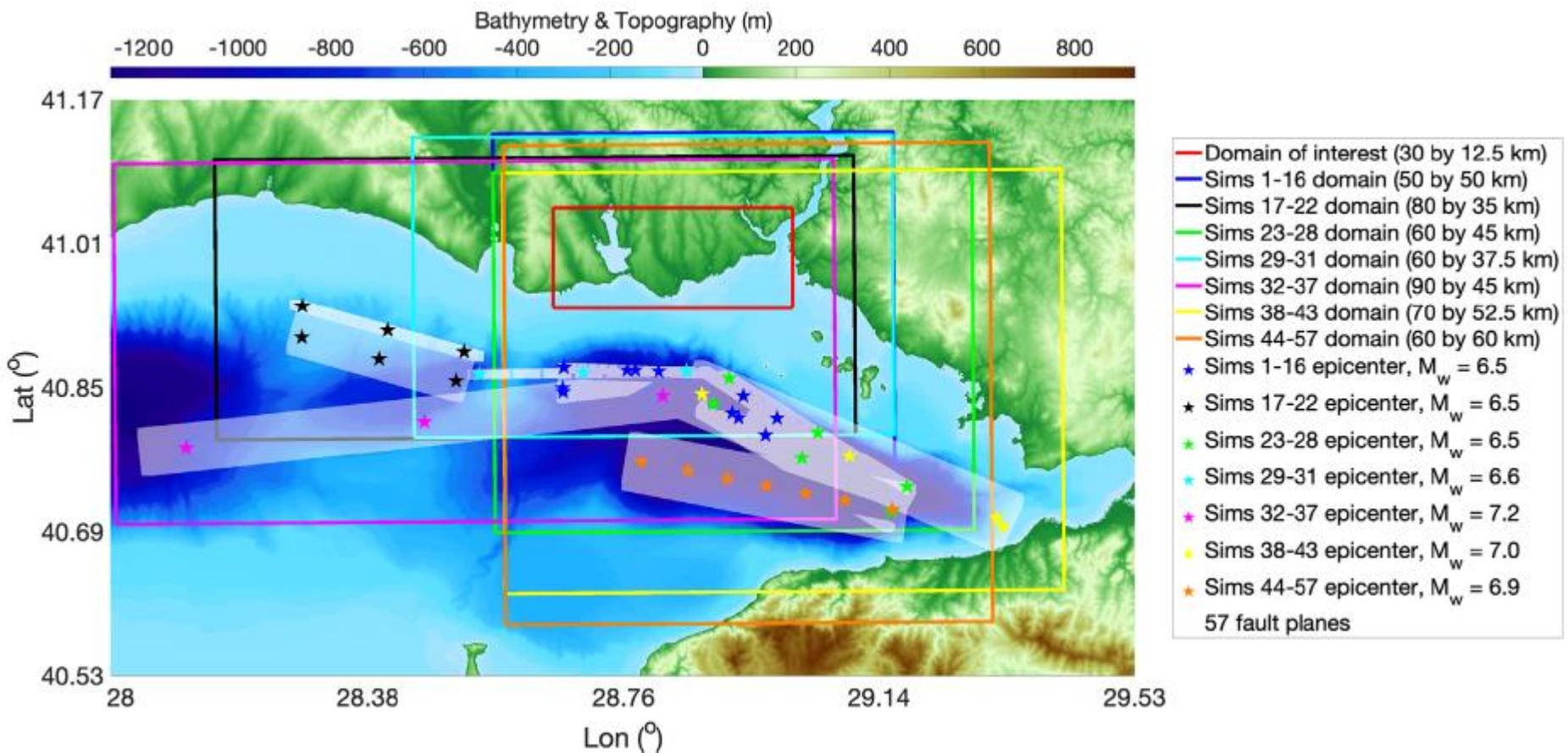
Velocity structure (spatial resolution ?)

Understanding wave propagation

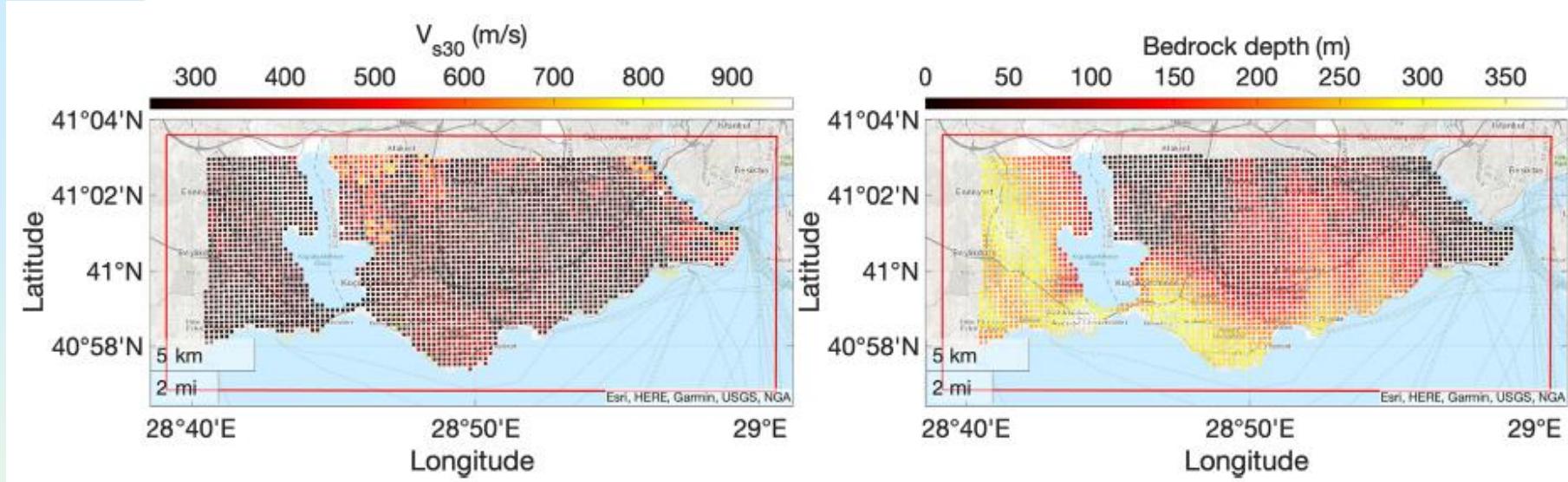
Modeling tools (computer resources)

# Istanbul Ground Motion Simulation

Zhang et al. (2022)

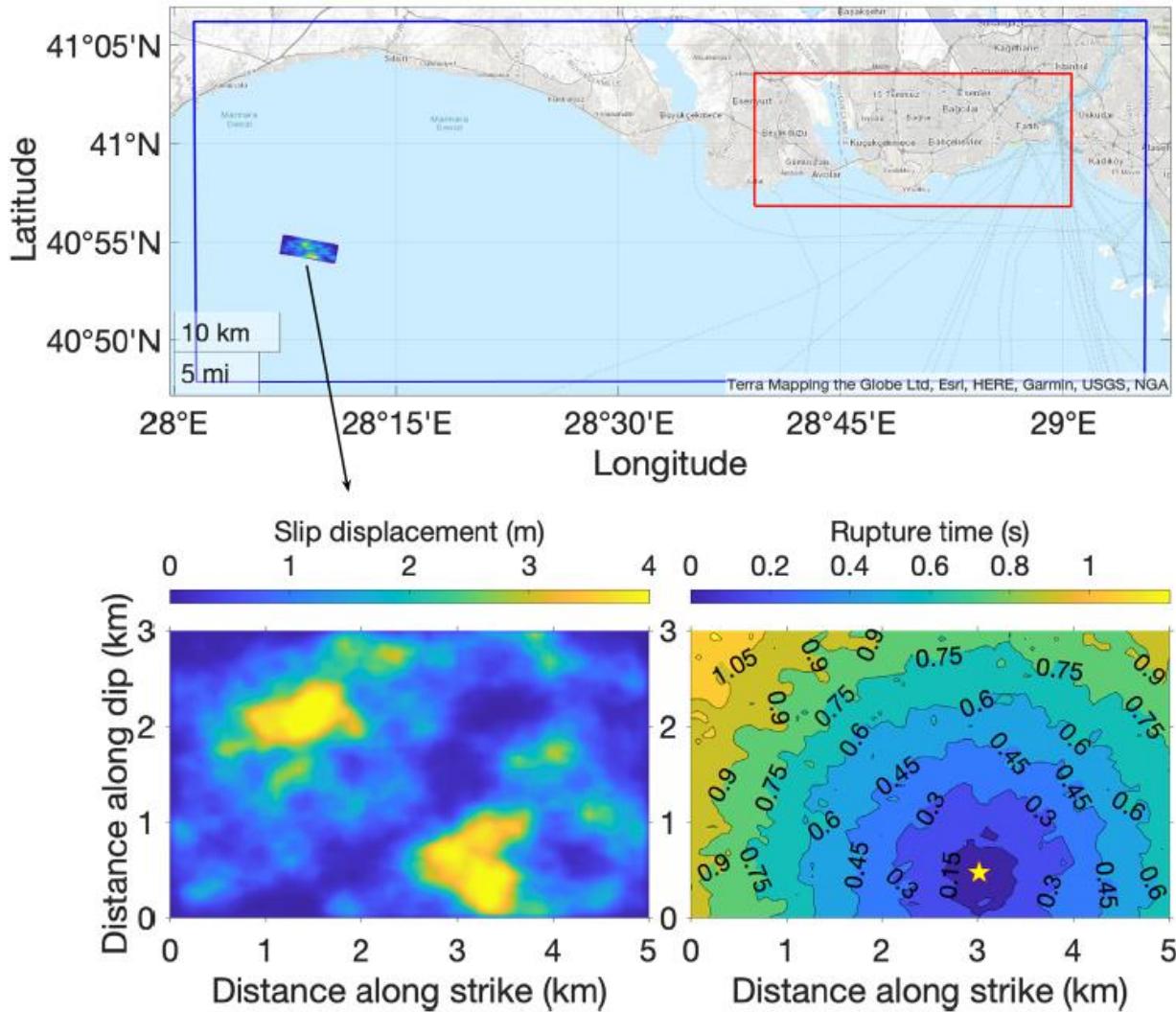


# Mixed layered+3D local model

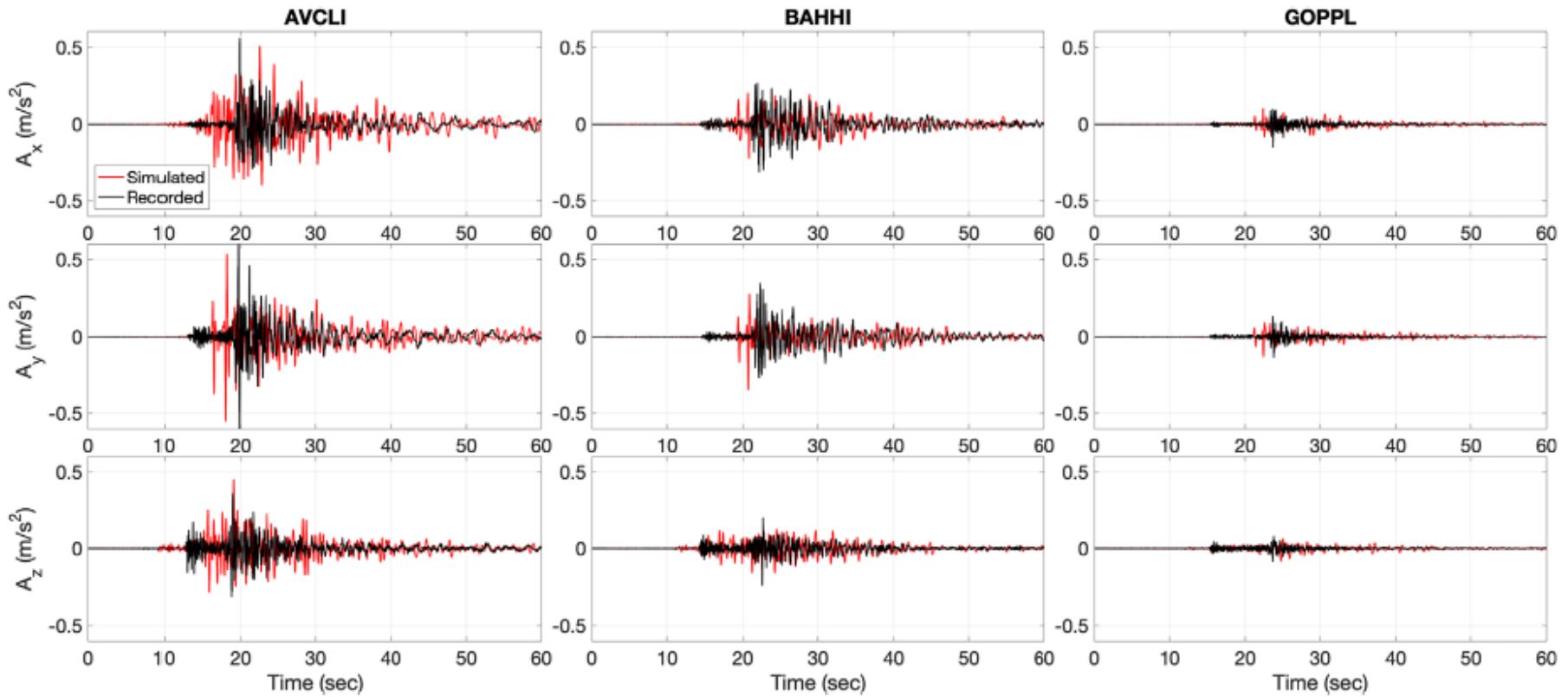


Depth at the surface of each soil layer (m)	Density (kg/m <sup>3</sup> )	$V_s$ (m/s)	$V_p$ (m/s)	$Q_s$	$Q_p$
0	1800	800	1600	80	160
300	2000	1000	2200	100	200
1000	3600	2250	2300	225	450
2000	4000	2500	2350	250	500
3000	4320	2700	2400	270	540
4000	4640	2900	2450	290	580
5000	5770	3490	2600	349	698
10000	6390	3500	2700	350	700
20000	6790	3920	2800	392	784

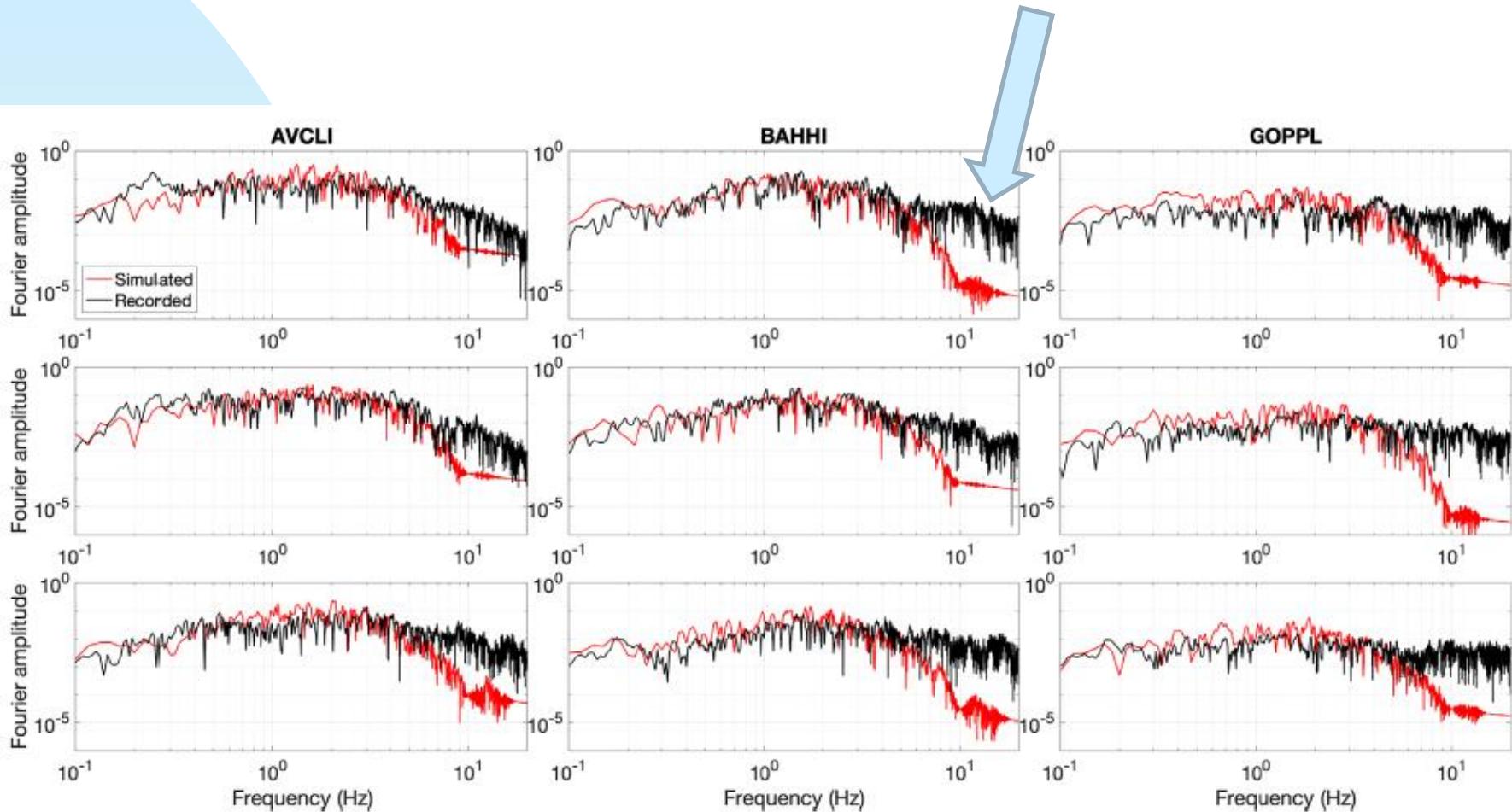
# Extended source



# Synthetic versus real records



# Synthetic versus real spectra





# Digression to

## EGF...

or

## Stochastic strategy...

# Limitations of deterministic approach

Challenging recovery of the small-scale velocity model : a remedy !

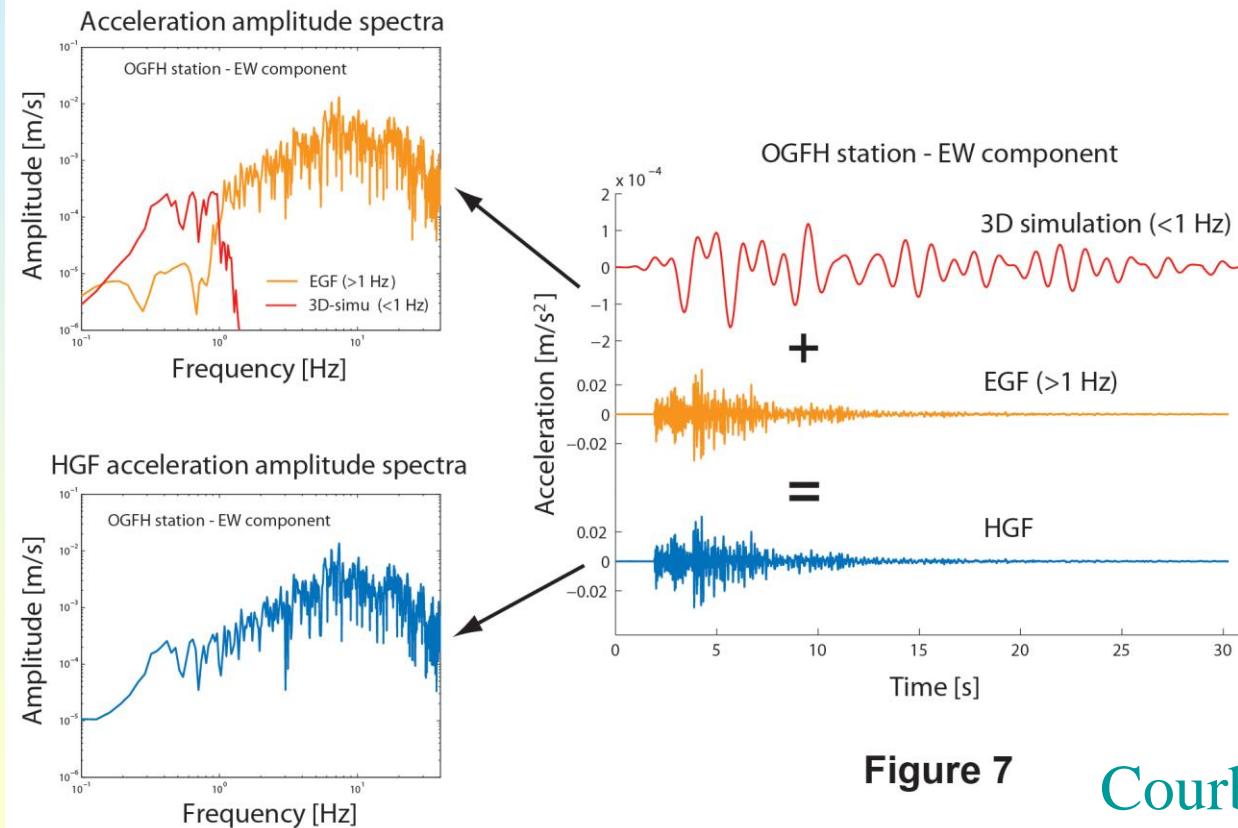
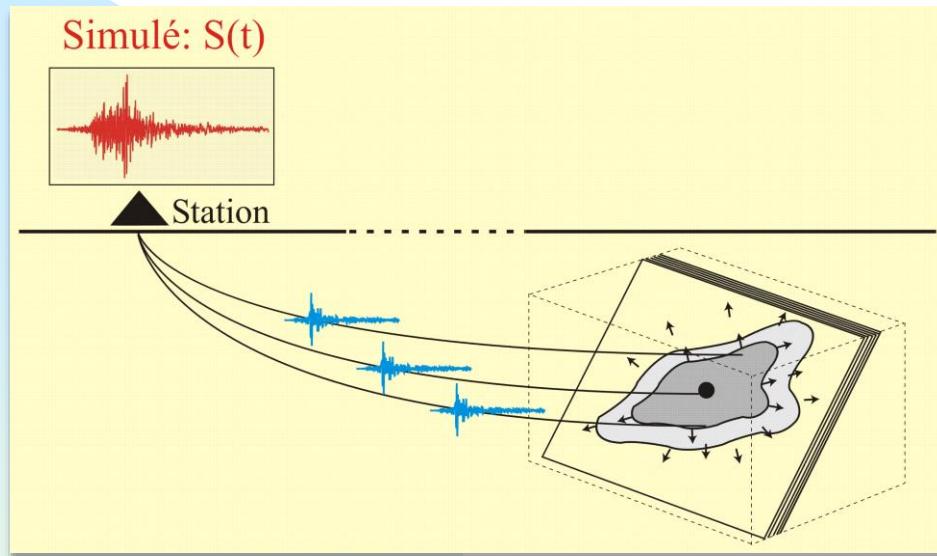


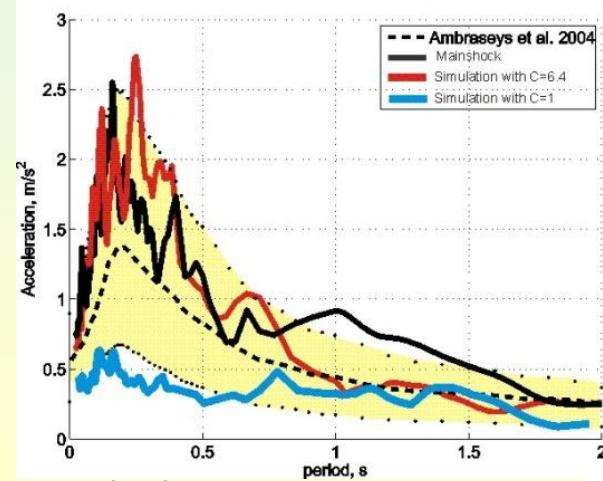
Figure 7 Courboulex et al. (1994)

# Empirical Green Function

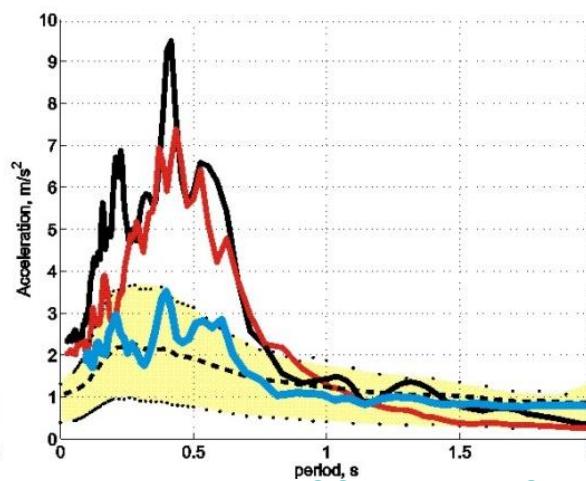


Using records from small events for the estimation of a new more important earthquake.

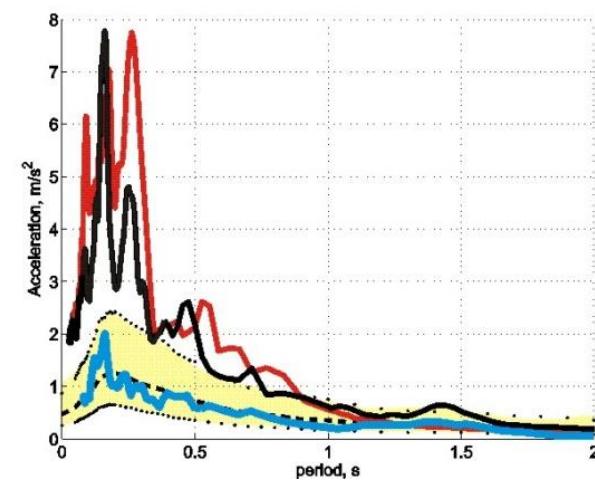
PRFA



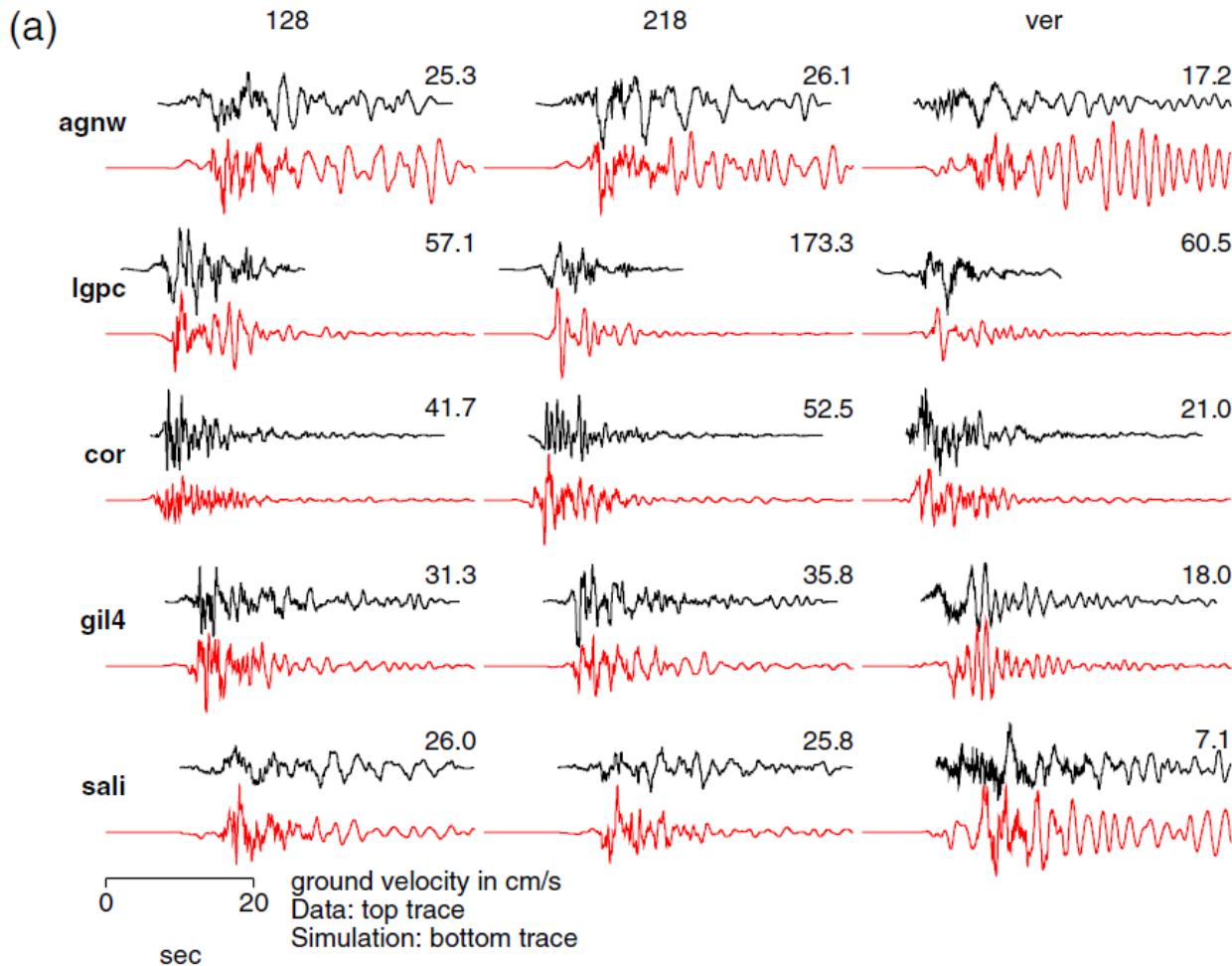
GHMA



GJYA



# (semi)-Stochastic approach

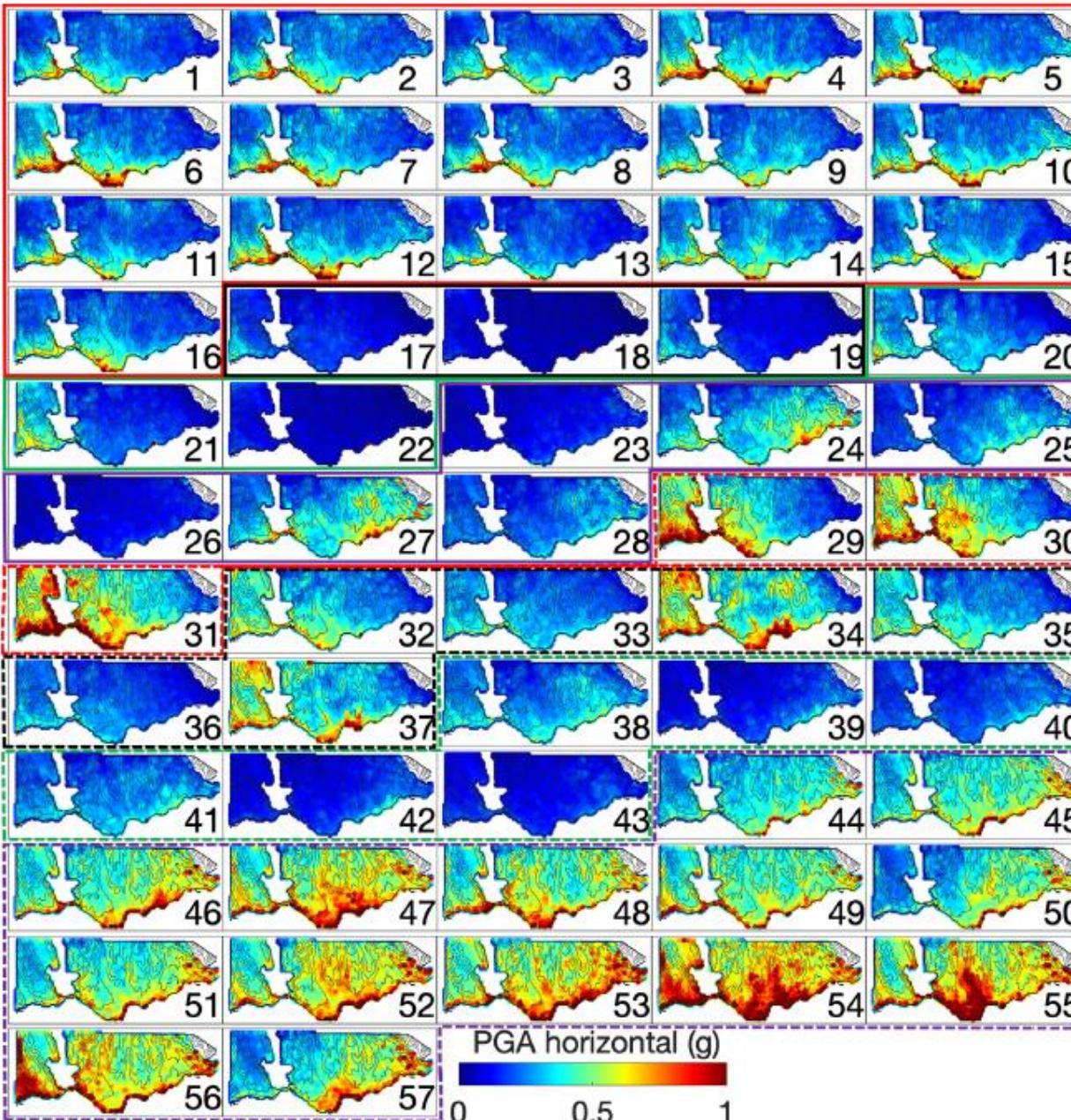


Hybrid method

Graves & Pitarka (2010)

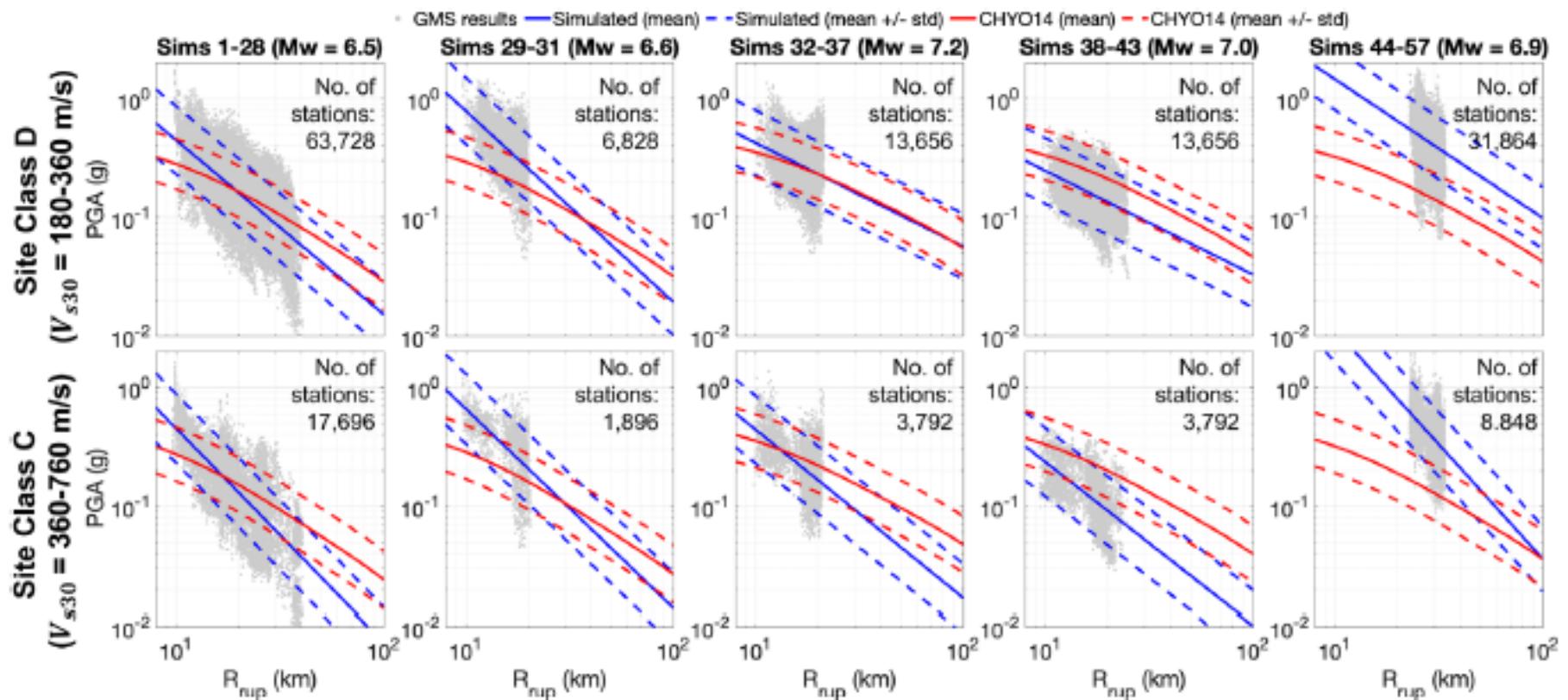
# End of digression

# Ground Motion Simulation



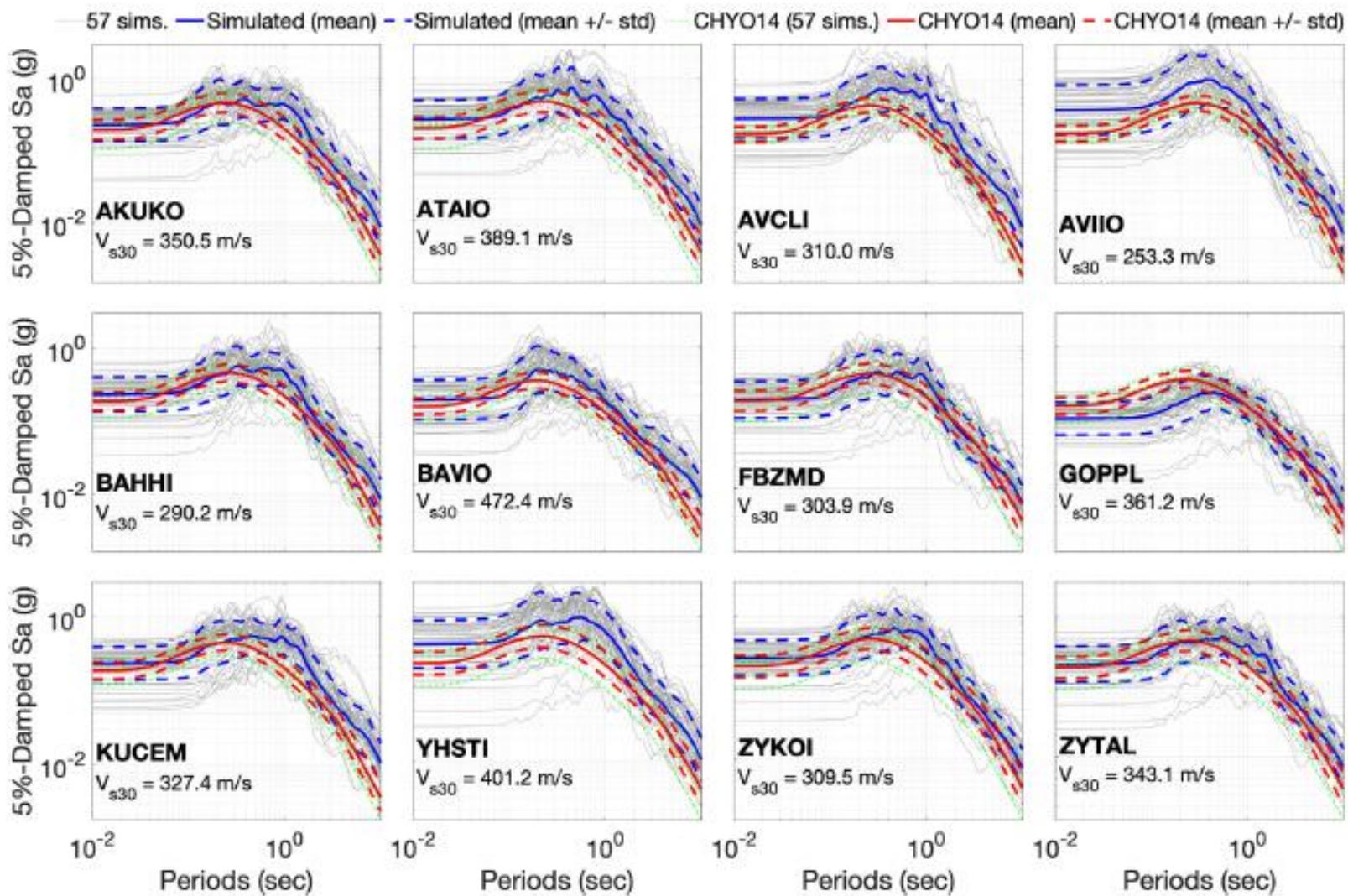
# PGA for GMPE (red) and GMS (blue)

with respect to distance



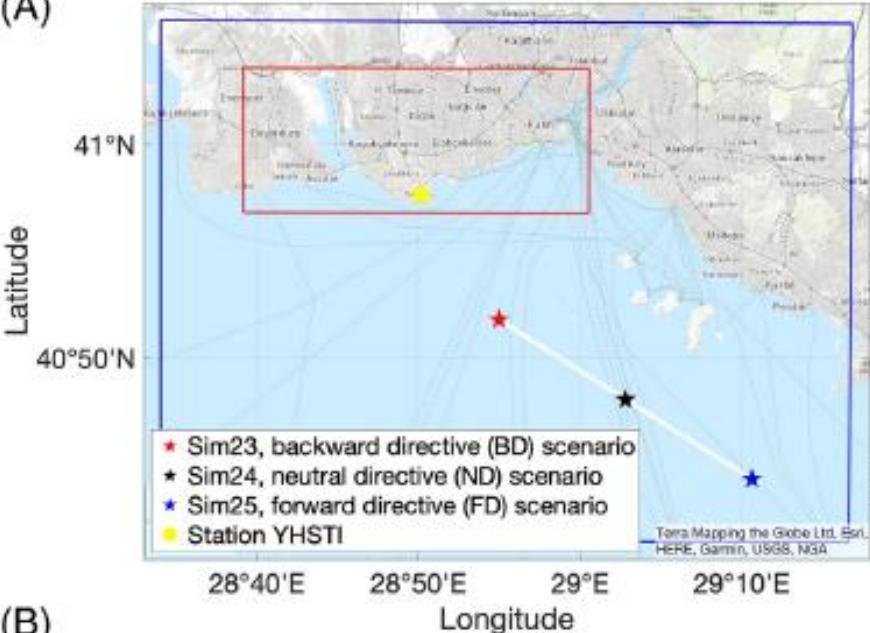
CHYO14 : GMM for Turkey (Chiou & Youngs, 2014)

# Response spectral acceleration

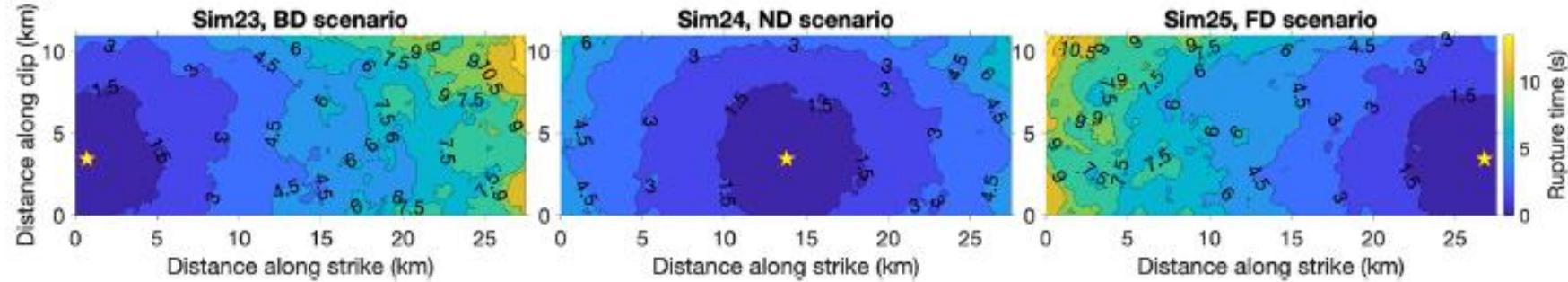


# Three different scenarios of GMS

(A)

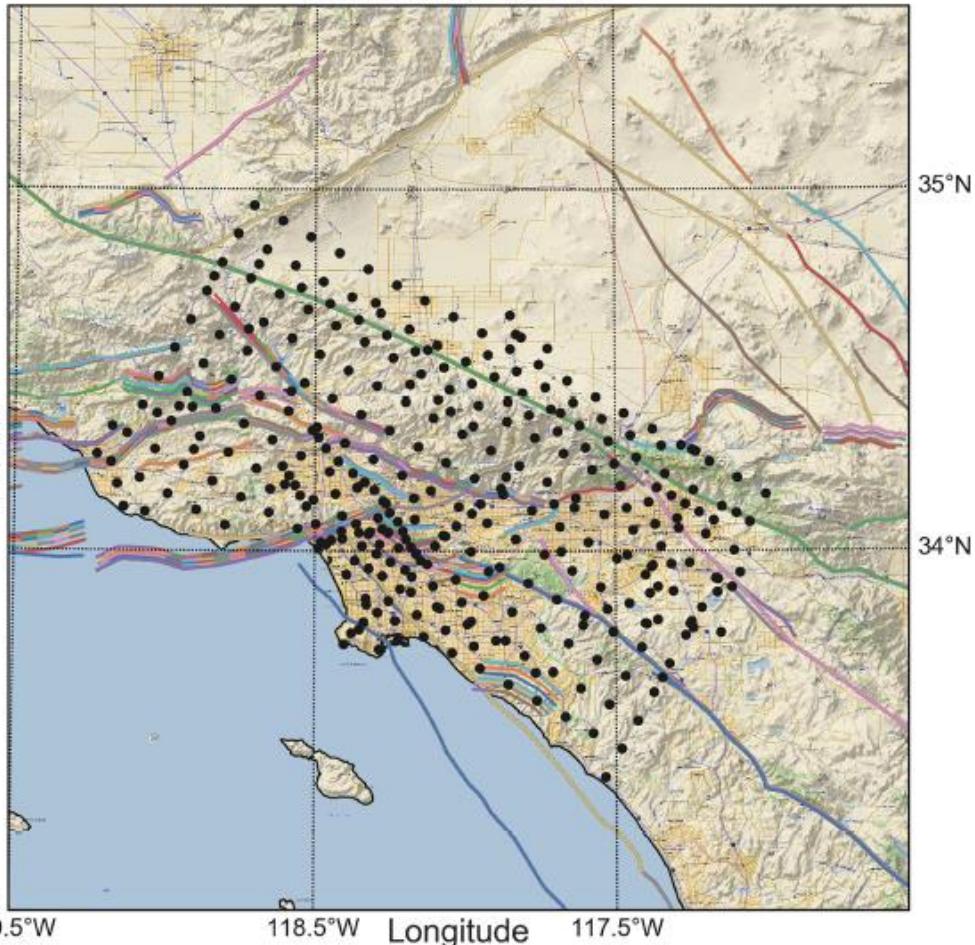


(B)



# GMPE/ML on synthetic data

Faults and Stations



~330 synthetic stations

~10000 fault geometries

SCEC resources

CyberShake simulations  
Velocity model (CVM-S4.26.M01)  
Period [0.1s-10s]

Withers et al. (2020)

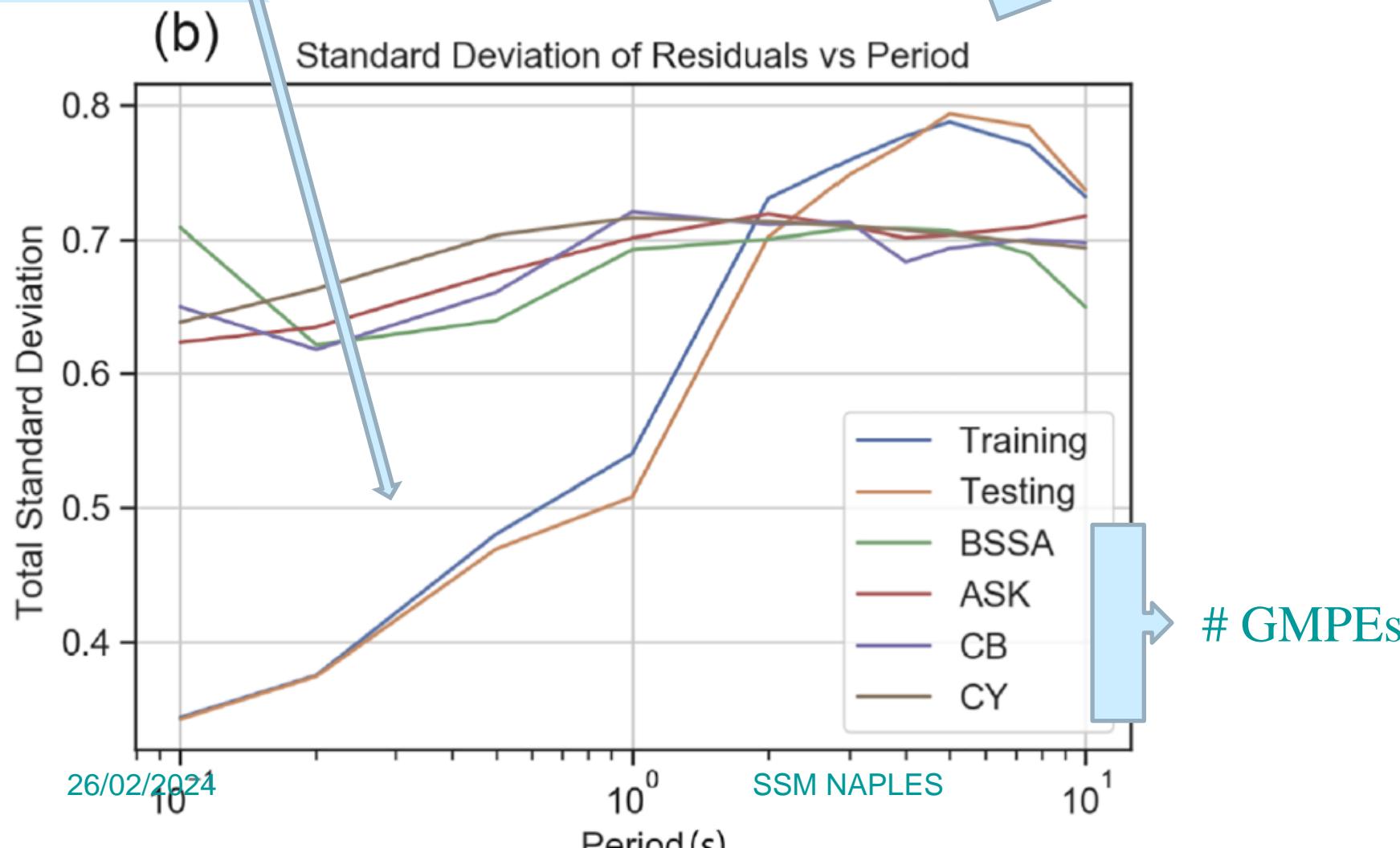
# GMPE/ML on data from simulations

Better predictability. However, not enough

model variations

(only large-scale velocity variations)

Less pertinent for  
LowFreq variability



# Soil amplification?

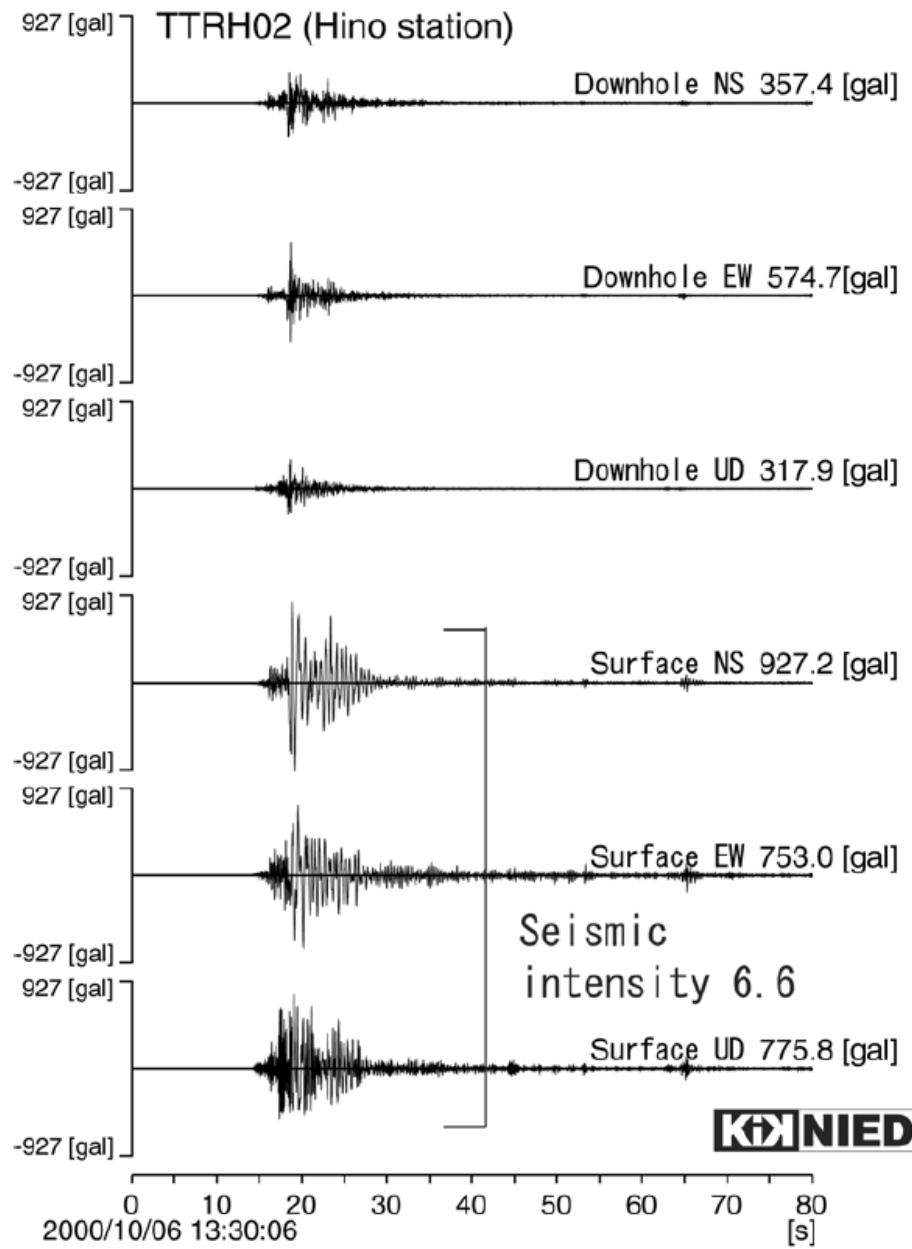
A deterministic challenge?

Limitations of models and parameters

Physics-based models ( $V_s > 500$  m/s)

Non-linear soil behavior

Prediction of soil seismic response based on  
recorded ground motions  
synthetic ground motions



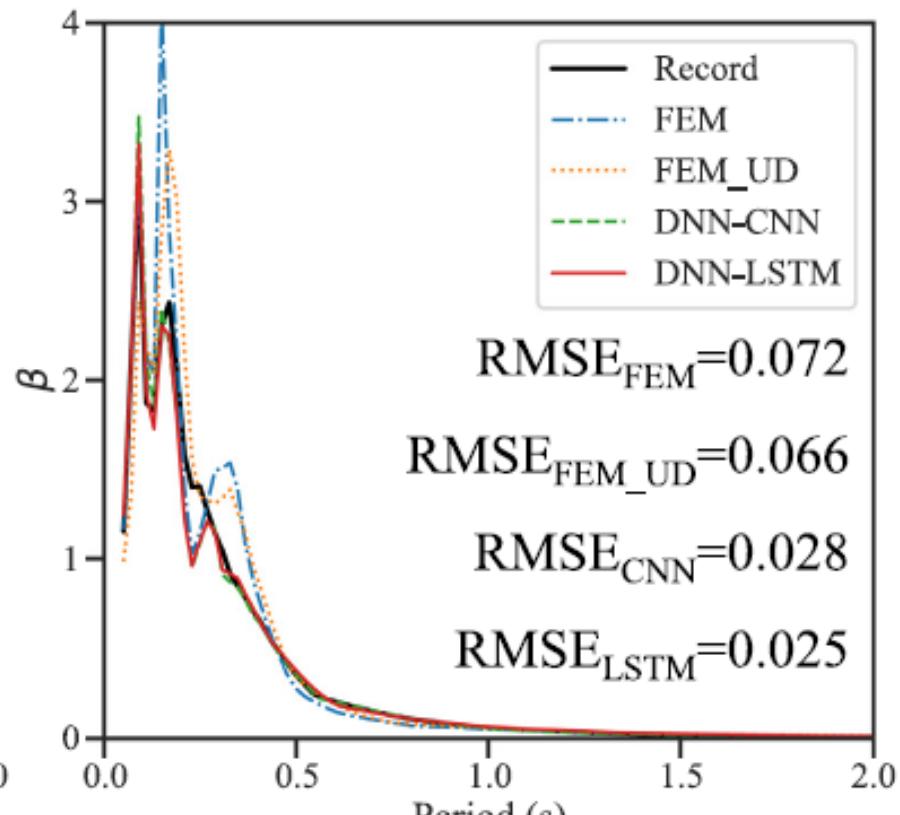
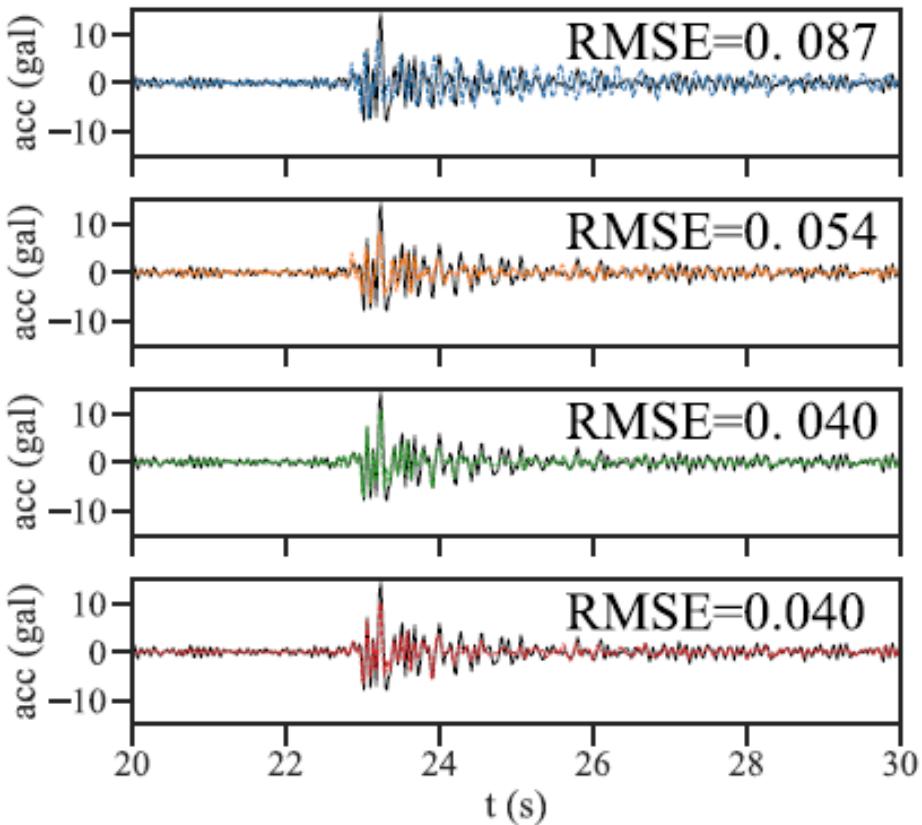
Depth (m)	Lithology	$V_p$ (m/s)	$V_s$ (m/s)
0 - 10	Weathered granite	250	170
10 - 20		460	280
20 - 30		2050	400
30 - 40		2050	600
40 - 50		3200	1050
50 - 60	Granite	4900	2600
60 - 70		4900	3000
70 - 80			
80 - 90			
90 - 100			
100			

Station  
IBRH13  
1D  
approximation  
valid

(Thompson et al., 2012)  
85

# Soil seismic response using FE methods and machine-learning approach

Station  
IBRH13



(Li et al., 2023)

# Many initiatives regarding GMS !



<https://speed.mox.polimi.it/project/>

SPEED: a high performance numerical code for seismic wave propagation

**MOX** Laboratory for Modeling and Scientific Computing  
Department of Mathematics

DICA Department of Civil and Environmental Engineering

POLITECNICO di MILANO  
Italy

Many available codes!



Do not discover the wheel again!

# Conclusion on Ground Motion Prediction

Data-driven strategies based on observed or synthetic datasets

Ad-hoc GMPE (empirical description)

Wave PDE (limitation from short-scale model variation)

Regression and/or Machine learning

Targetted model for ground motion prediction: STABLE! HOW?

**Large-scale & short-scale velocity variations !**

Remark: very # from reservoir characterization and monitoring:  
tracking fluid migration and rock multi-phasic physics

Remark: very # from seismic rupture physics

weakening zones, asperities, stress concentration

# Seismogram hierarchy!

## Hope for GM simulation

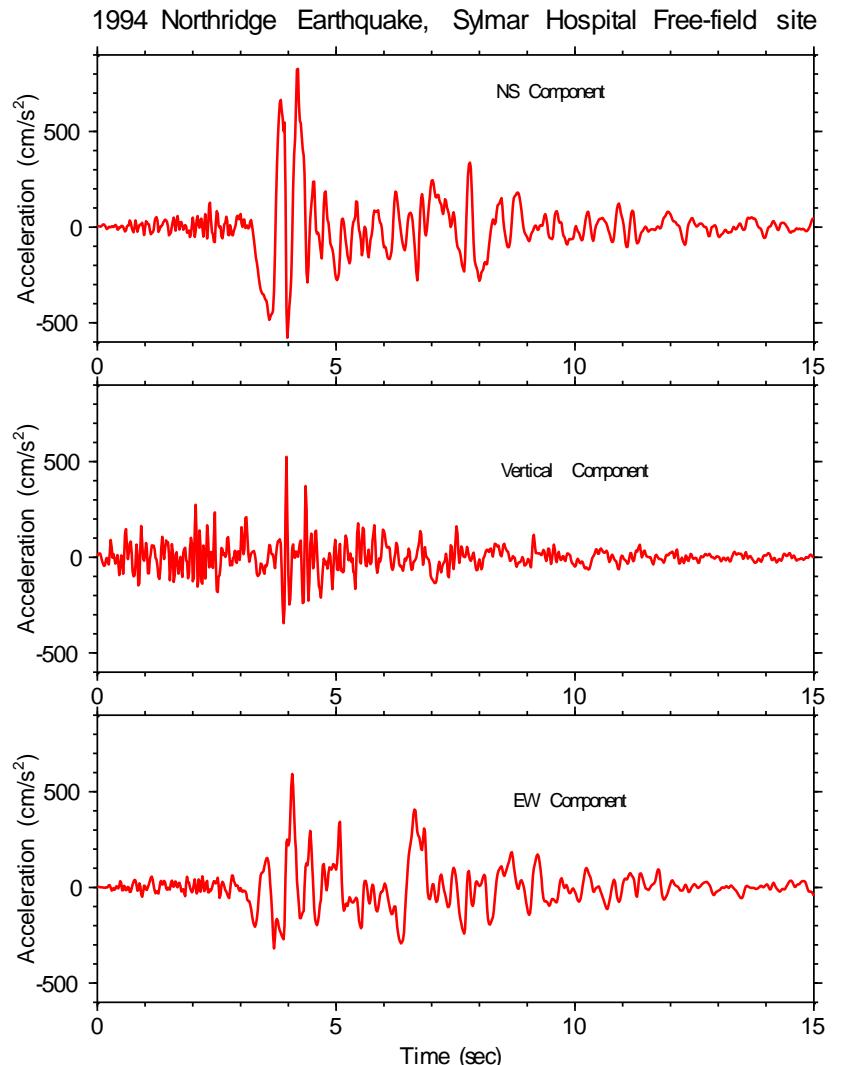
### Body-wave phases

P wave arrives before S wave. S-Trigger time = 3.2 sec, hypocentral distance between approx.  $5 \times 3.2 = 16$  km and  $8 \times 3.2 = 26$  km

P-motion much higher frequency than S, and predominately on vertical component.

Is the horizontal S-wave motion polarized?

### Surface-wave amplitudes



# Seismogram hierarchy!

## Hope for GM simulation

Body-wave phases

P wave arrives before S wave. S-Trigger time = 3.2 sec, hypocentral distance between approx.  $5 \times 3.2 = 16$  km and  $8 \times 3.2 = 26$  km

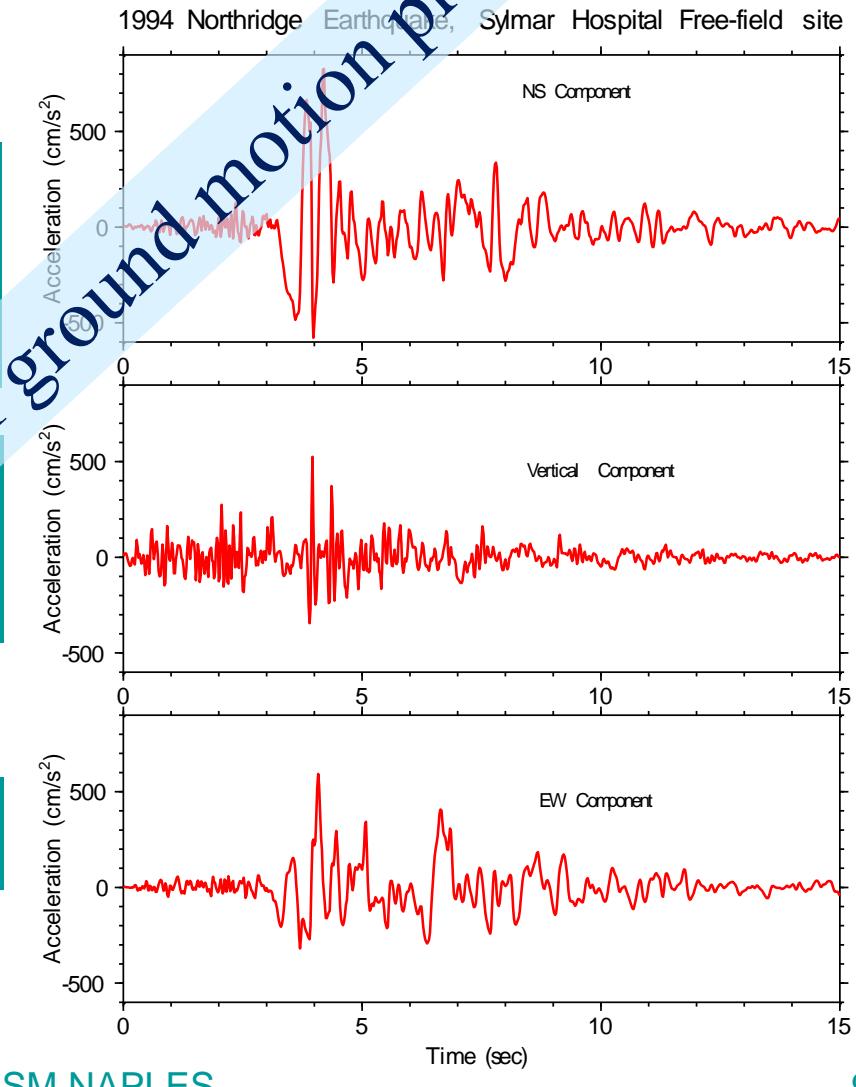
P-motion much higher frequency than S, so predominately on vertical component.

Is the horizontal S-wave motion polarized?

Surface-wave amplitudes

26/02/2024

The most constrained part of ground motion prediction



SSM NAPLES

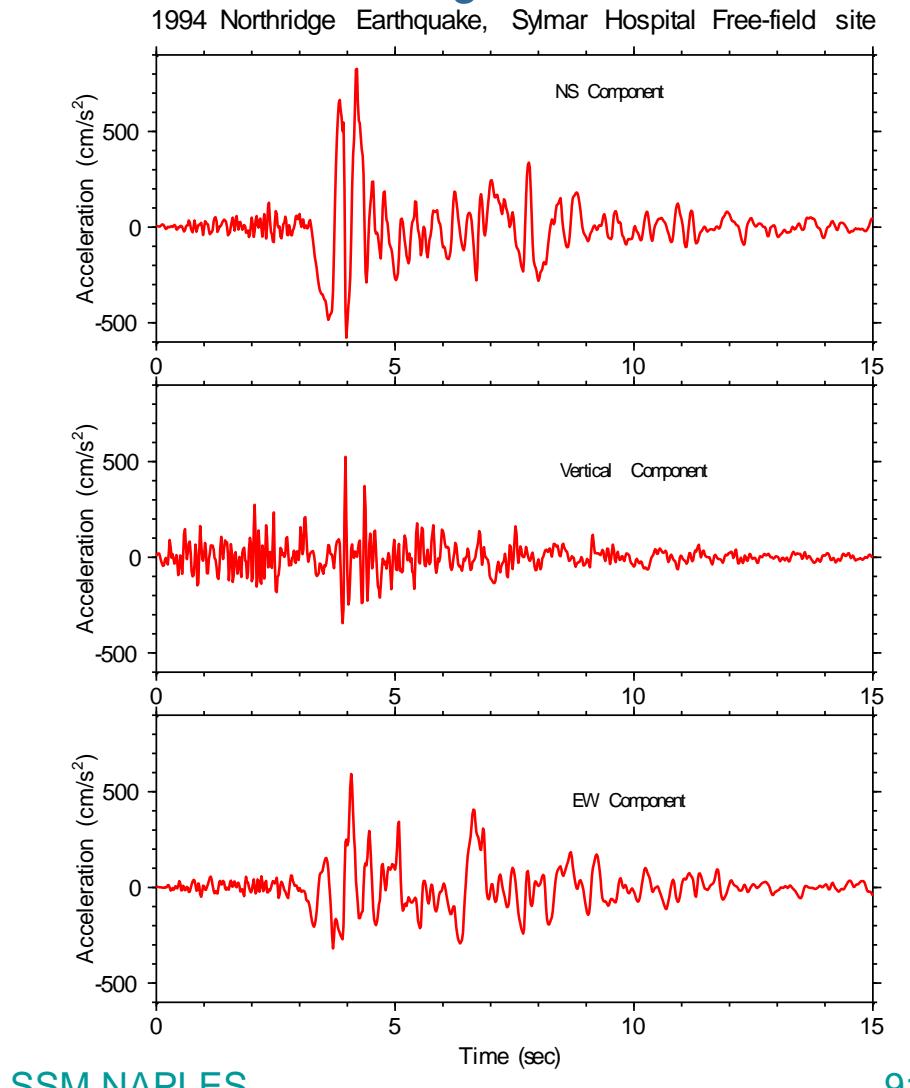
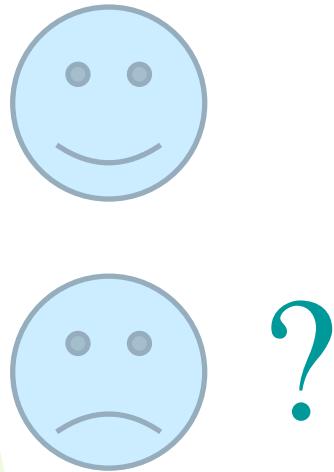
90

# Seismogram hierarchy!

## Hope for velocity model

Large-scale  
velocity model

Short-scale  
velocity model



# Seismogram hierarchy!

## Hope for velocity model

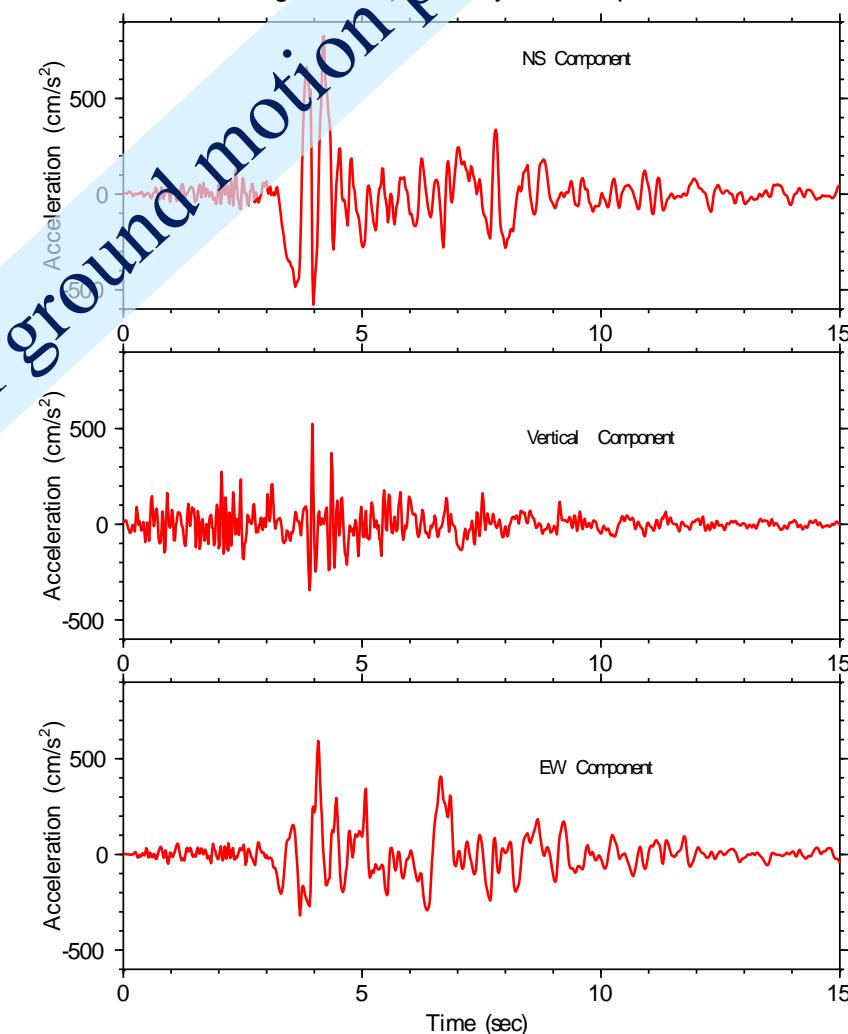
Large-scale  
velocity model

Short-scale  
velocity model

The most constrained part of ground motion prediction?

26/02/2024

1994 Northridge Earthquake, Sylmar Hospital Free-field site



SSM NAPLES

92

# Characterization of crustal models for quantitative ground motion estimation

## B – Model Design (large-scale velocity structure)

Jean Virieux

Emeritus Professor at UGA

Some slides are inspired from Seiscope Group  
(PIs Romain Brossier & Ludovic Métivier)