Characterization of crustal models for quantitative ground motion estimation

A – Ground Motion Estimation

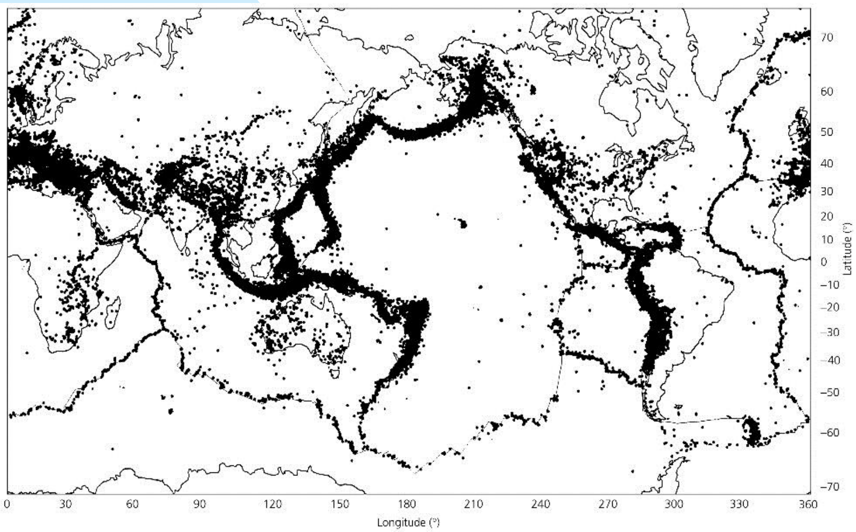
Jean Virieux

Emeritus Professor at UGA

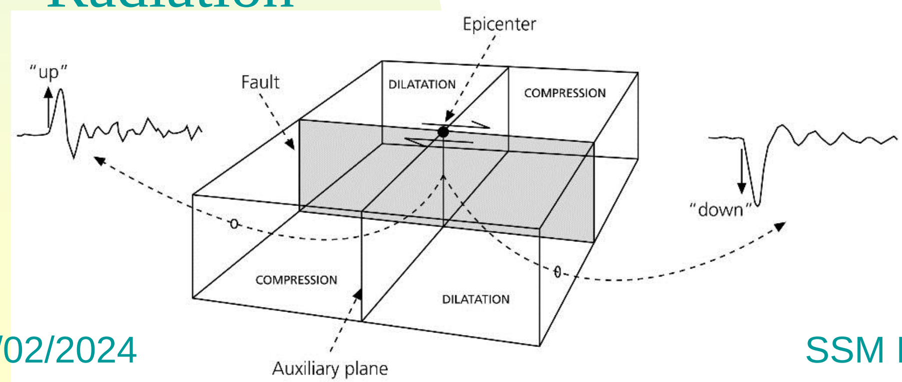
Some slides are inspired from Dave Boore's presentation and from Arthur McGarr's presentation

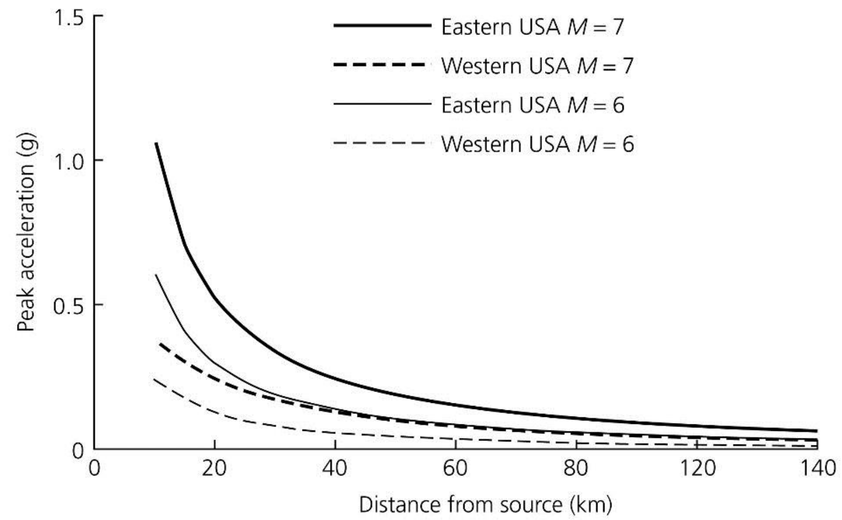
Wave propagation in the Earth
Natural events : earthquakes

Source



Radiation



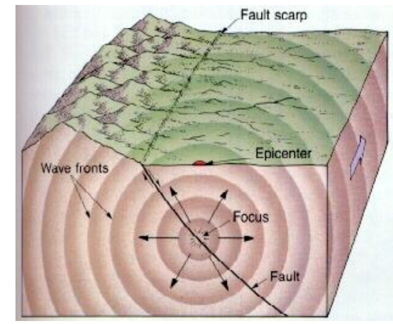


Geometrical attenuation: amplitude decreases with distance

Translucent Earth

1600 years before first sensors in Europe (XIXcentury)

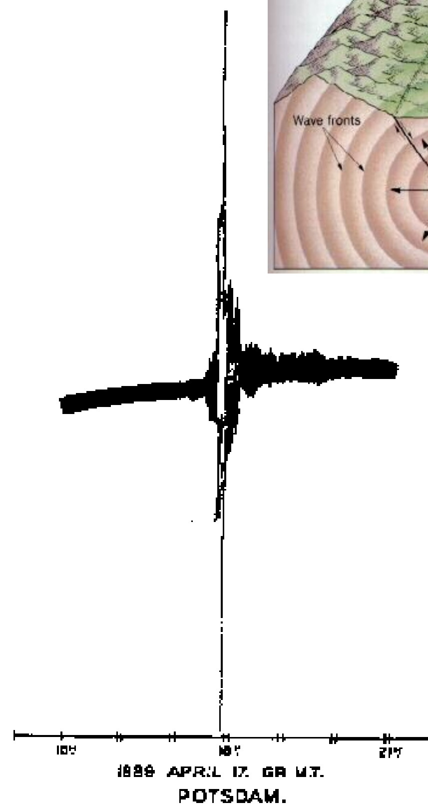
- Ground vibration away from quakes



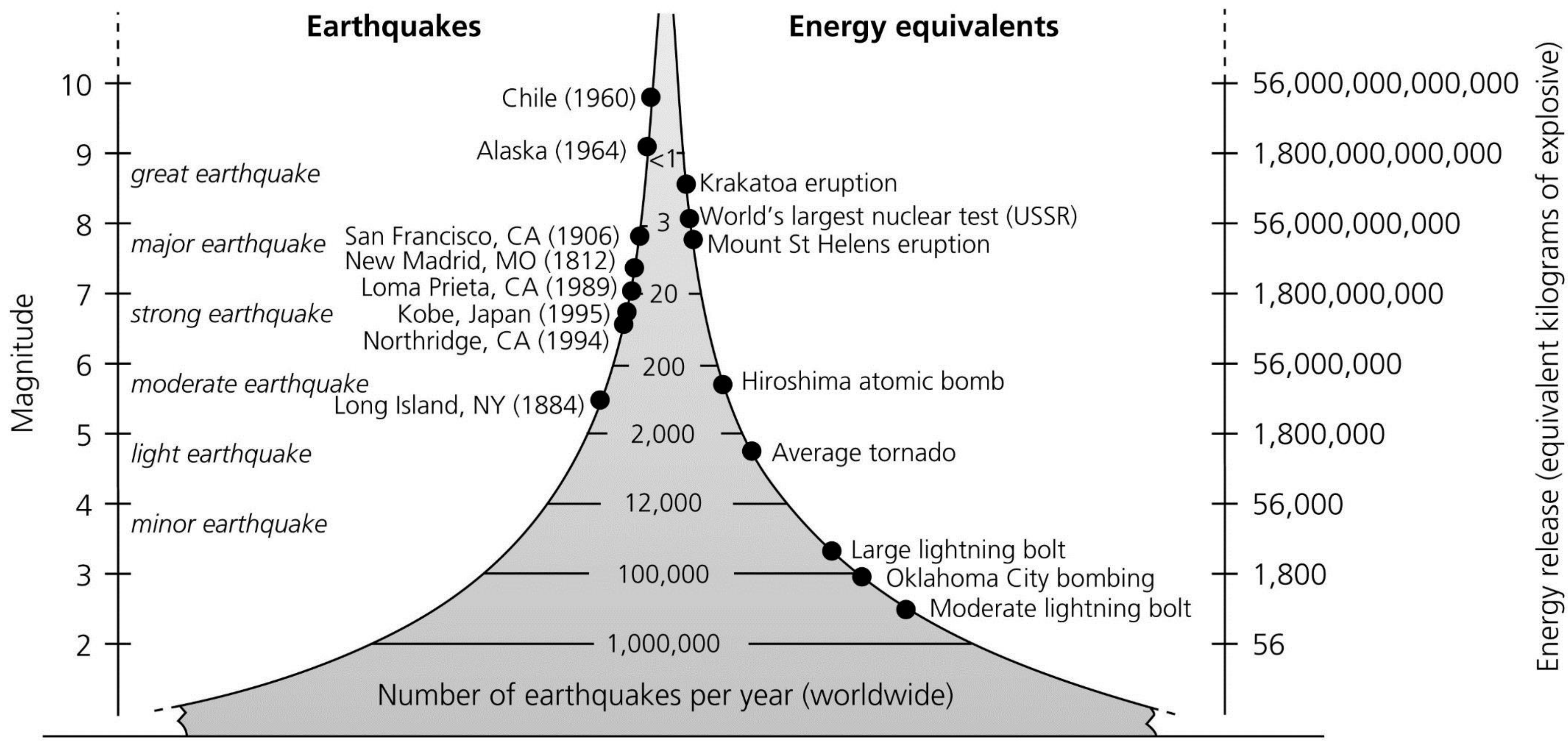
Earthquakes and local effects known for a long time

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

The modern seismology was born



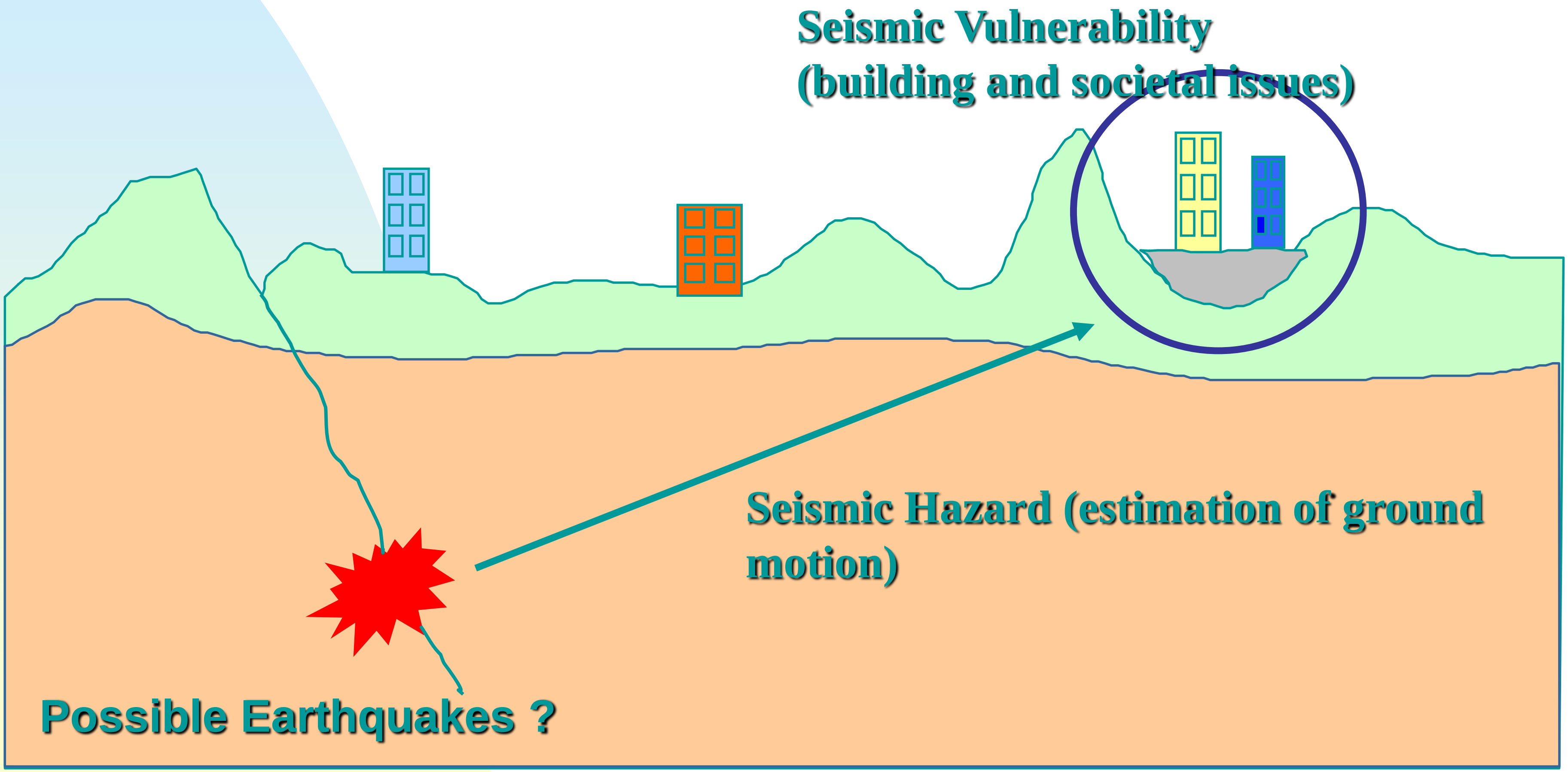
Source energy!



Estimation of magnitude is important in the second time

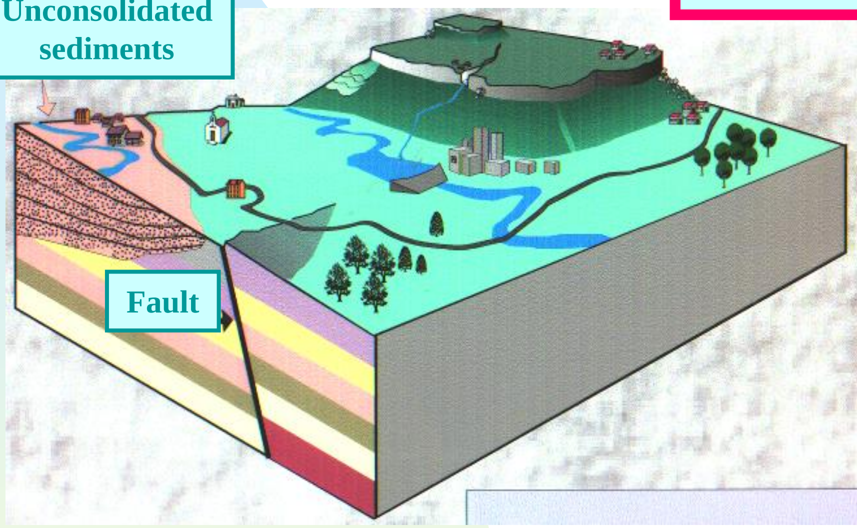
Seismic Risk Mitigation

In the framework of mitigation, different components must be considered

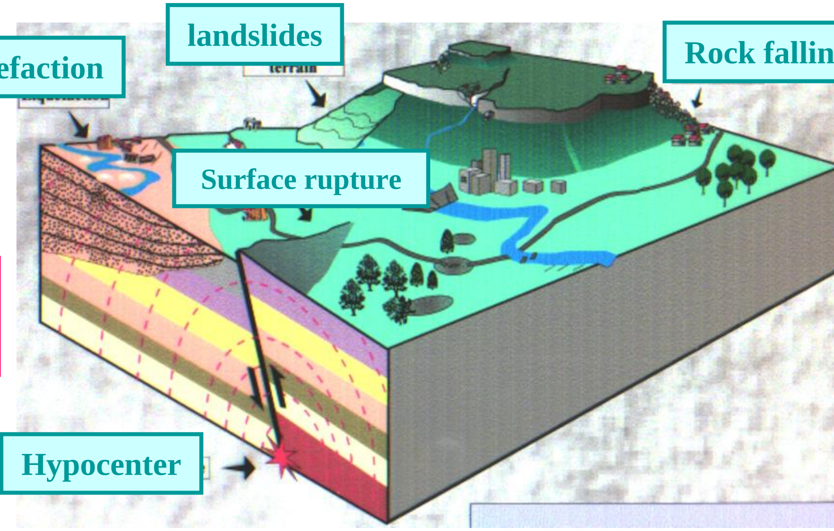


Various impacts of seismic waves (from earthquakes)

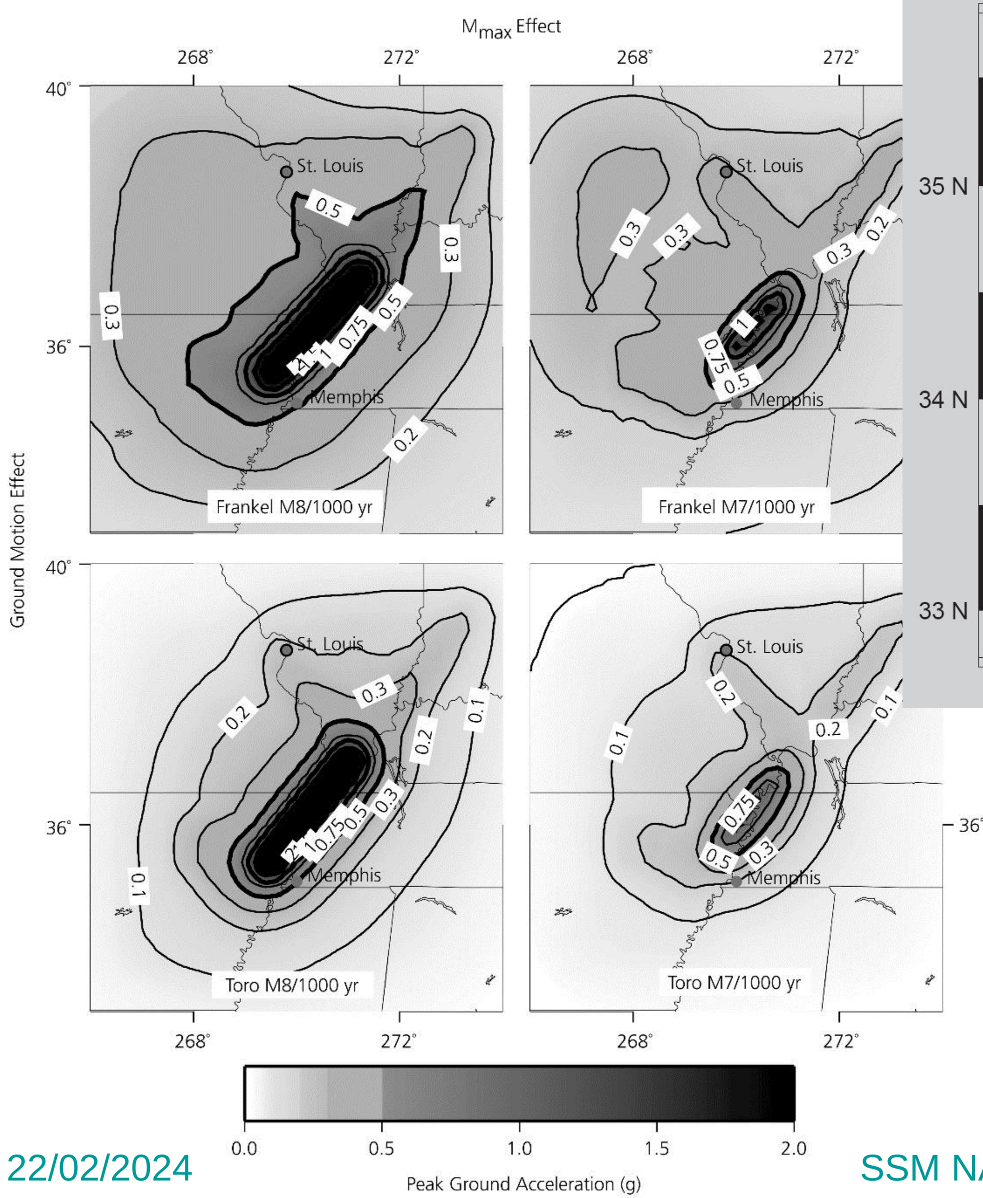
Before quake

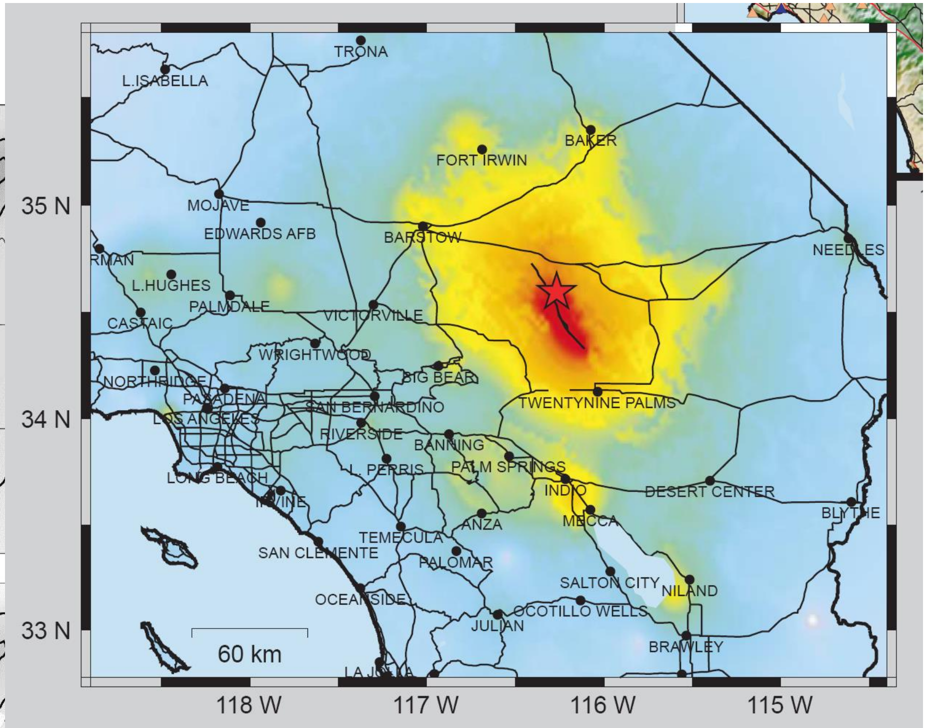


After quake



Seismic wave impact

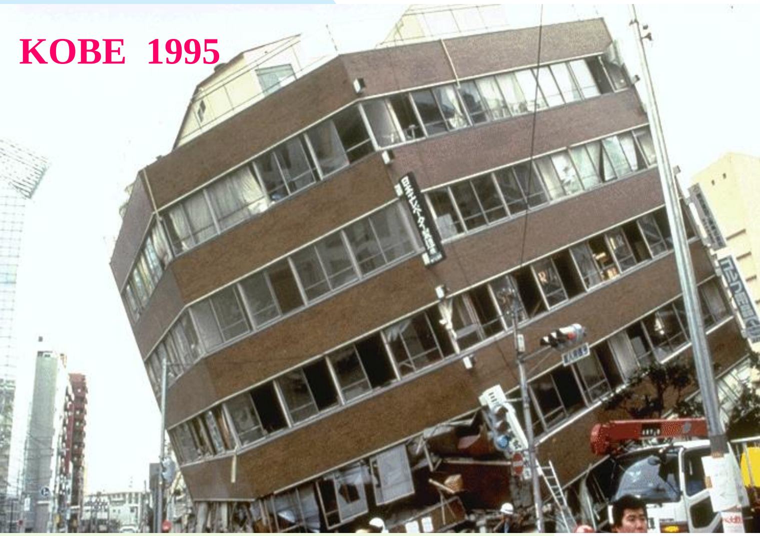




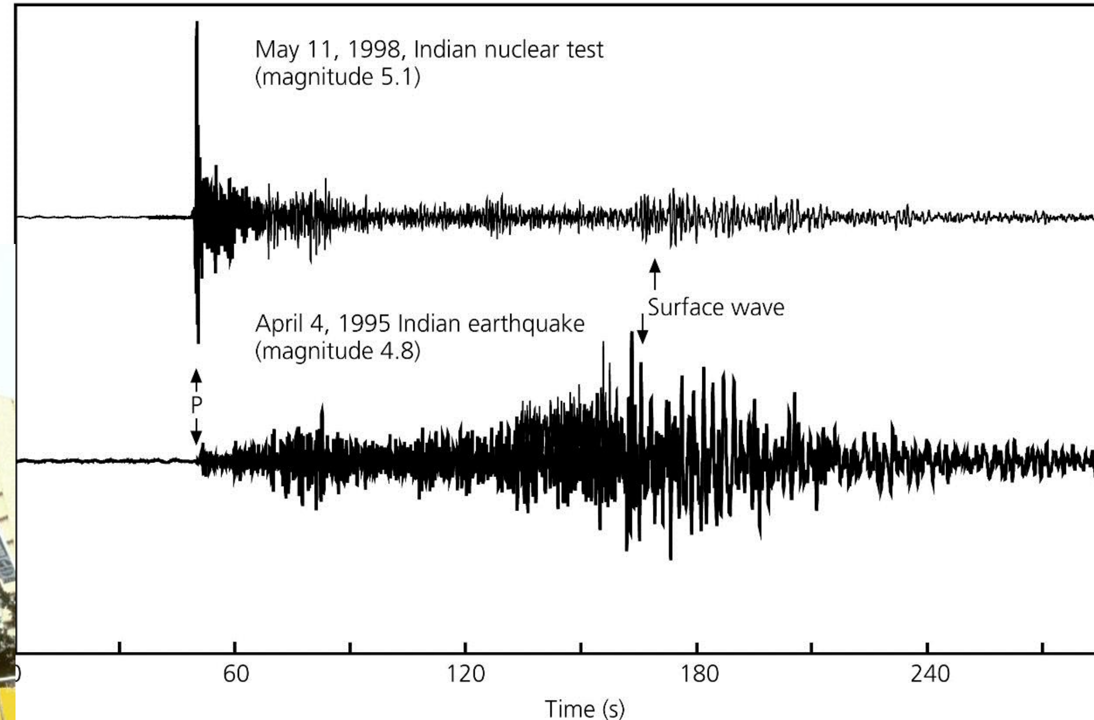
Obviously, the pattern with distance is more complex than a simple decrease with distance : we must tackle this phenomenon and quantify it the best we can.

Destruction by waves !

Importance of the radiation pattern



KOBE 1995



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

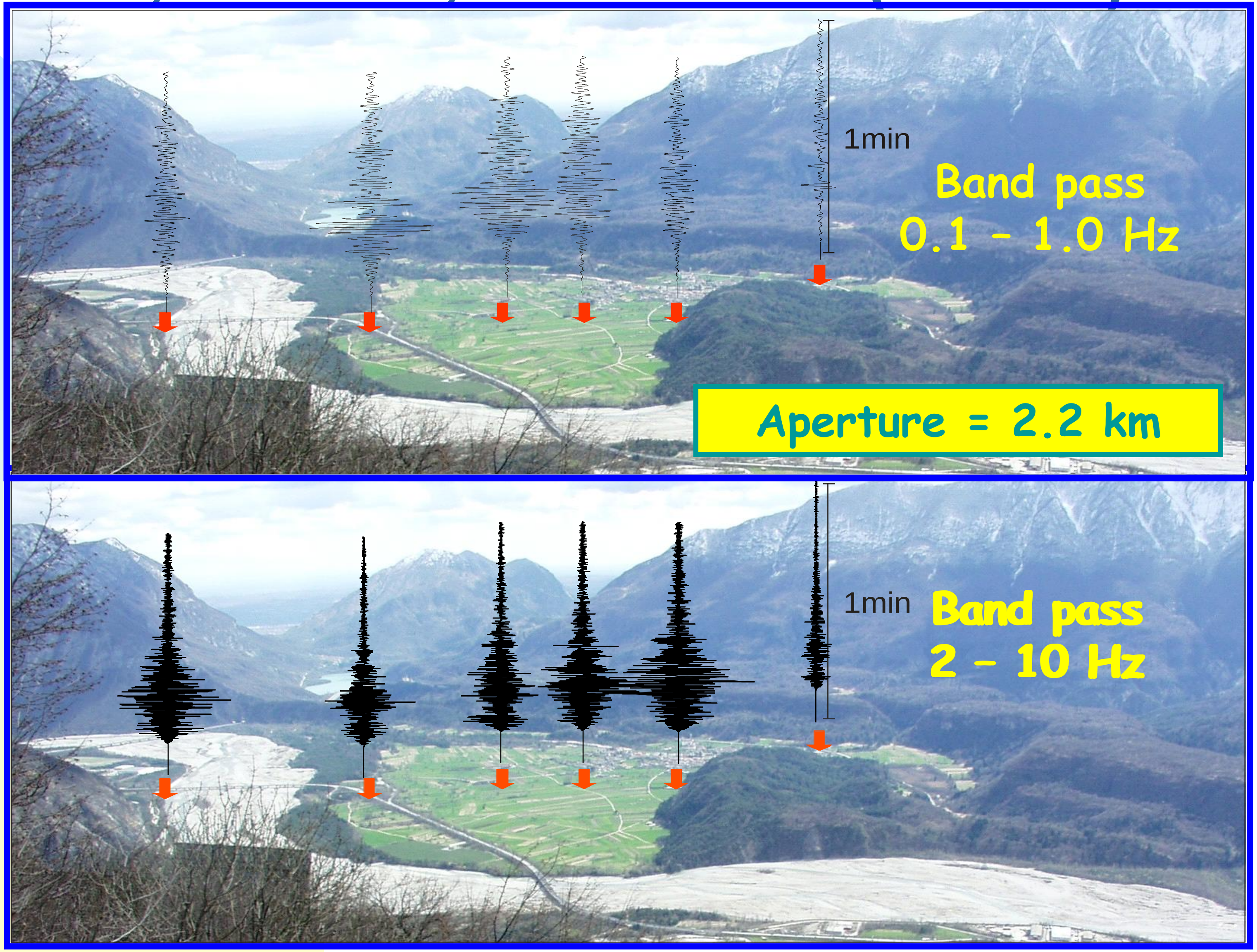
Education

Could we believe in science! How useful is it?

Large-scale structures

Basin or Valley

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

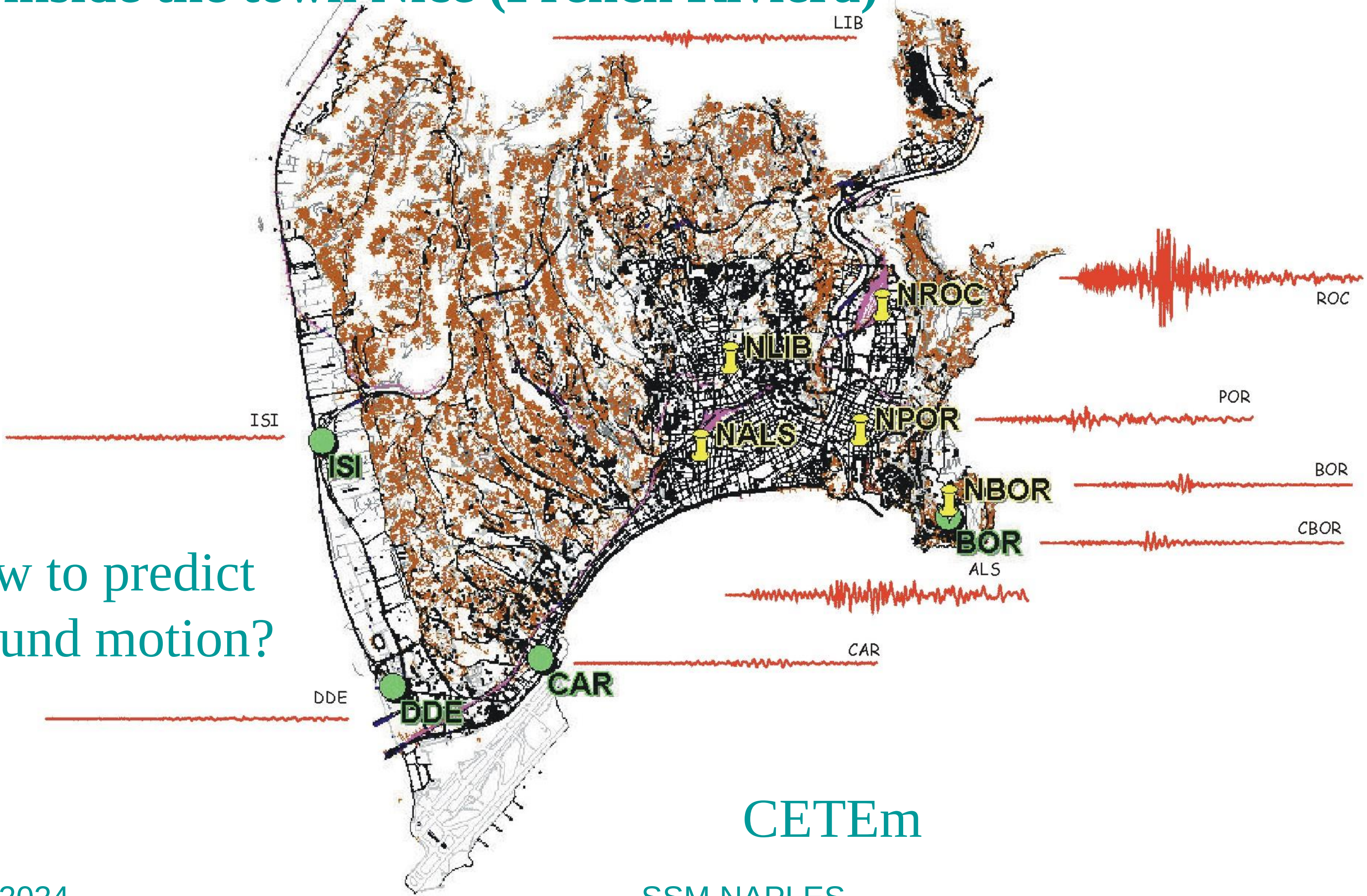


(Vuan et al., 2006)

Spatial Variability

Recorded seismograms for a small earthquake

inside the town Nice (French Riviera)

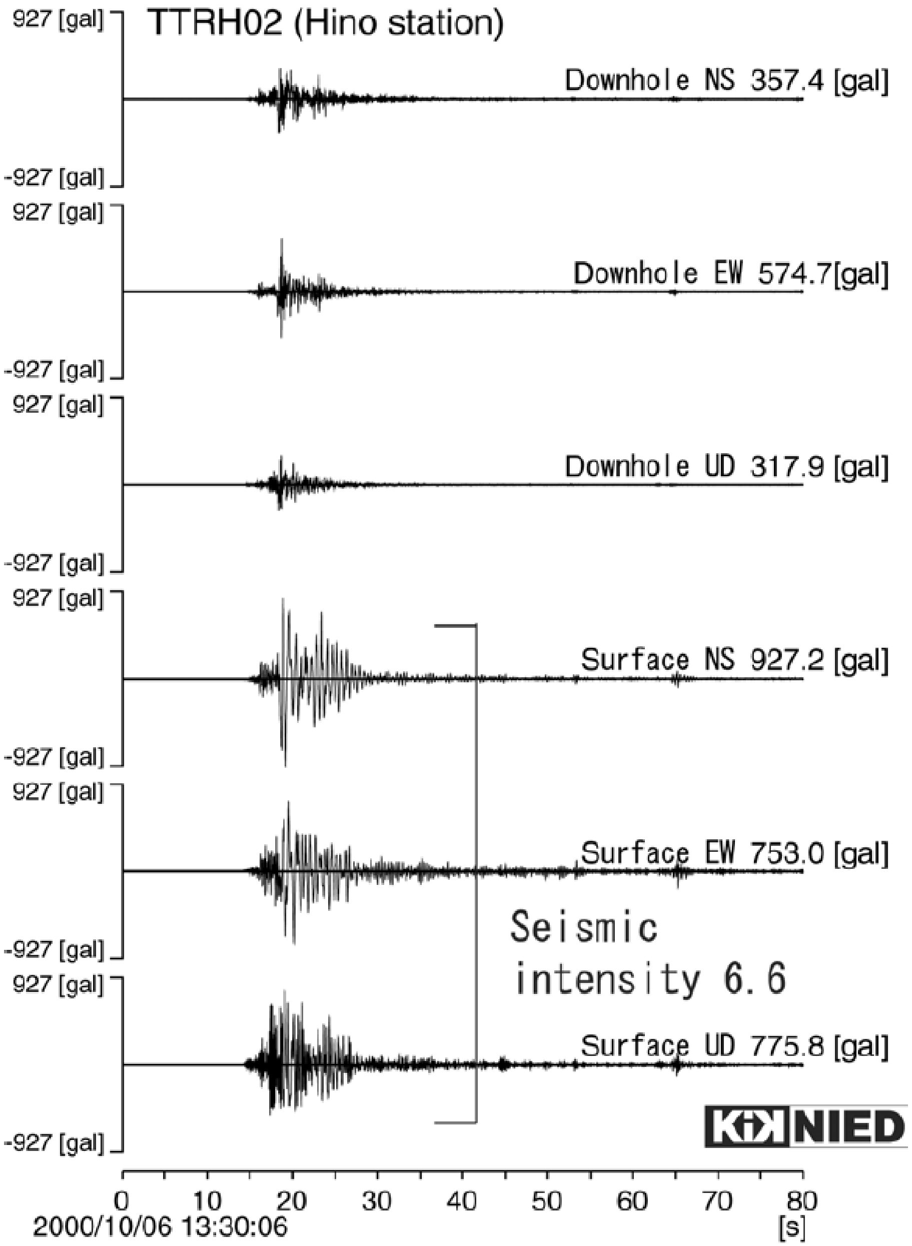


How to predict
ground motion?

CETEm

Short-scale structures

Weathered zone!



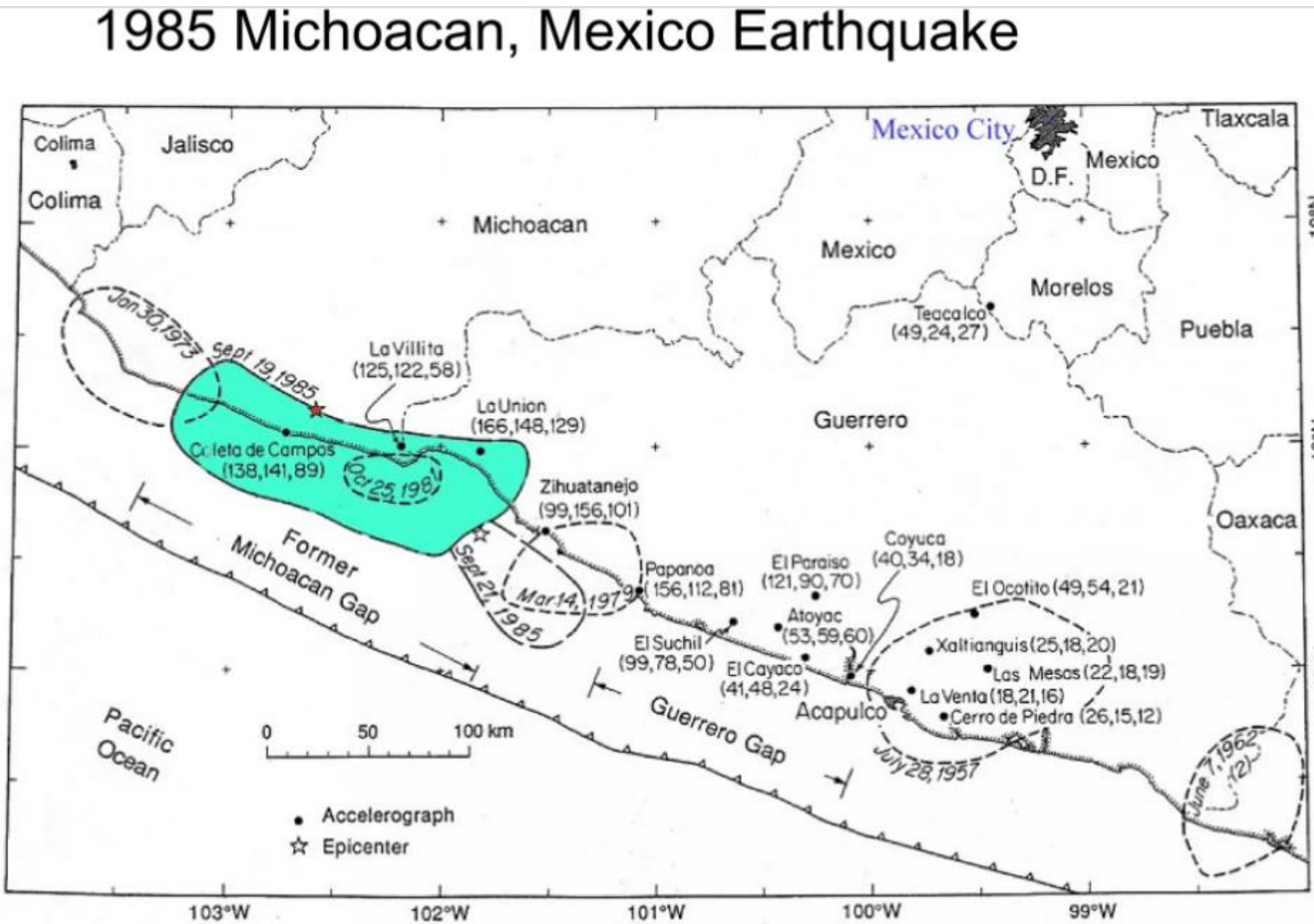
Short-scale structures

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

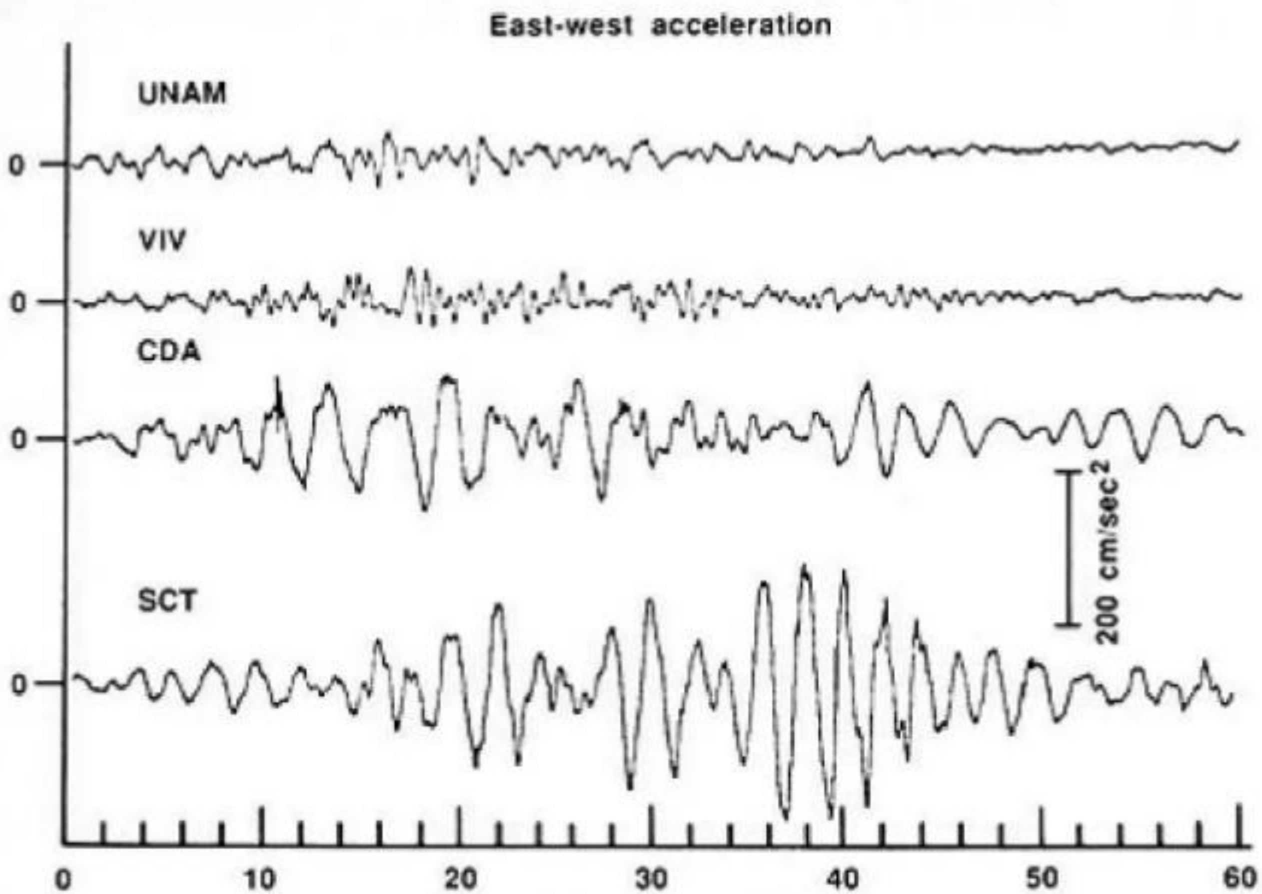


Michoacan M 8.1 earthquake

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

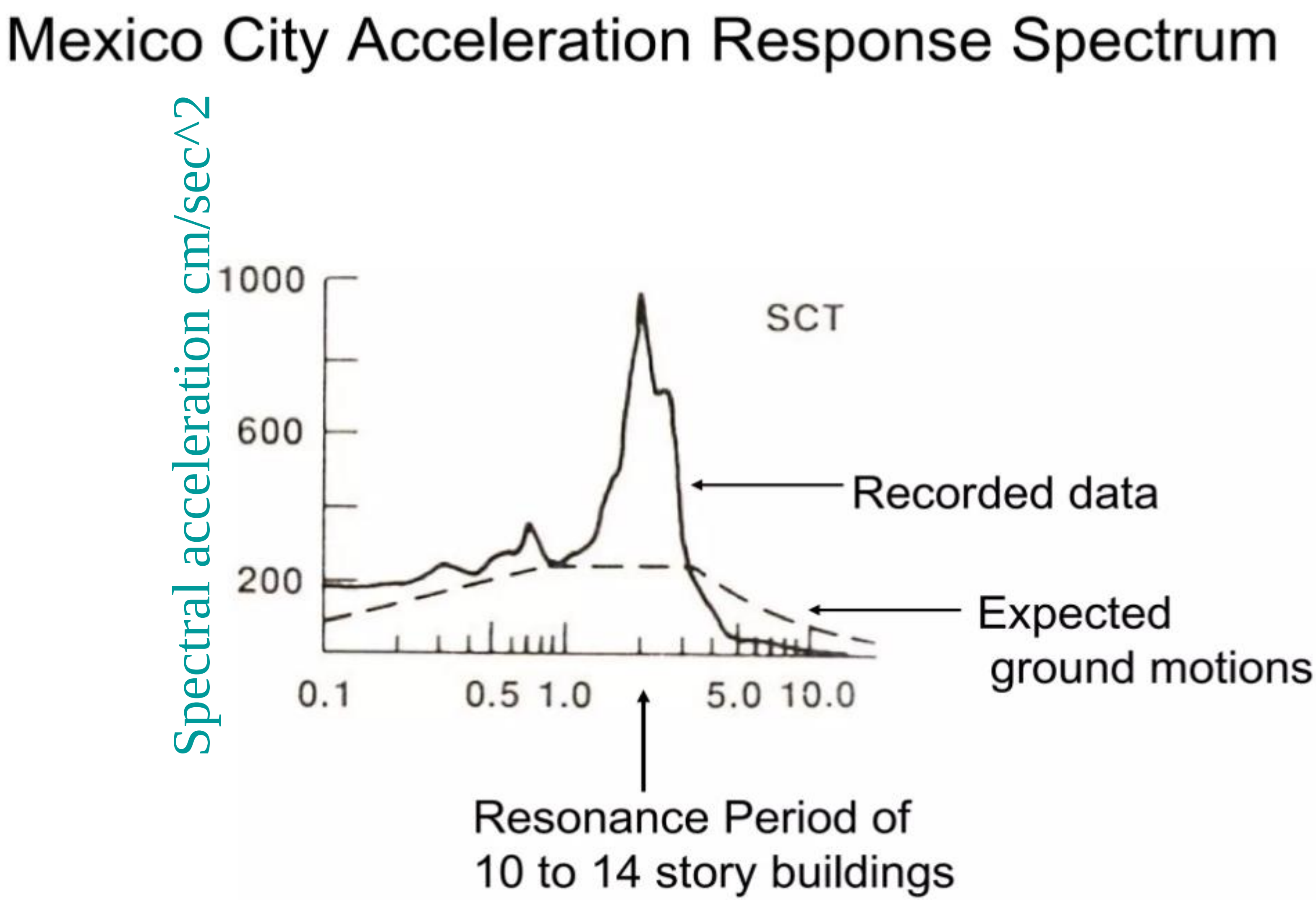


hard rock hills

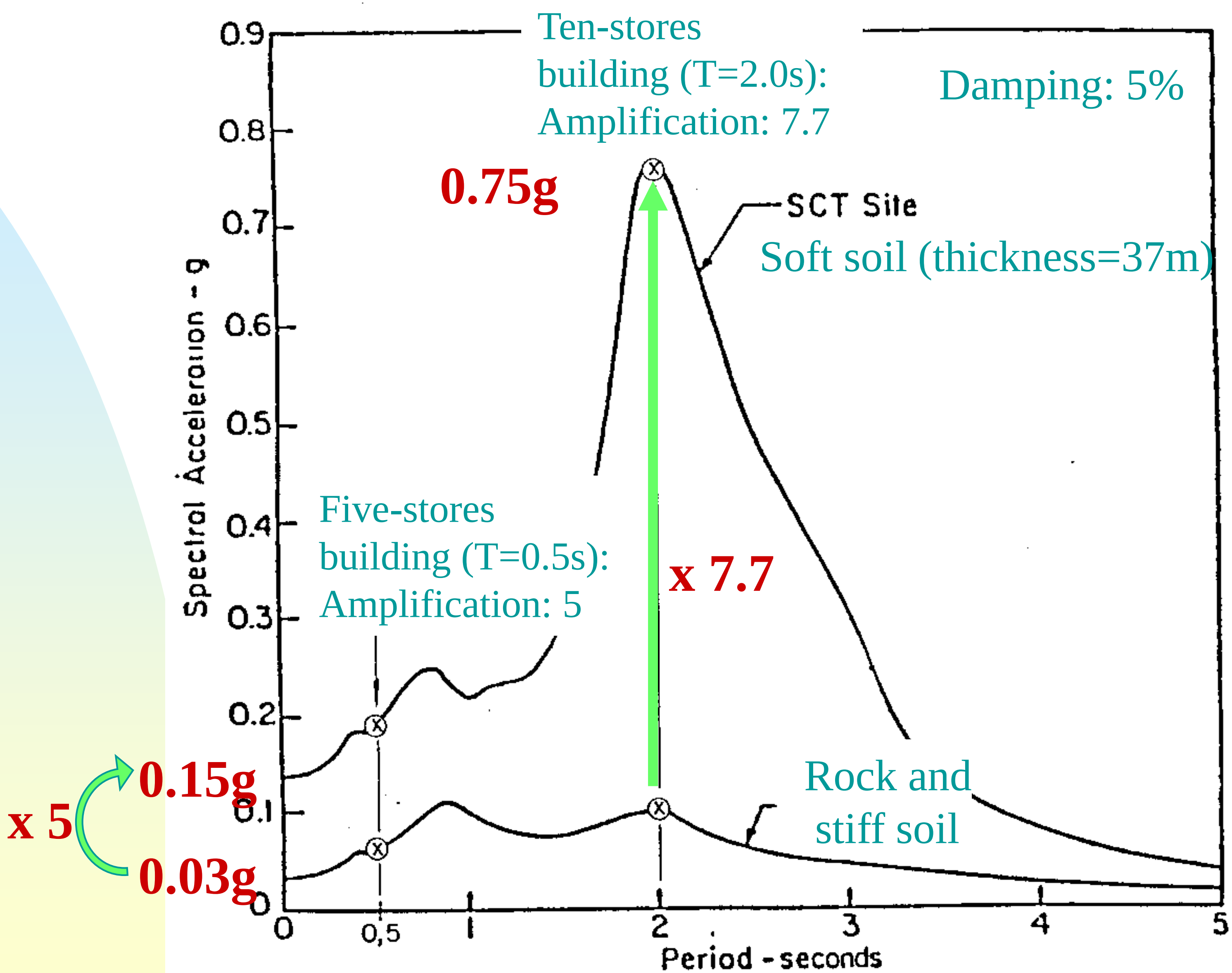
Surface-wave amplitudes!

old lake bed

The « 2 sec. » amplification!



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?

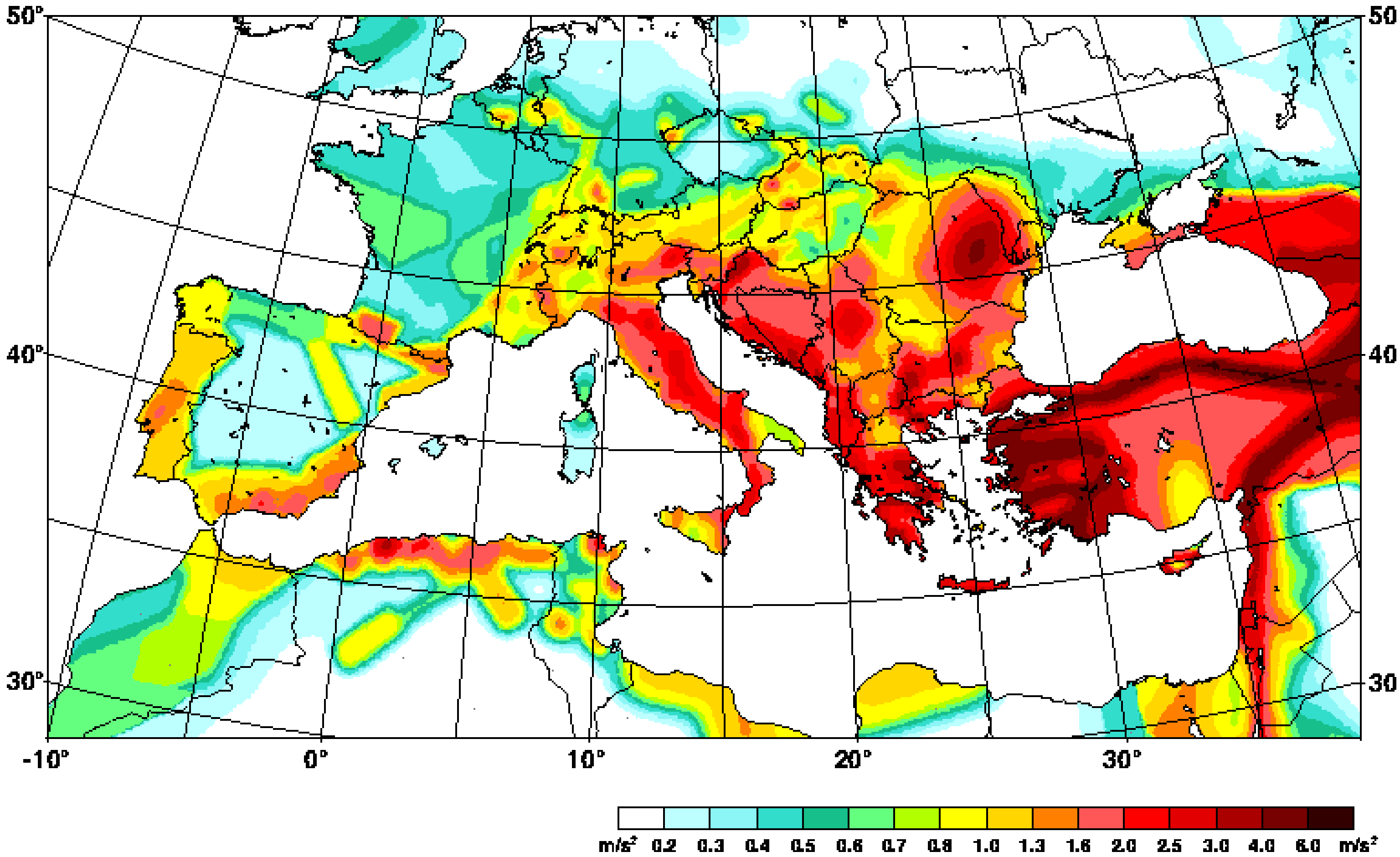
Measures of ground-motion for engineering purposes

- 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

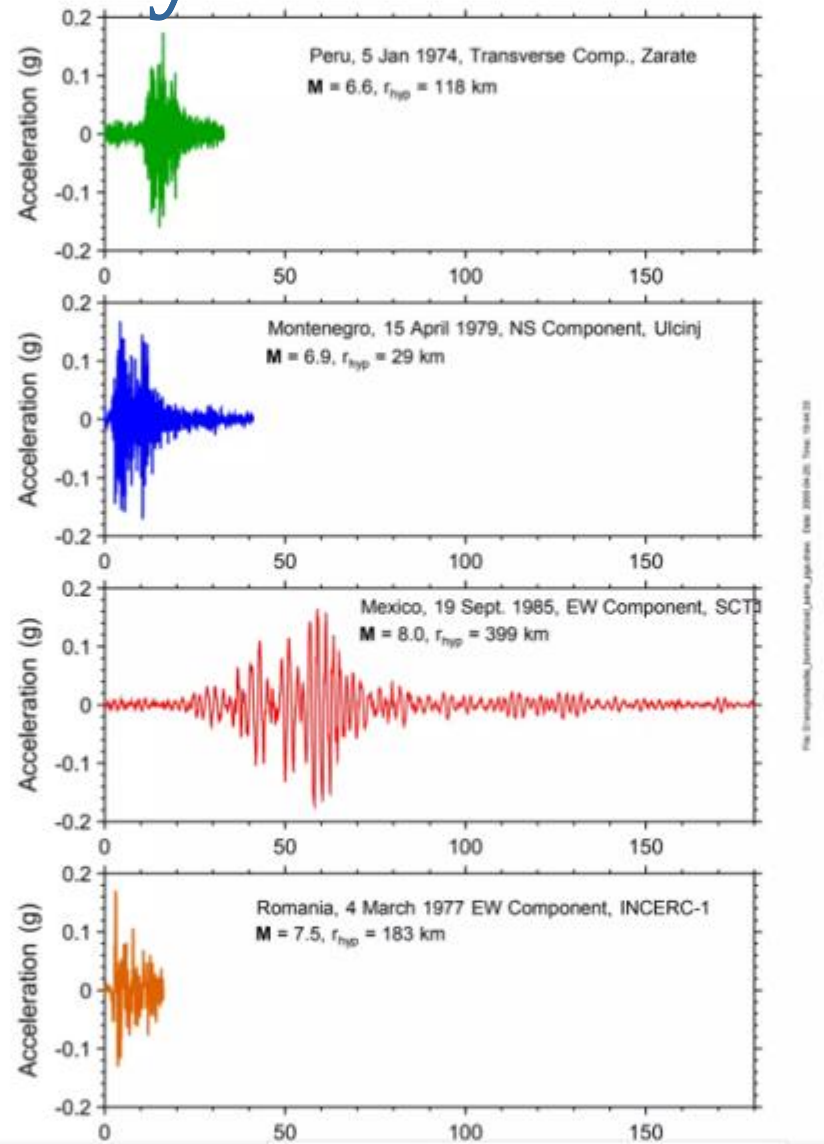


PGA = Peak Ground Acceleration

How to design these maps very useful for territory management.

Ground-motion intensity

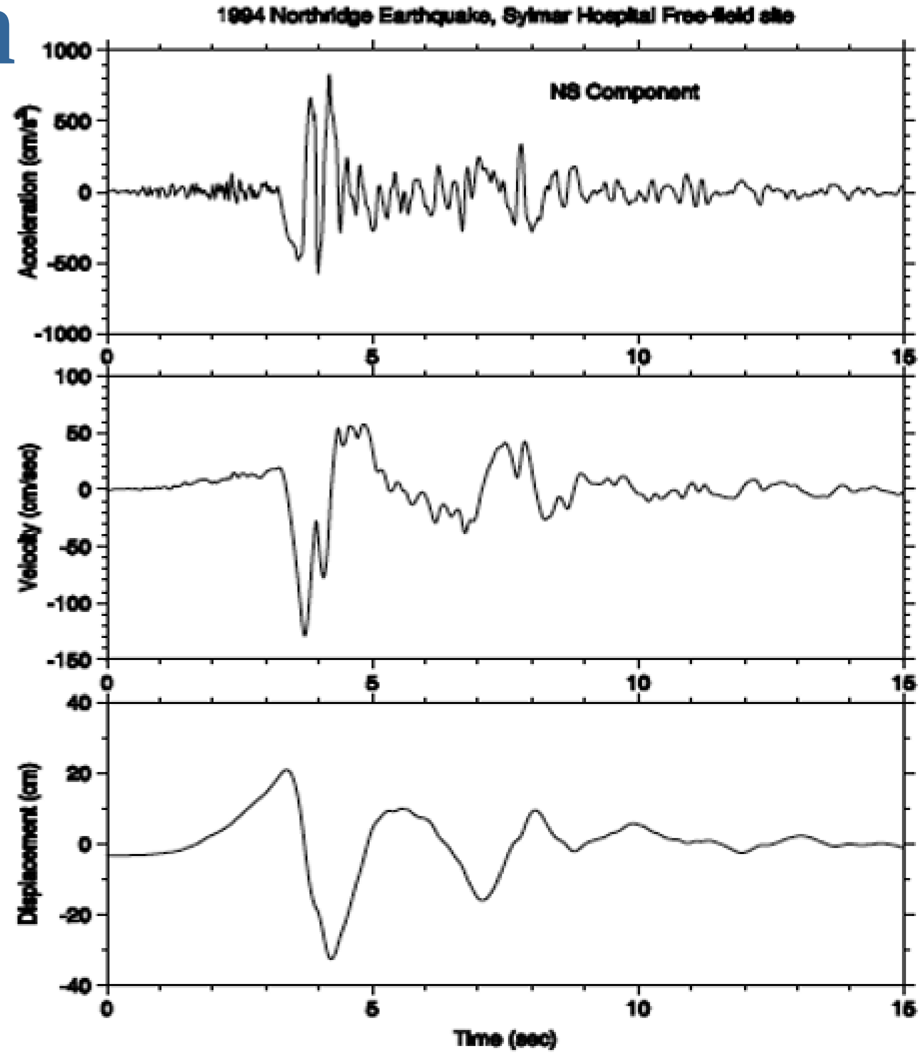
All of these time series have the same PGA



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



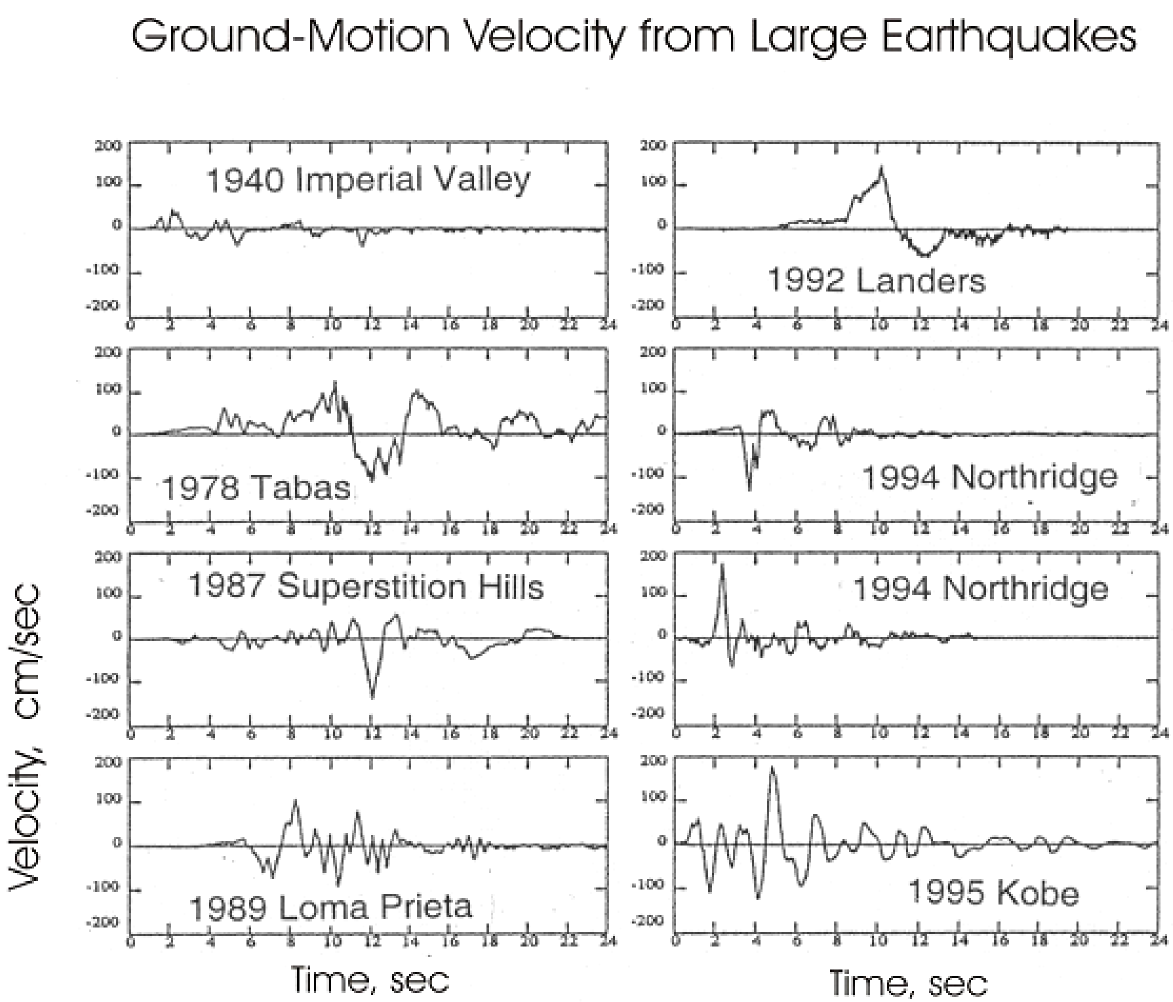
Acceleration, velocity and displacement time-series for the NS horizontal component of the Sylmar record

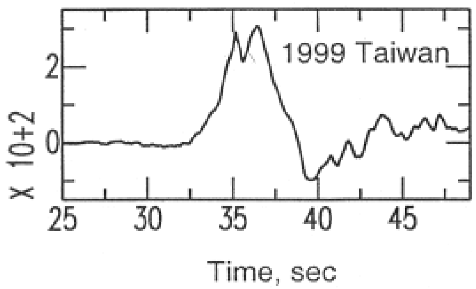
Peak ground velocity (PGV)

- 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)





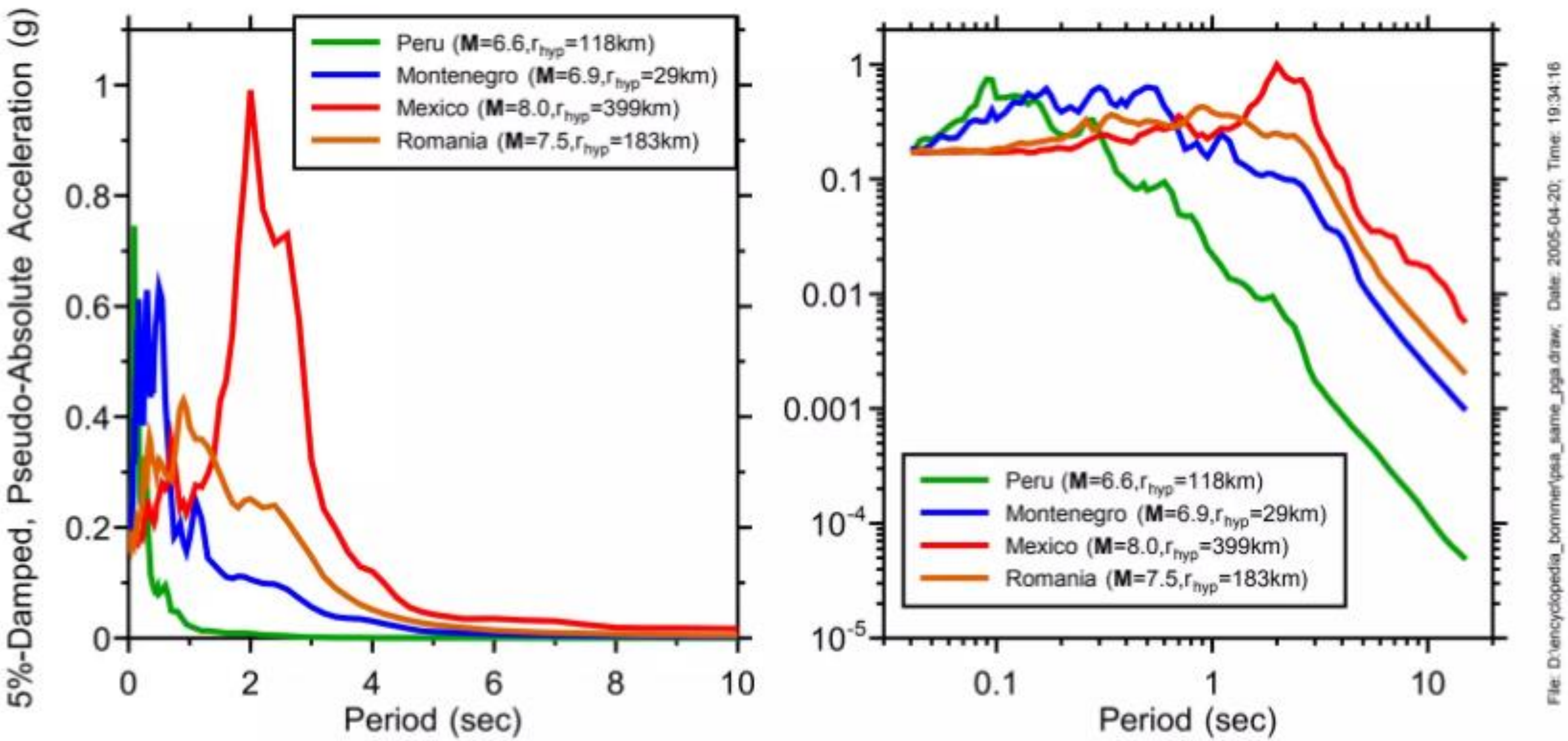
Peak ground displacement (PGD)

- 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?

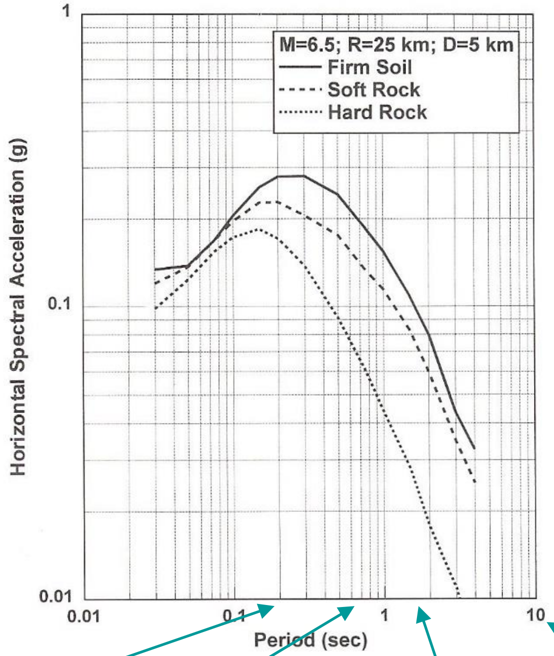
not recommended by David Boore

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):

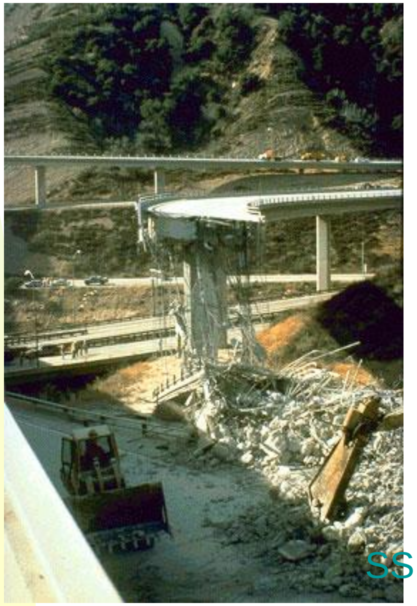


Frequency response of structures



Unexplored topic!

2023 Turkish quake



What ground motion estimation for seismic hazard assessment?

- Unknown sources ? Site variability
- 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 Mw

Rupture directivity

Asperities

Path effects

Spreading (geometrical decrease) (Body vs Surface)

Scattering (extrinsic attenuation)

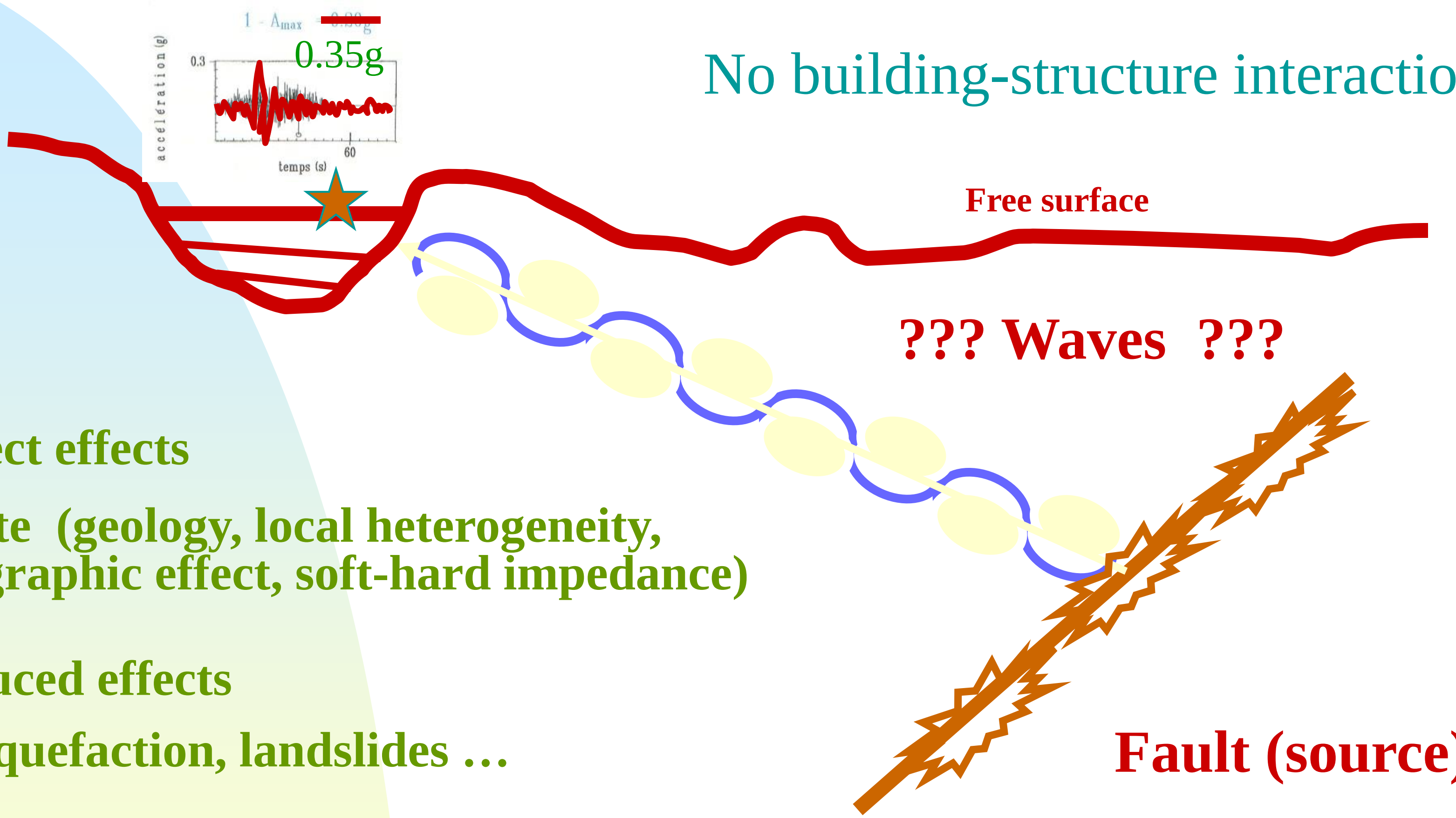
Damping (intrinsic attenuation)

(global attenuation)

Site effects

Local amplification

Seismic Hazard Mitigation



***Direct effects**

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

***Induced effects**

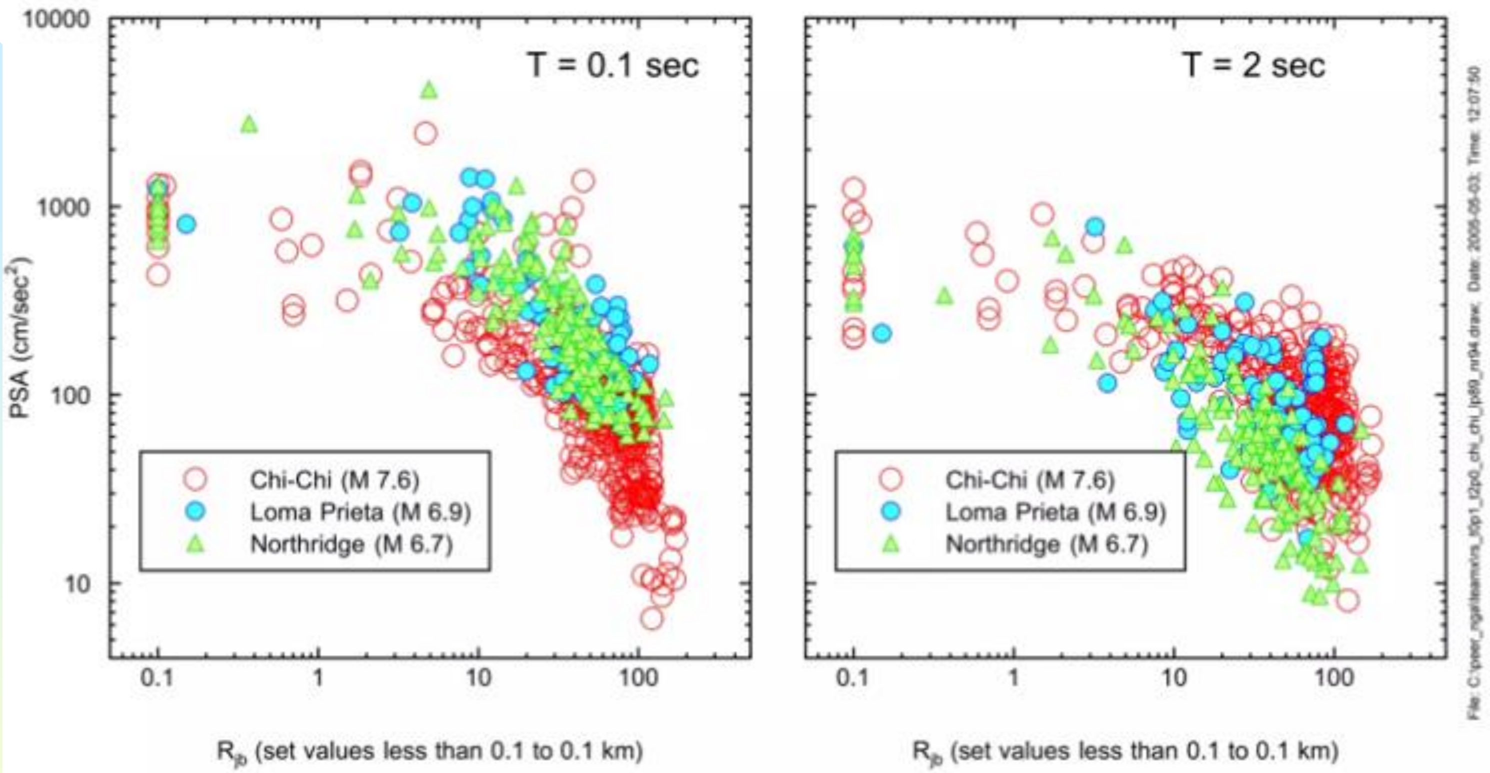
+ liquefaction, landslides …

***Near-source effects**

+ breaking free surface

Improvement goes through better estimations of these components and the wave propagation factor is one factor with most uncertainties

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

$$M_0 \equiv \mu S A$$

μ = modulus of rigidity

S = slip over fault area

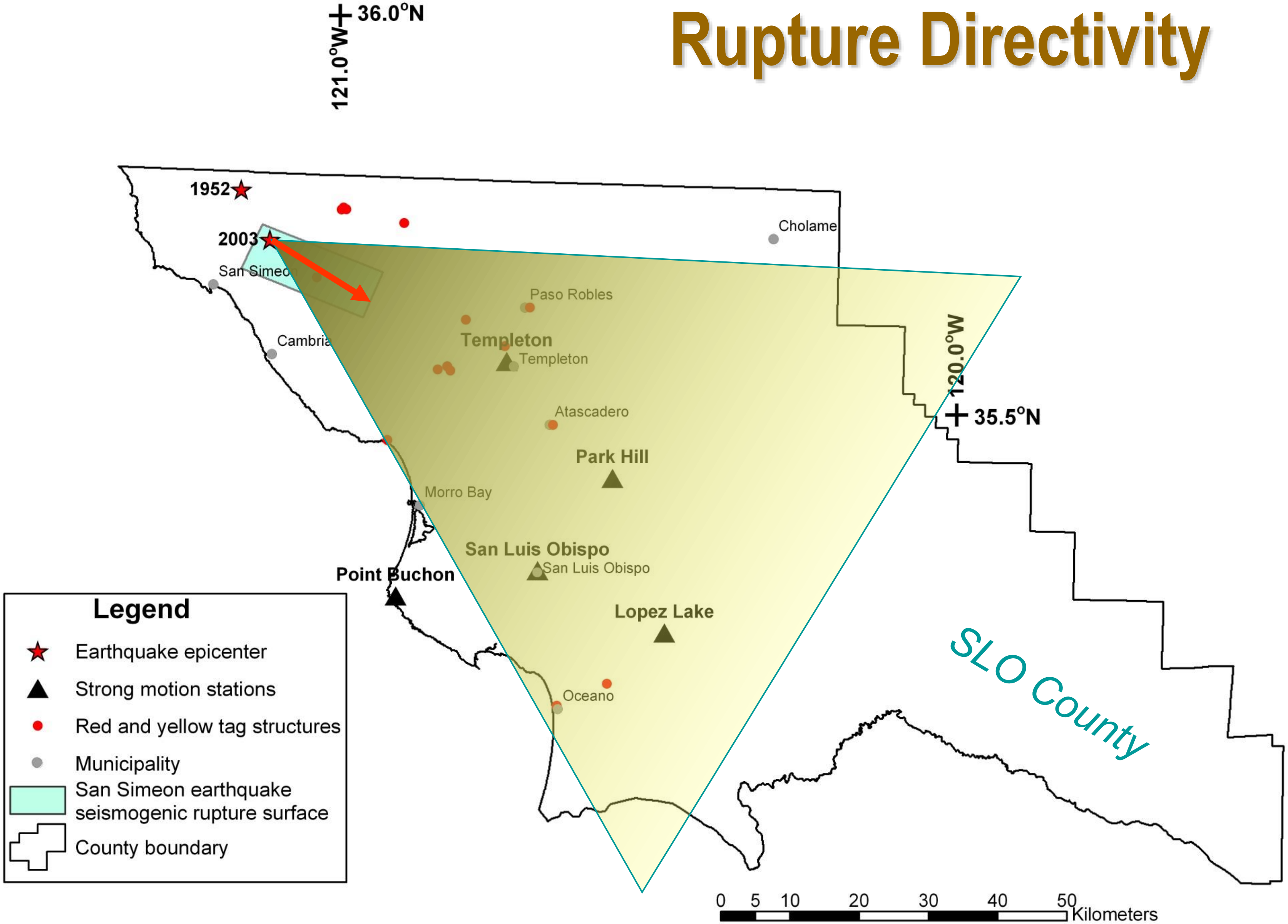
A = area of fault

Moment Magnitude

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

Source effects

Rupture Directivity



Damage in Oceano

2003 San Simeon Earthquake

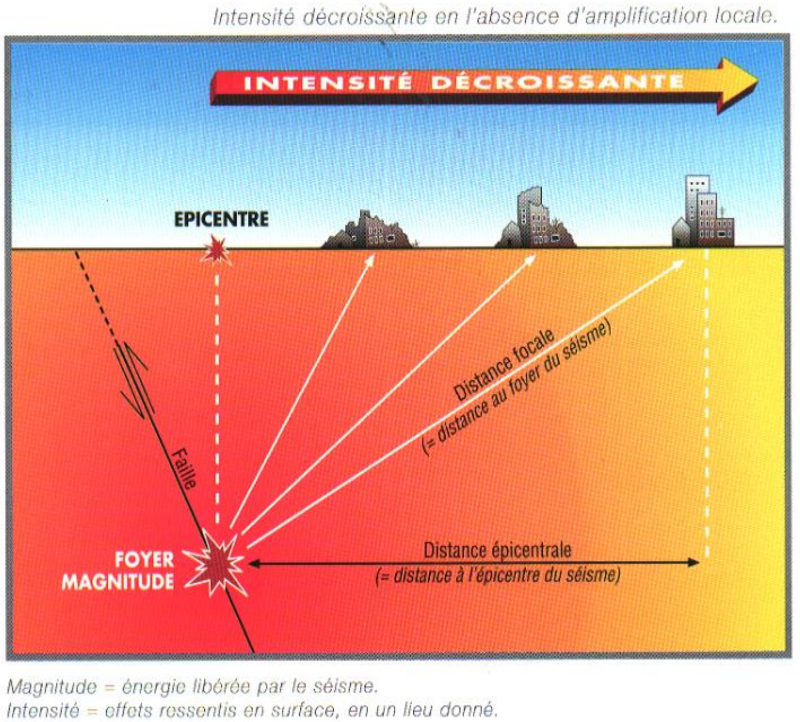
Path effects

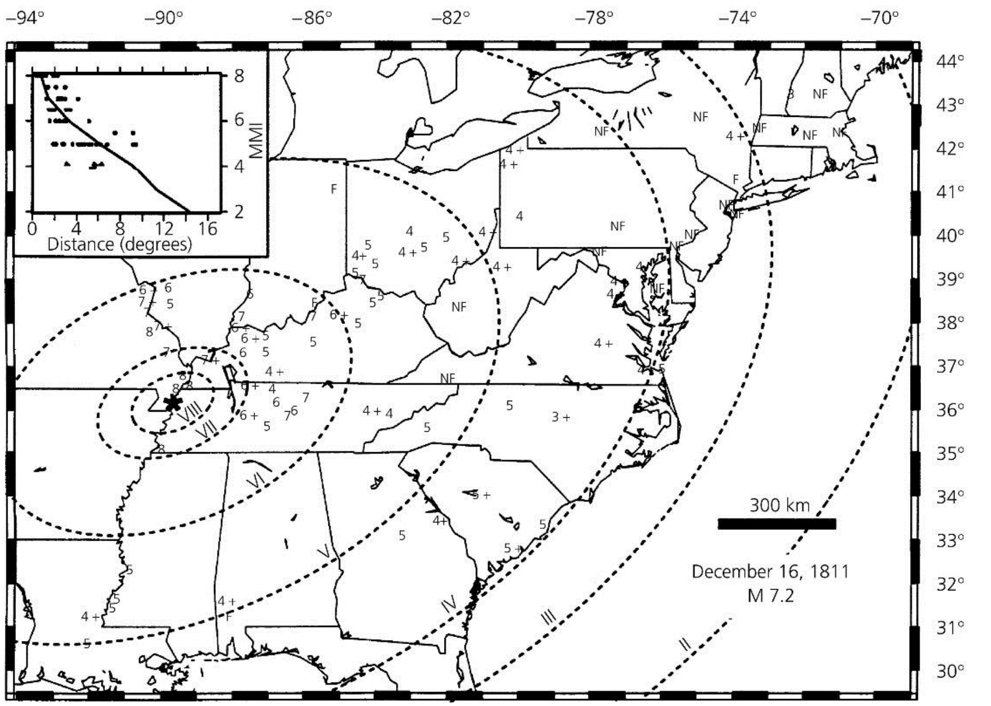
How does the motion depend on distance?

- 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





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?

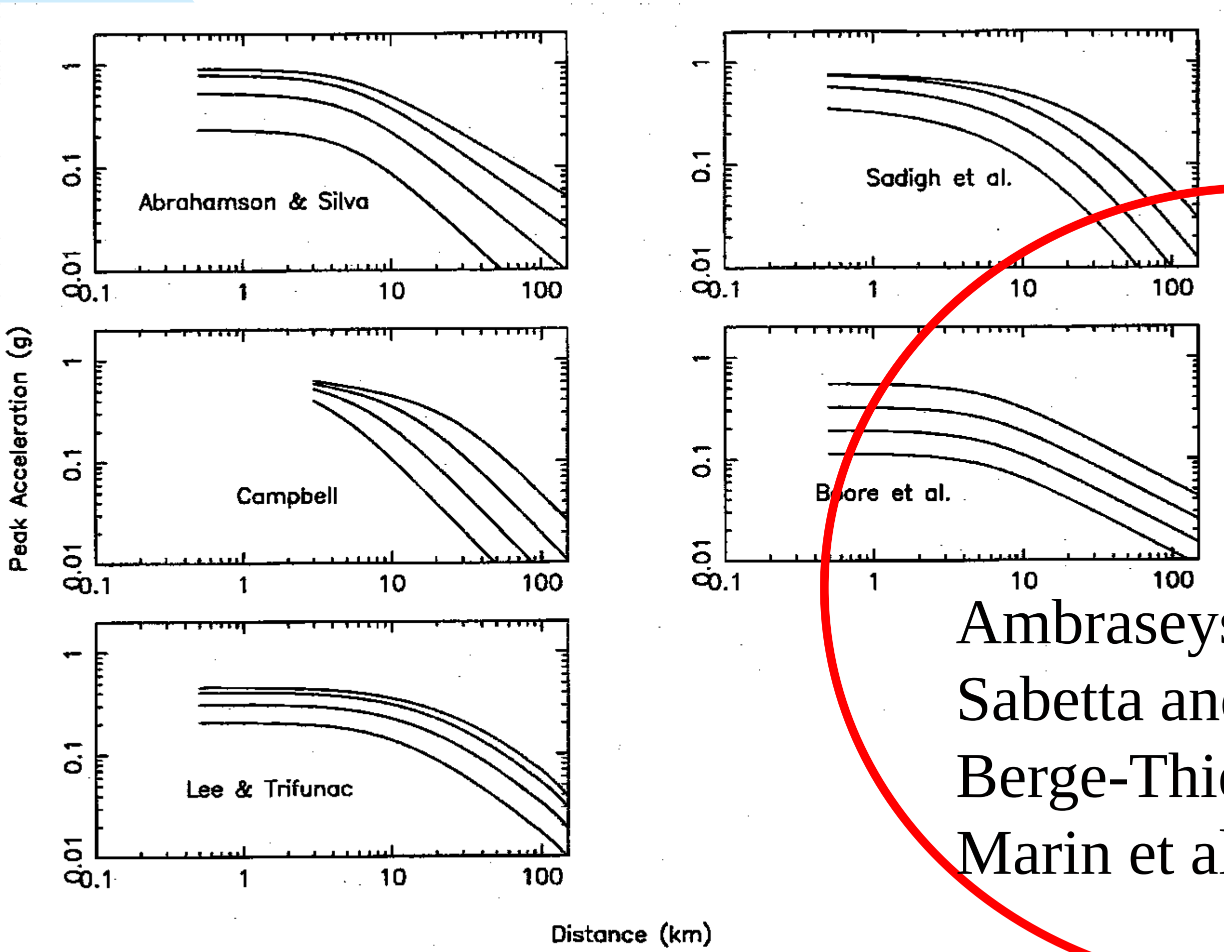
Ground Motion Prediction Equations (GMPE)

- Empirical regressions of recorded data

- Estimate ground shaking parameter (PGA, PGV, PSA, PSV) as a function of
  - ✓ Magnitude, depth
  - ✓ Distance
  - ✓ Site (rock, soft, Vs30, slope)

- Possible fault parameters (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

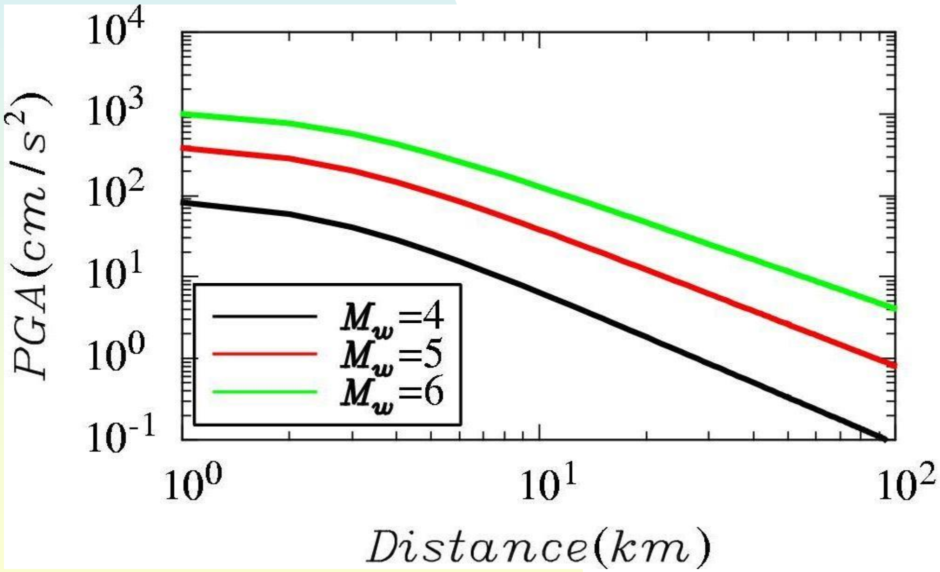
$$\log\left(PSA(f)\right) = \boxed{a(f)\cdot M} + \boxed{b(f)\cdot R - \log(R)} + \boxed{c(i,f)}$$

Source | Distance | Site

- Response spectra
- The magnitude scaling of ground motion does not depend on magnitude
- The ground motion decay does not depend on magnitude

Magnitude/distance dependence

$$\log\big(PSA(f)\big) = a1(f).M + a2(f).(8.5 - M)^2$$
$$+[b(f) + c(f).M]\log\left(\sqrt{R^2 + h^2}\right) + d(f)$$



Fall-off faster
for small earthquakes
than for important ones

Courtesy of Fabian Bonilla

Ground motion prediction equations: GMPEs

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 $\mathrm{m/s^2}$, 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)

Many GMPEs are data-driven through regression

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

L Very soft soil: approximately $V_{s,30} < 180\,\mathrm{m/s}$, (combine with category S) $\Rightarrow S_A = 0, S_S = 1$, 4 records.

S Soft soil: approximately $180 \leq V_{s,30} < 360\,\mathrm{m/s} \Rightarrow S_A = 0, S_S = 1$, 87 records.

A Stiff soil: approximately $360 \leq V_{s,30} < 750\,\mathrm{m/s} \Rightarrow S_A = 1, S_S = 0$, 68 records.

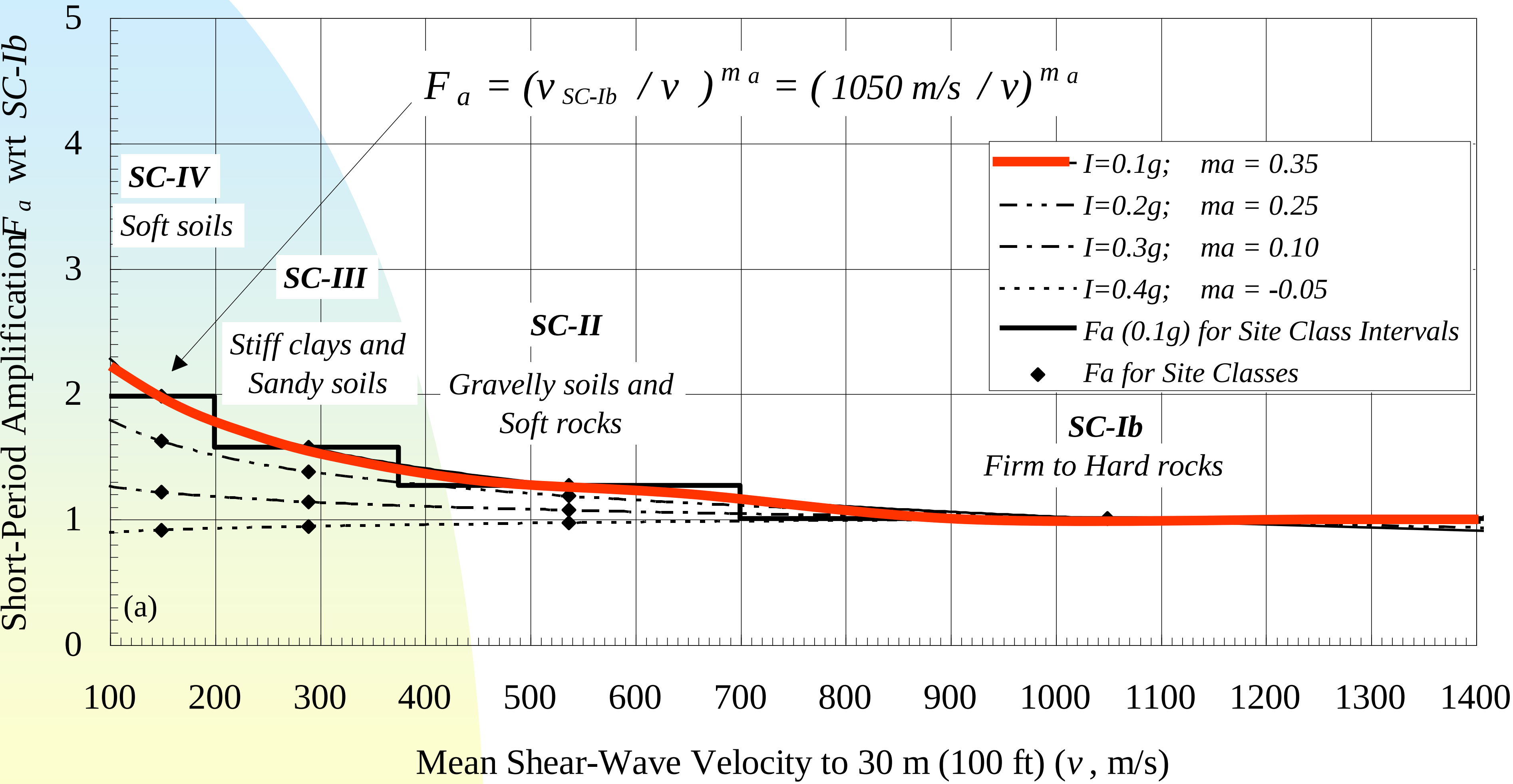
R Rock: approximately $V_{s,30} > 750\,\mathrm{m/s} \Rightarrow S_A = 0, S_S = 0$, 23 records.

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

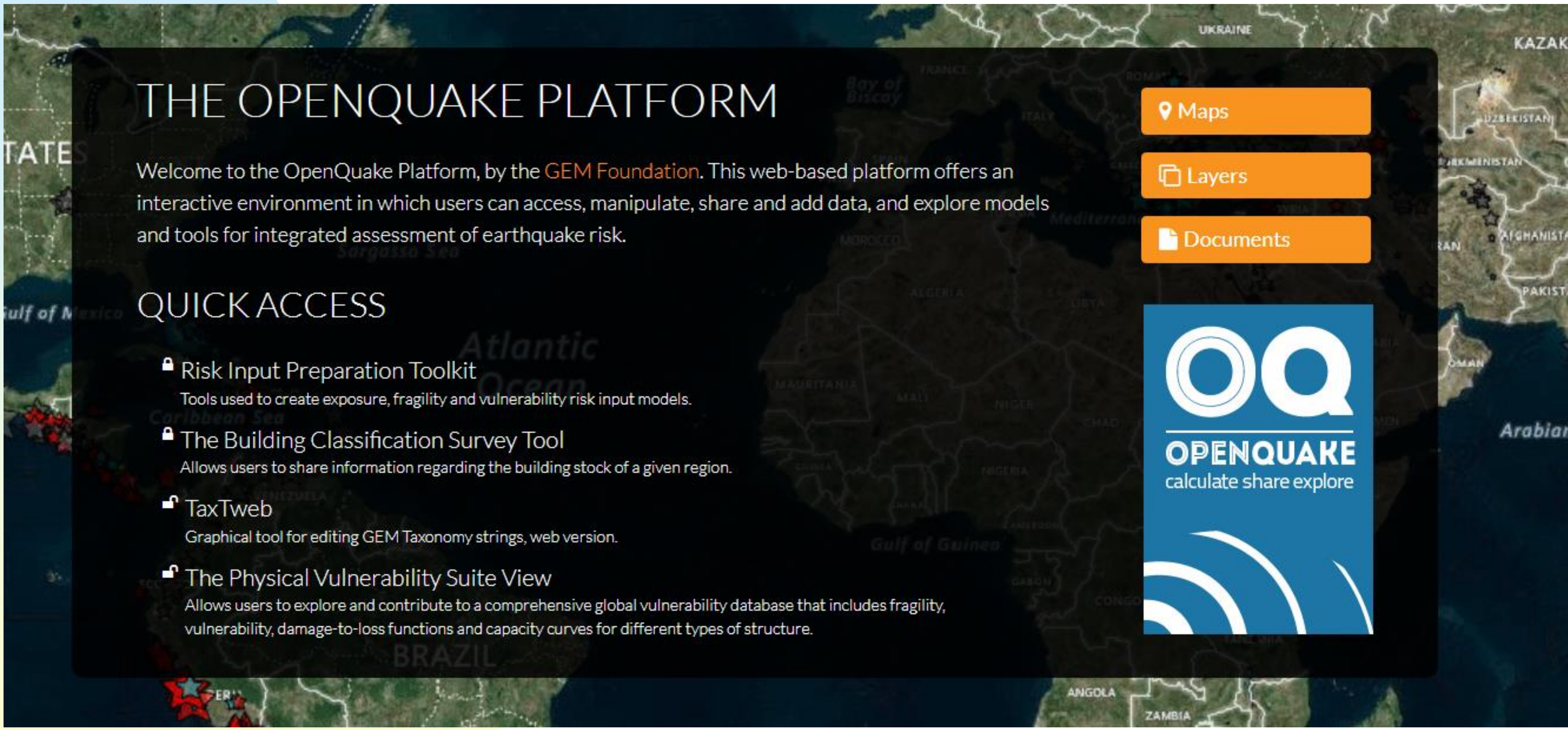
This report summarizes, in total, the characteristics of 289 empirical GMPEs for the prediction of PGA and 188 empirical models for the prediction of elastic response spectral ordinates. In addition, many dozens of simulation-based models to estimate PGA and elastic response spectral ordinates are listed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

(Douglas, 2011)

Amplification of PGA as a function of Vs30



Available tools: https://platform.openquake.org



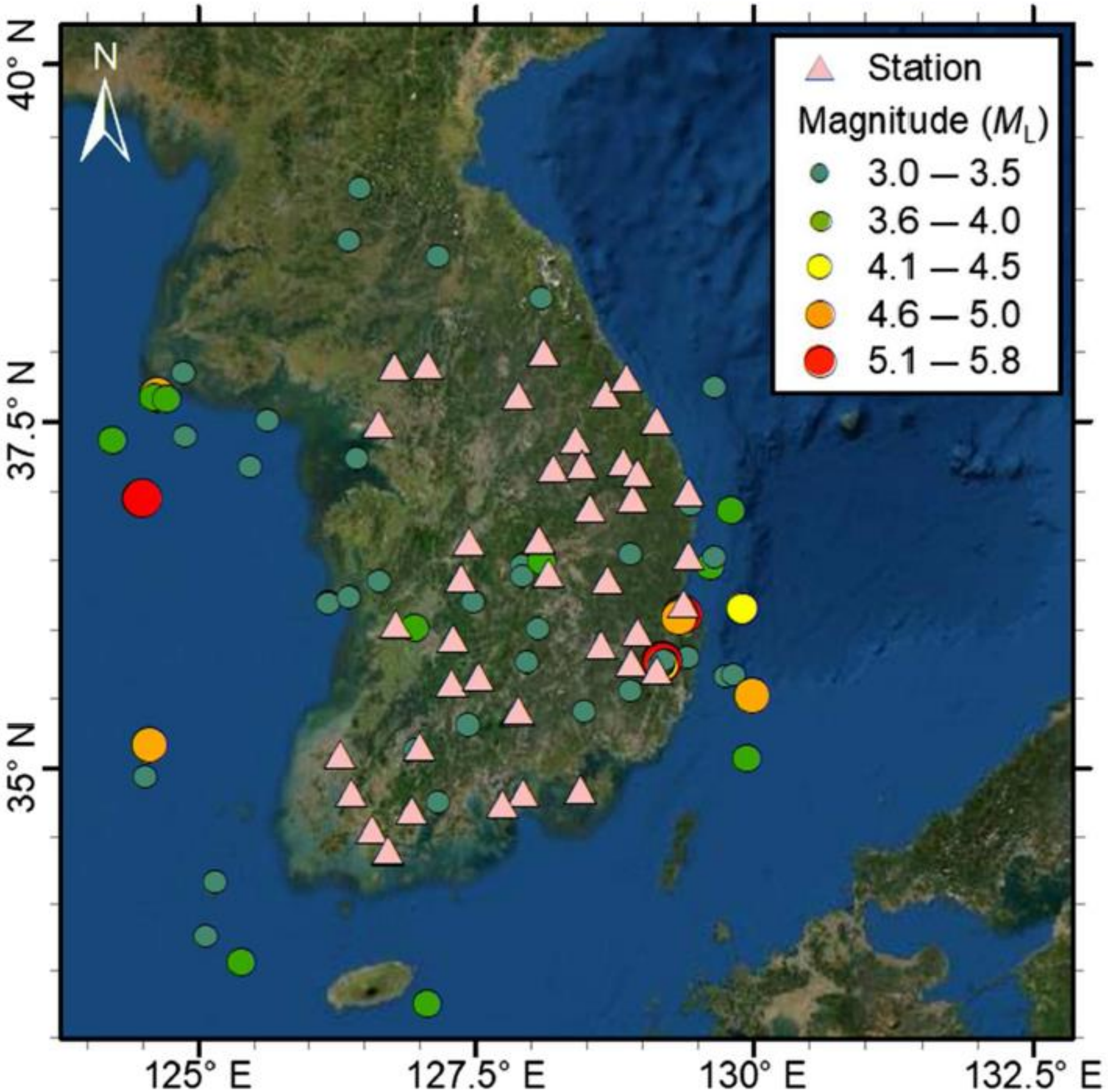
Earthquake engineering

Game-changers

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

missing: velocity structures!

Machine-learning-based PSA

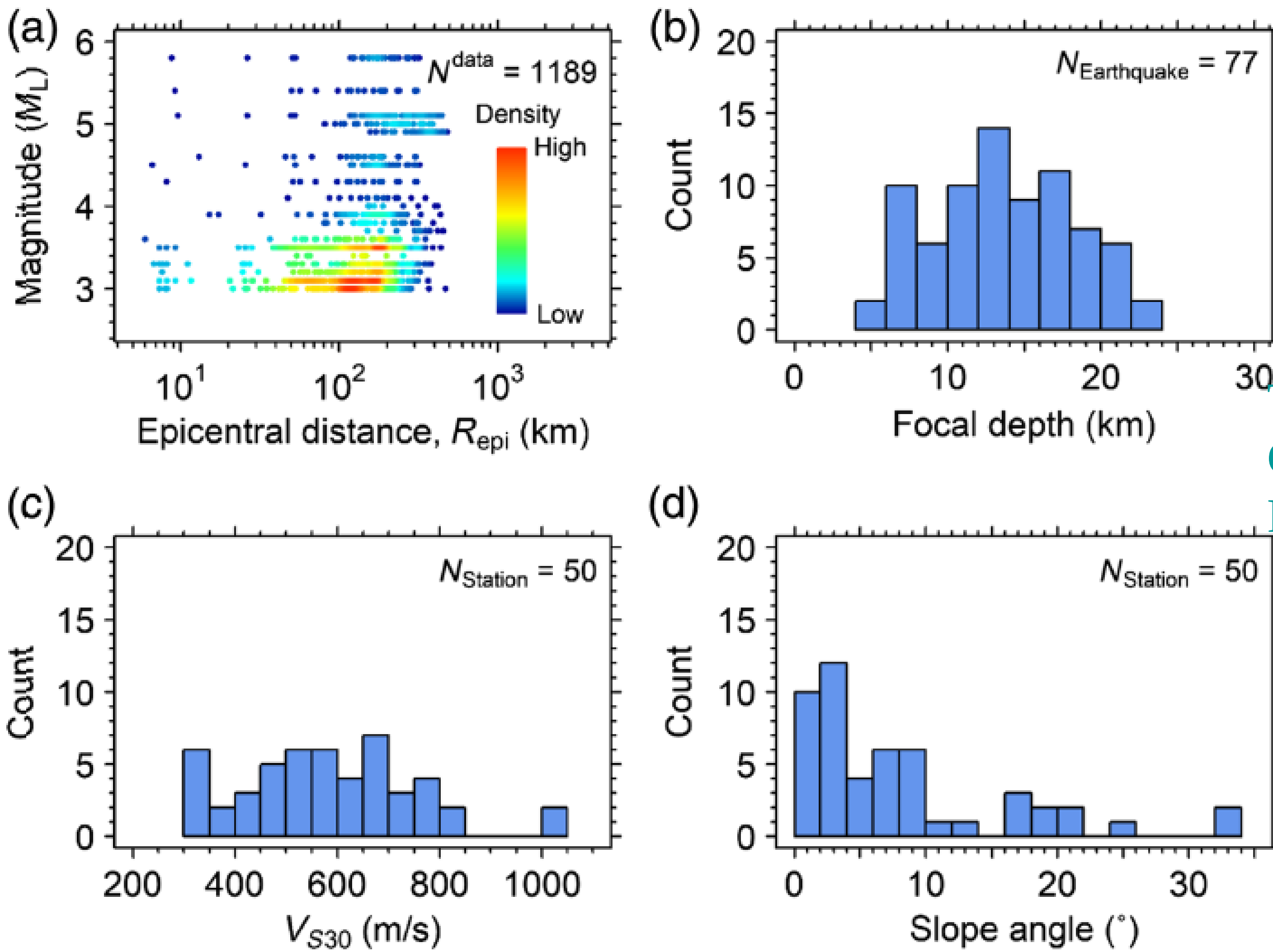


Low-to-Moderate seismicity

Seo et al. (2021)

Database

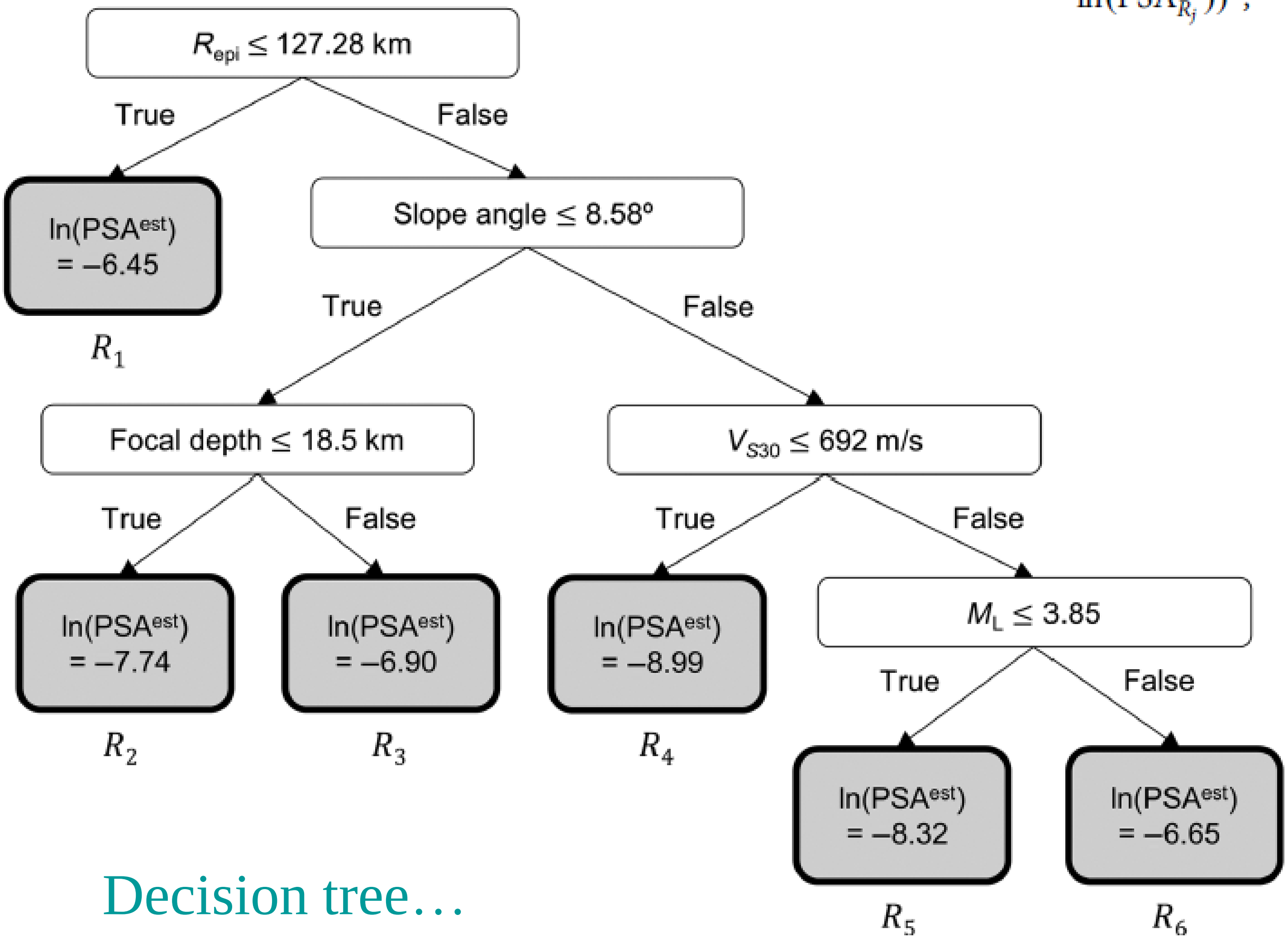
50 KMA stations: EW & NS records for 77 events, with two recent events.



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

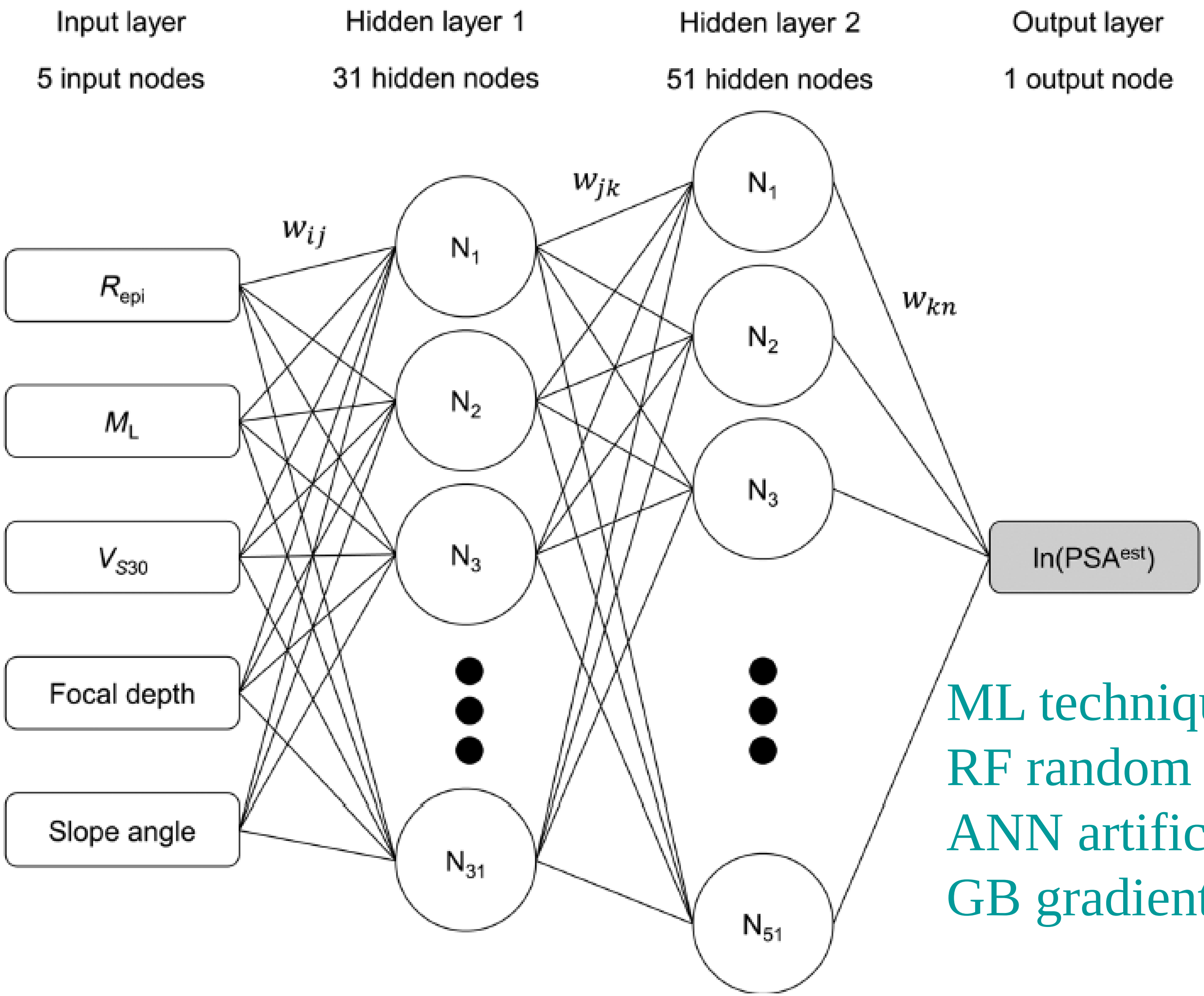
Logic-tree approach

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



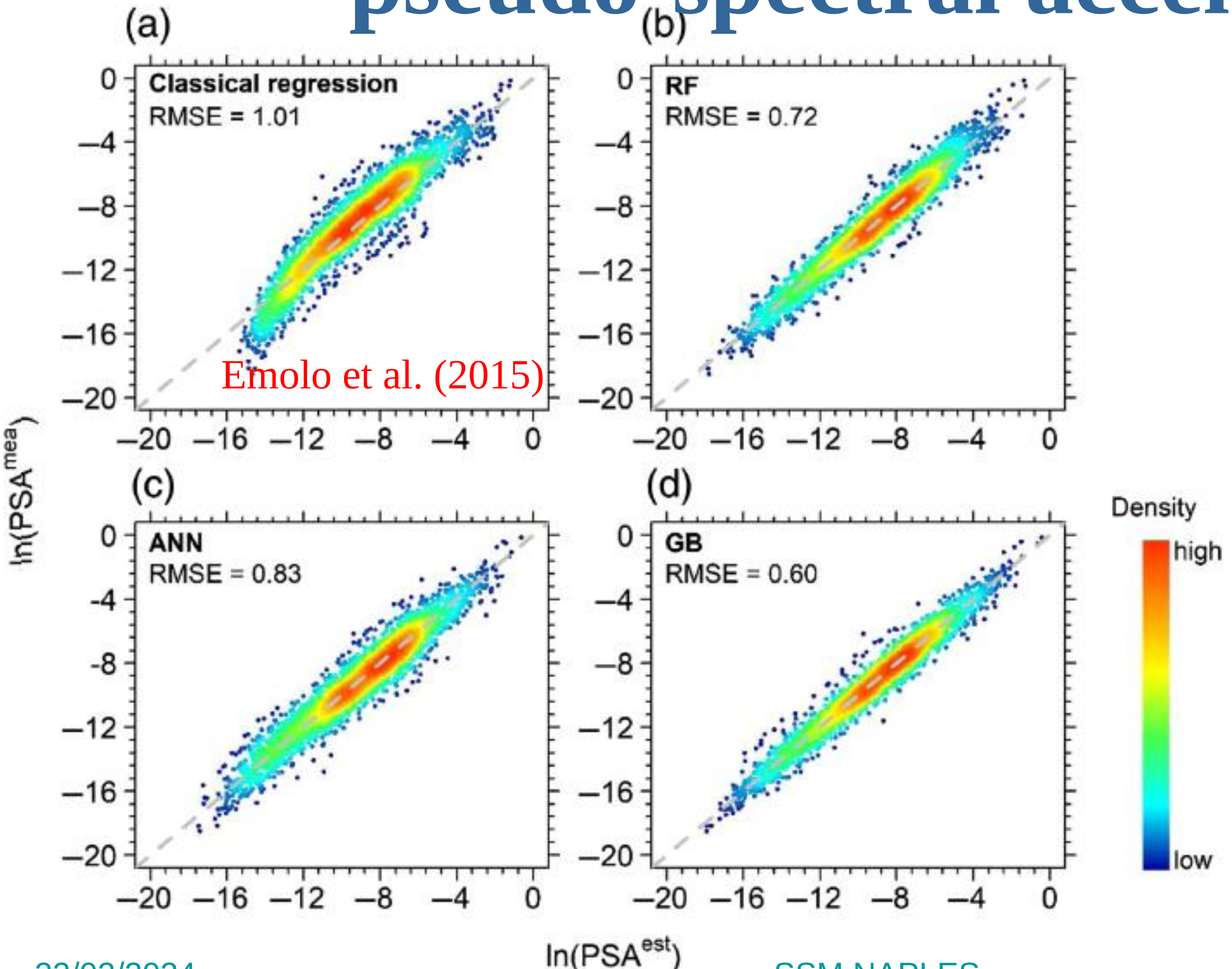
Decision tree…

Machine-learning techniques



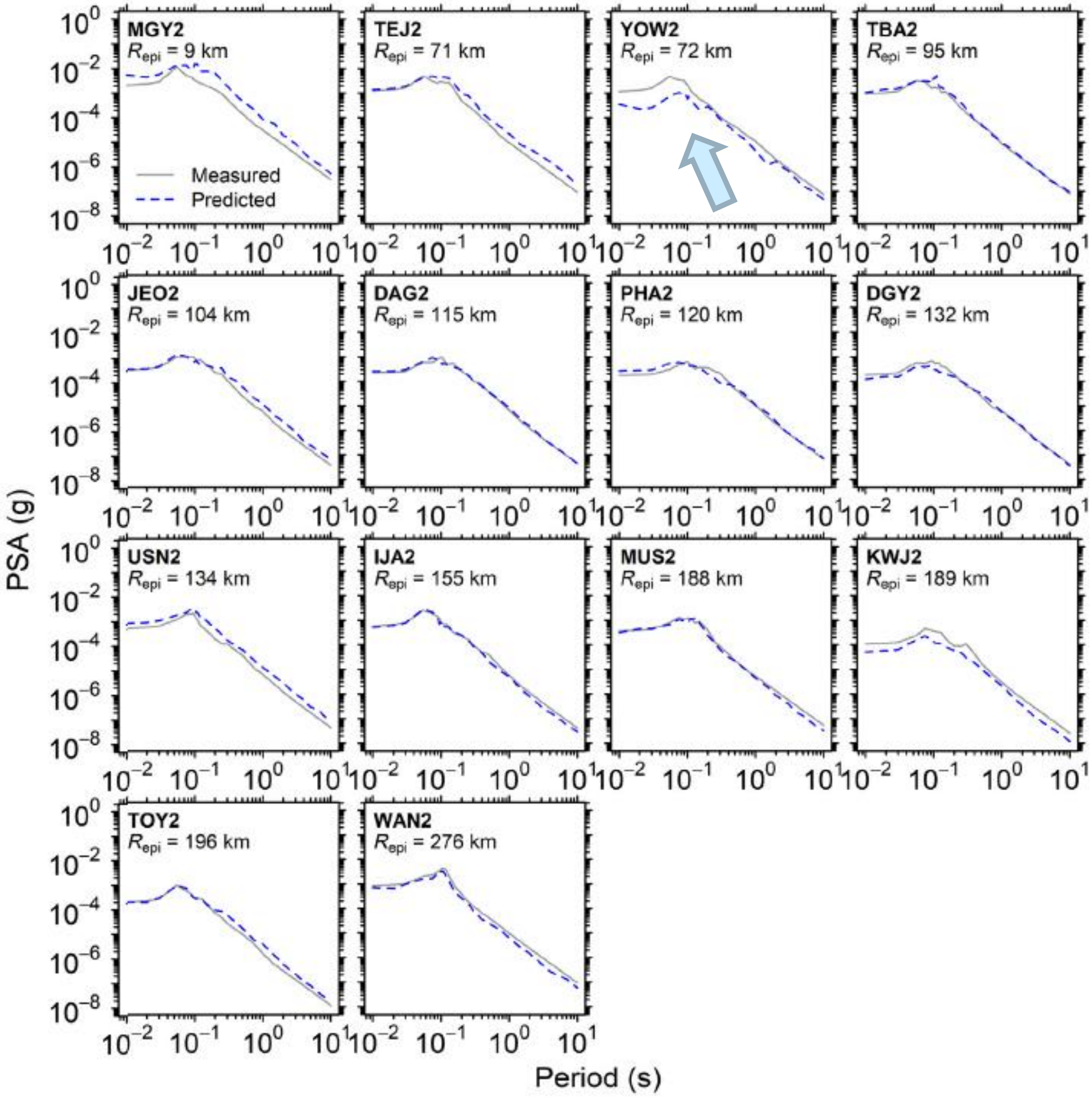
ML techniques
RF random forest
ANN artificial NN
GB gradient boosting

Measured versus estimated pseudo-spectral accelerations



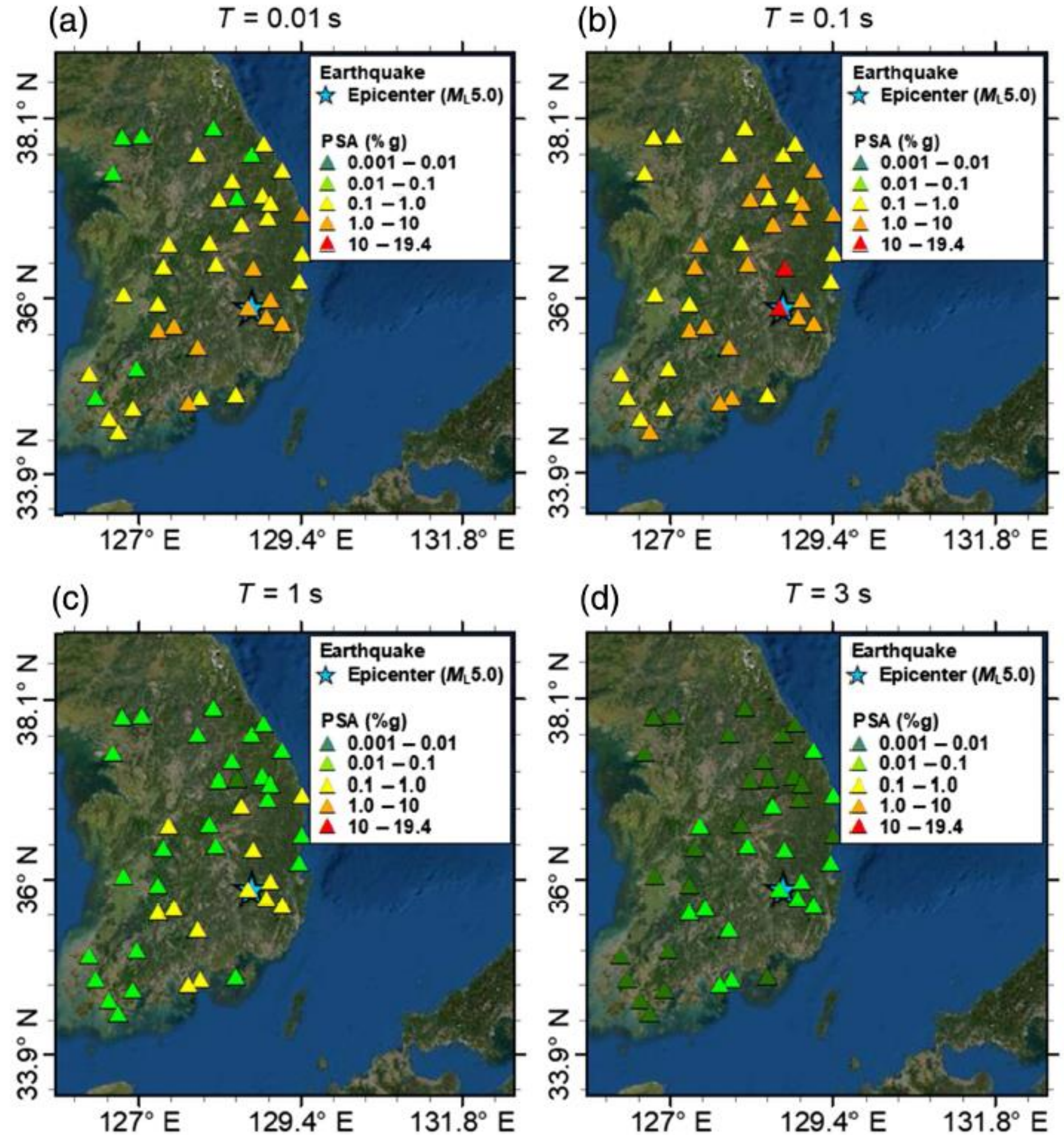
Emolo et al. (2015)

Application to real quakes (2020)



Machine-learning strategies often overcome standard regression analysis

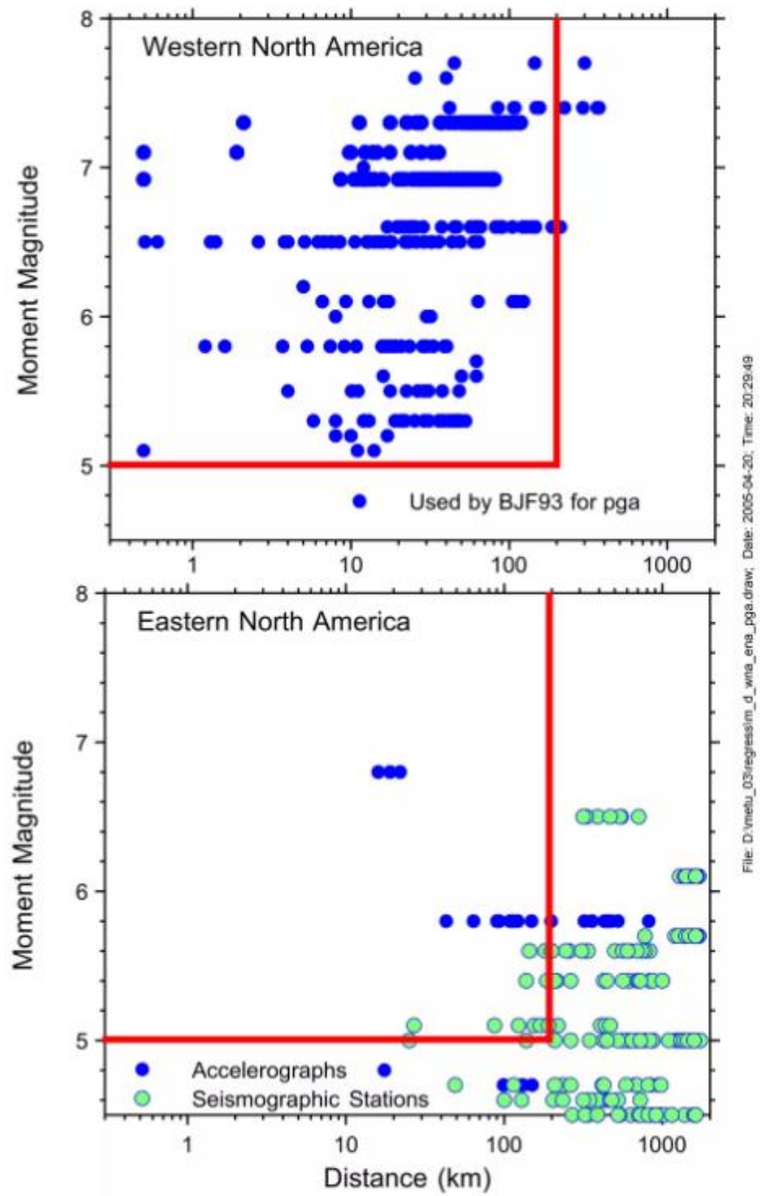
Earthquake scenario



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
- Machine-learning approaches (new!)

When adequate data are lacking:

- Regression analysis of simulating data (PDE or PDE-Empirical Green function)
- Hybrid methods capturing complex source effects form observed data and modifying for regional differences

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

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.

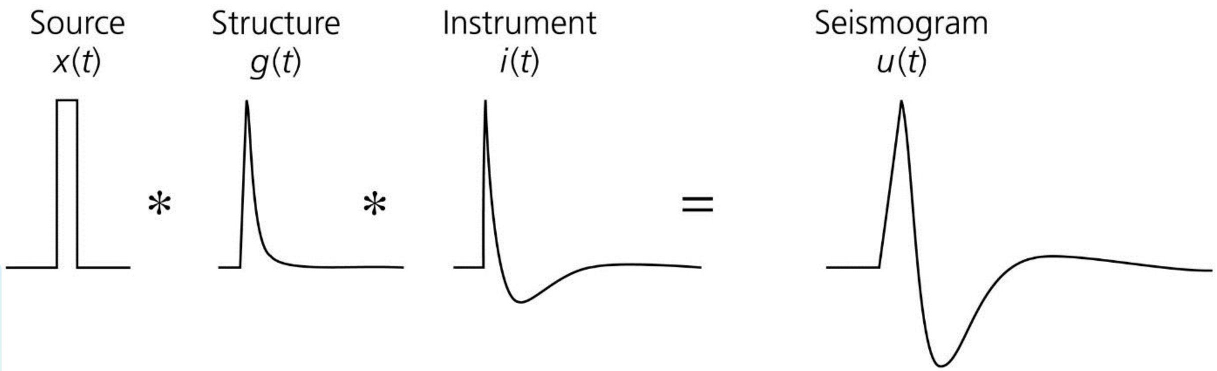
We’re looking forward to sharing new research and fostering a lively discussion about the ways the field is expanding.

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

and also site



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

How to estimate the Green function (propagation component)?

How to estimate more accurately the propagation effect

- Ad hoc 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 :

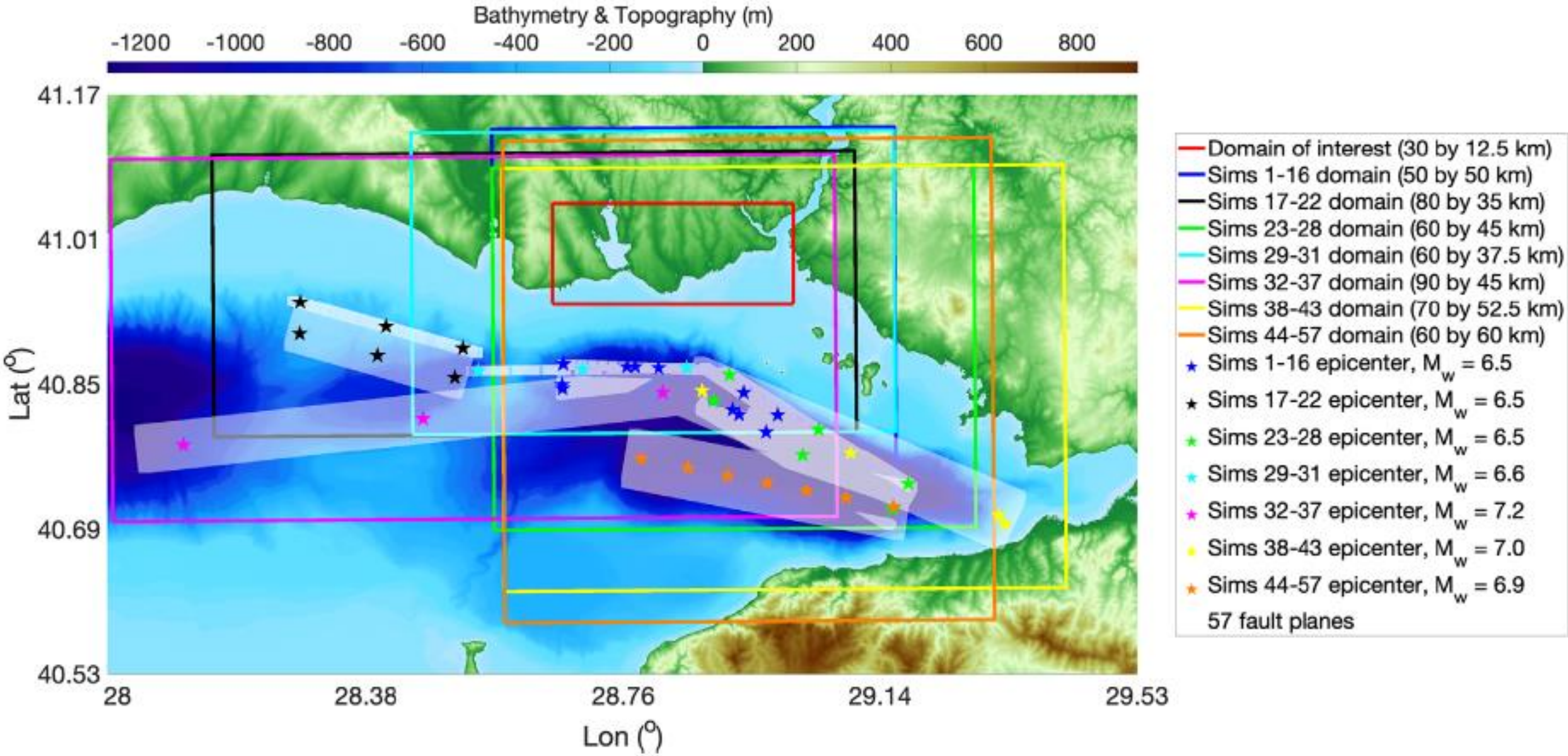
Velocity structure (spatial resolution ?)

Understanding wave propagation

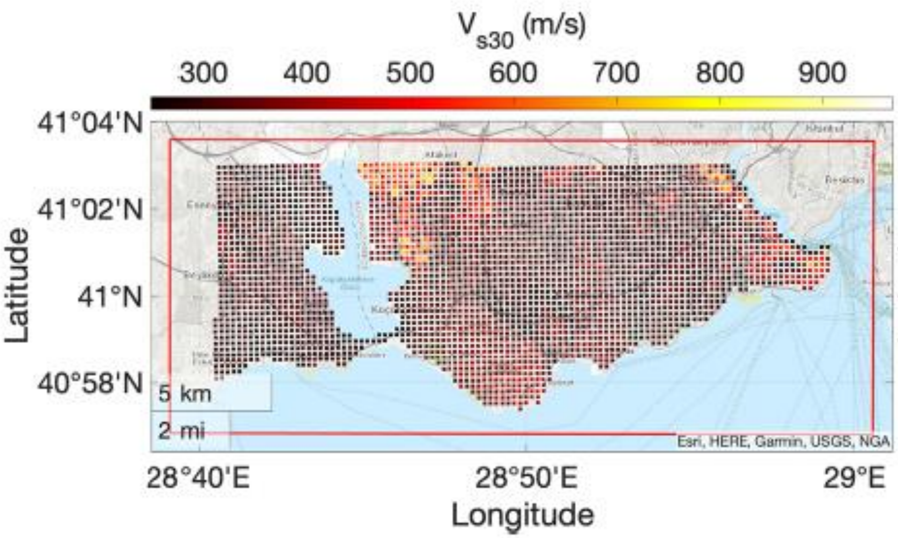
Modeling tools (computer resources)

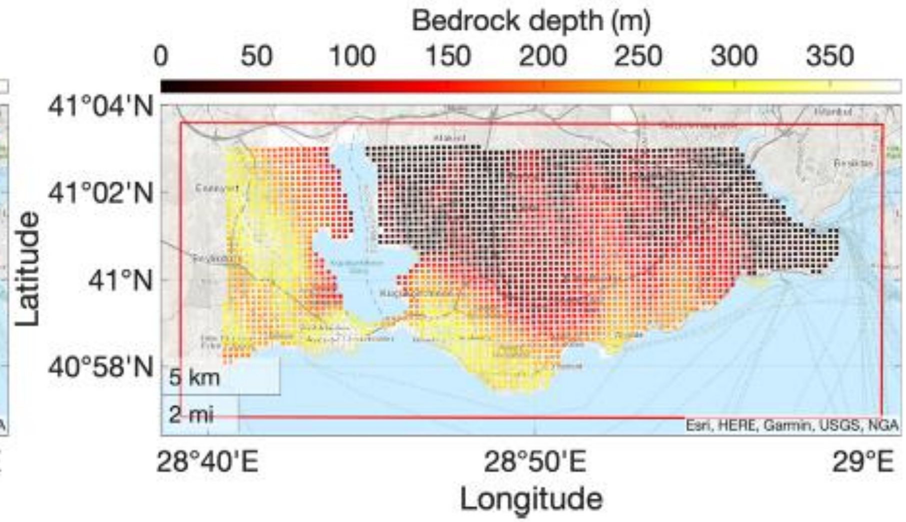
Istanbul Ground Motion Simulation

Zhang et al. (2022)



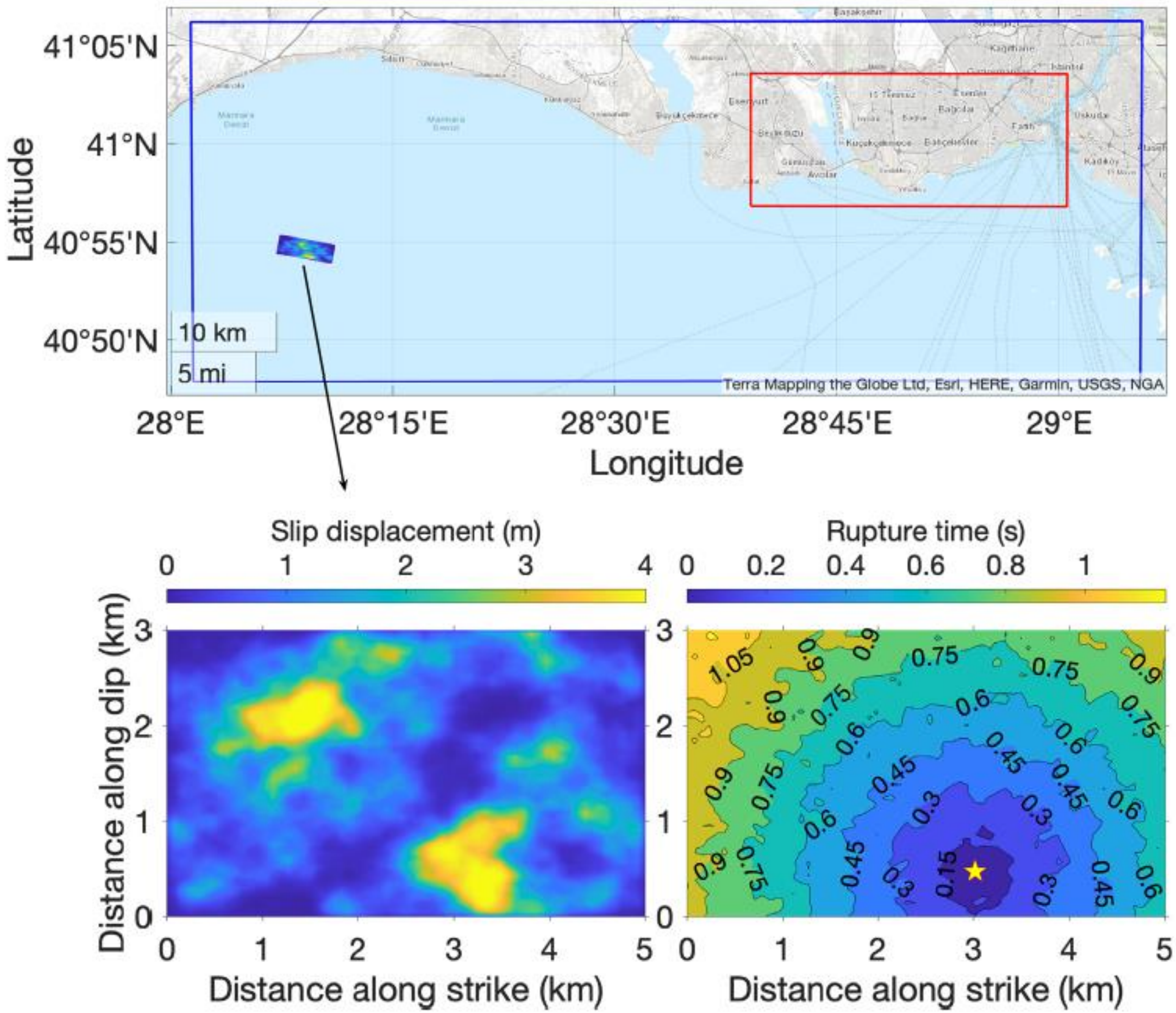
Mixed layered+3D local model



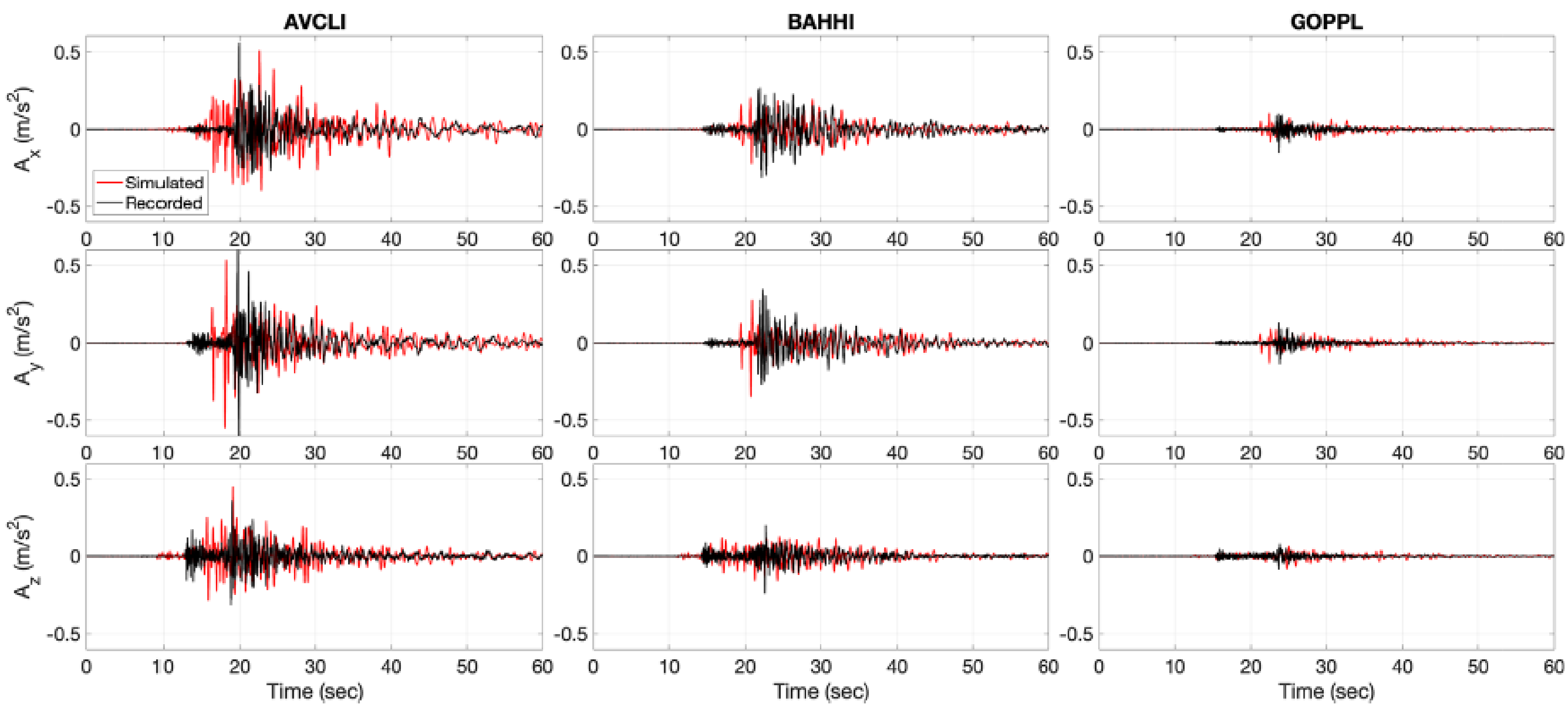


Depth at the surface of each soil layer (m)	Density (kg/m³)	V_s (m/s)	V_p (m/s)	Q_s	Q_p
0	1800	800	1600	80	160
300	2000	1000	2200	100	200
1000	3600	2250	2300	225	450
2000	4000	2500	2350	250	500
3000	4320	2700	2400	270	540
4000	4640	2900	2450	290	580
5000	5770	3490	2600	349	698
10000	6390	3500	2700	350	700
20000	6790	3920	2800	392	784

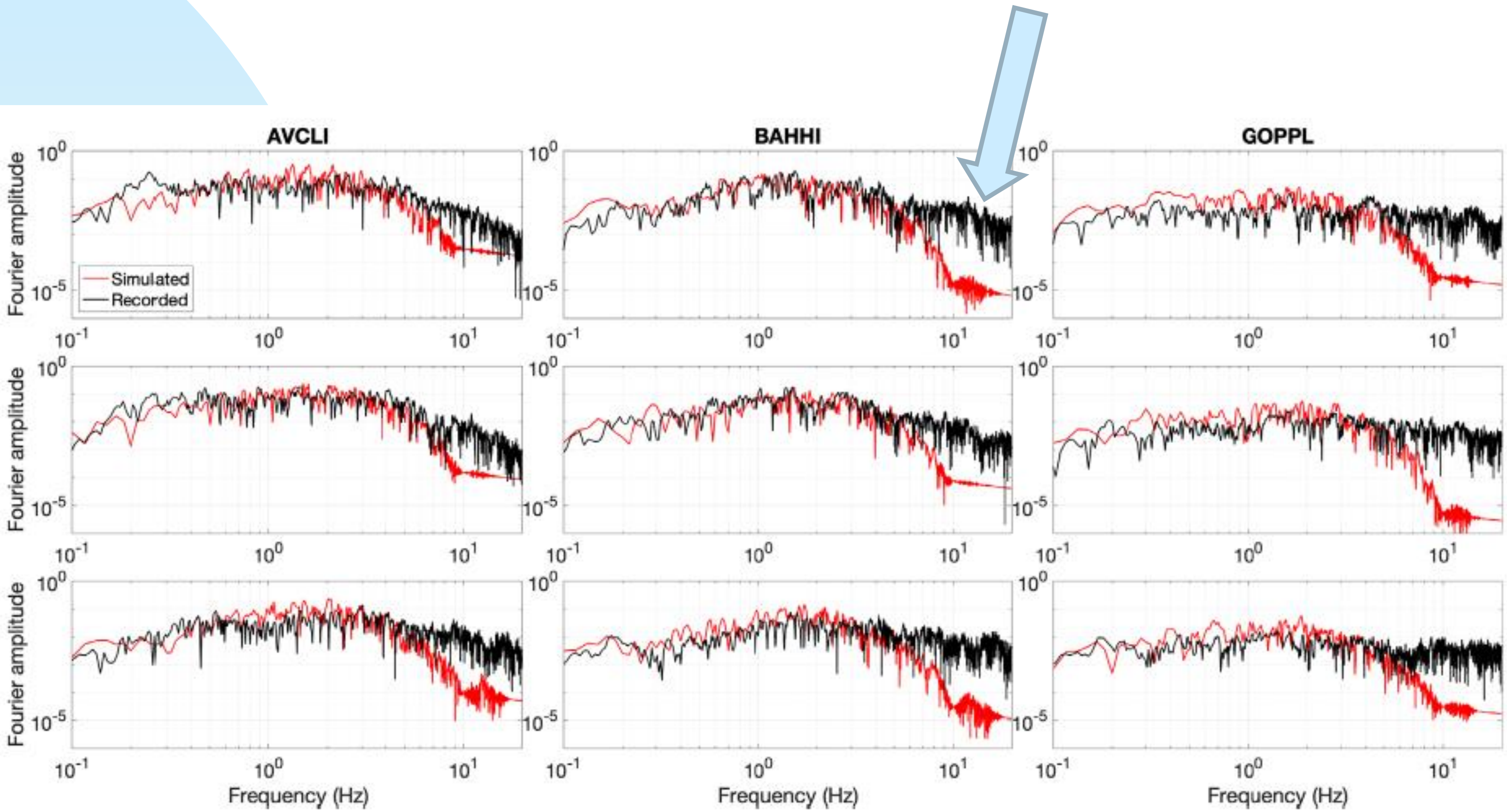
Extended source



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 !

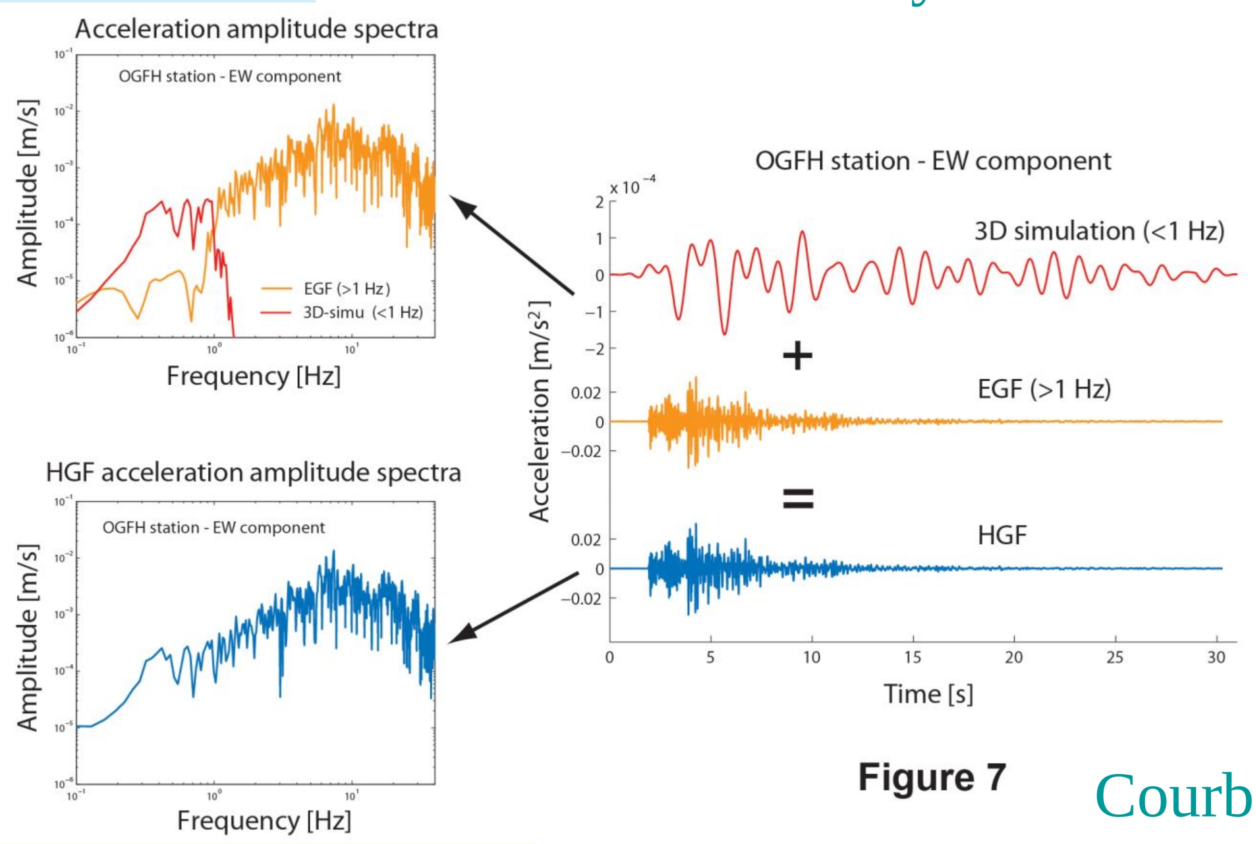
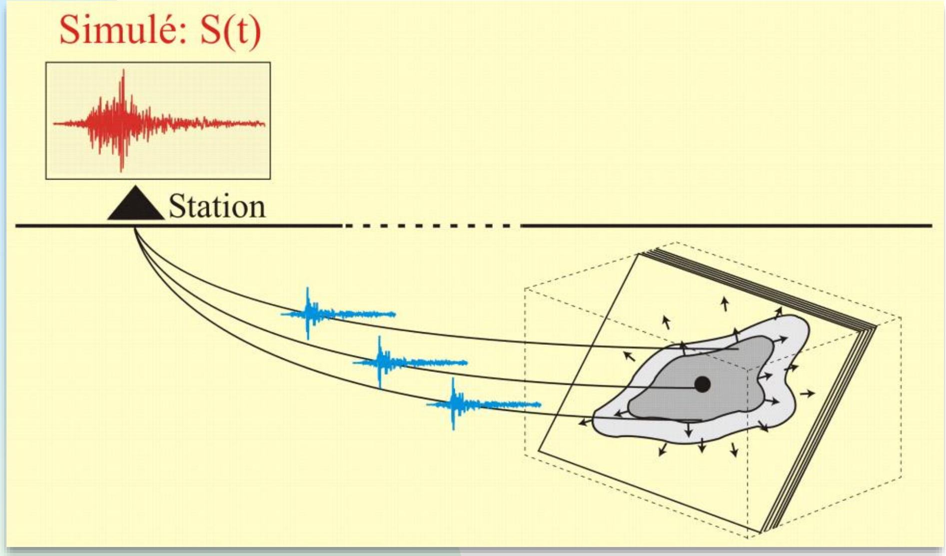


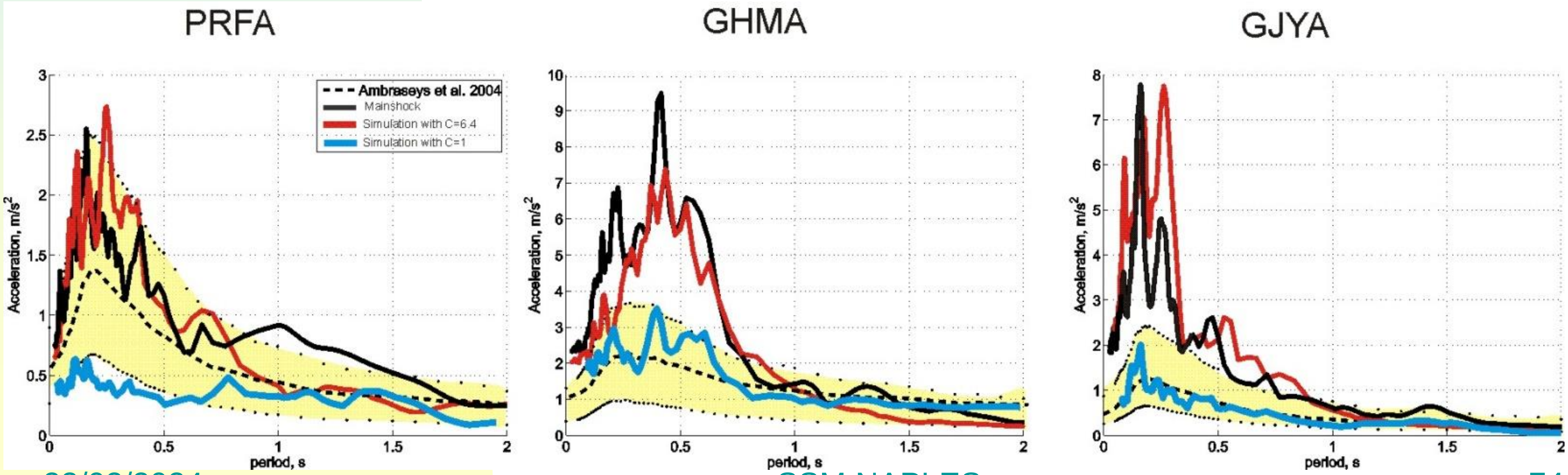
Figure 7

Courboulex et al. (1994)

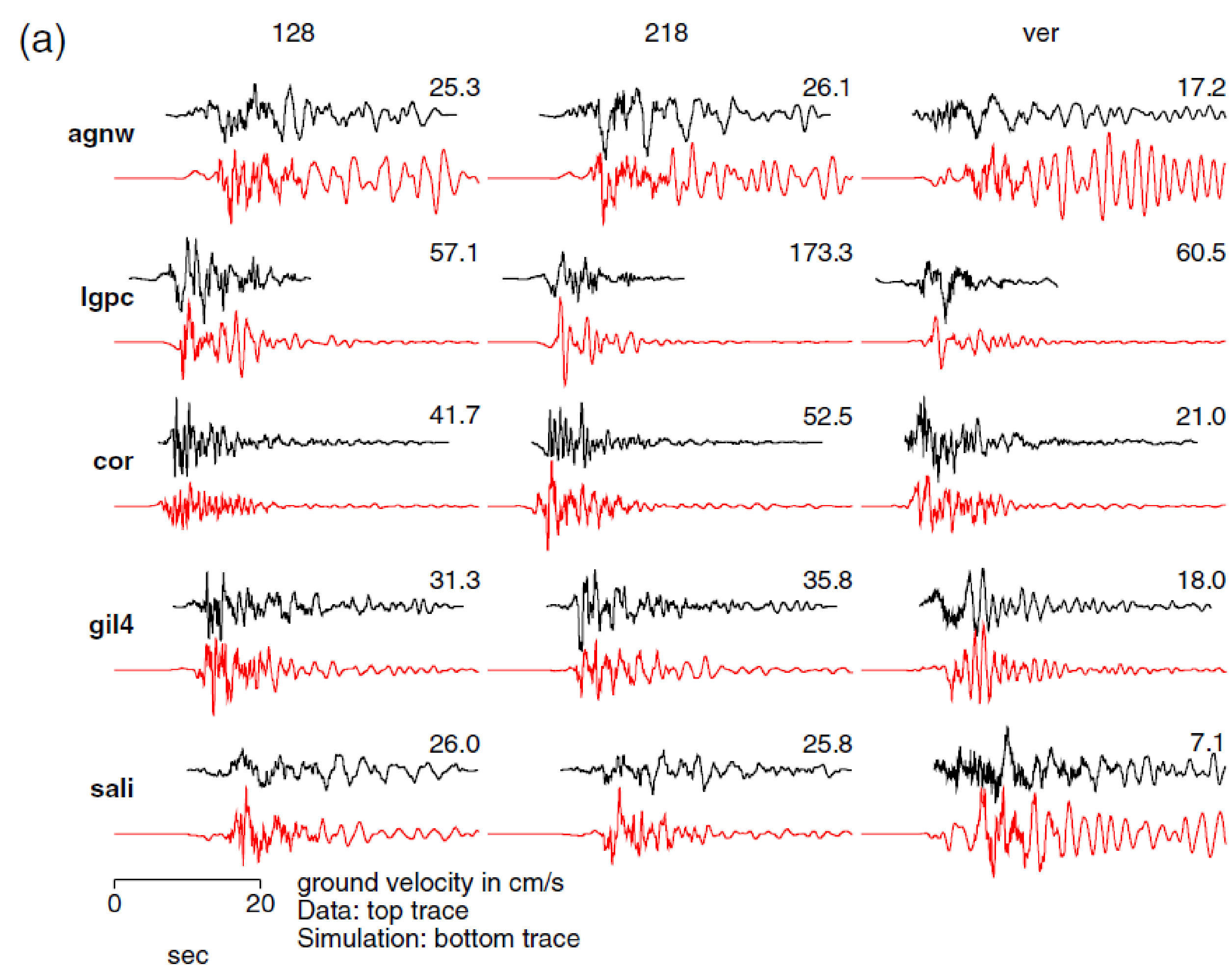
Empirical Green Function



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



(semi)-Stochastic approach

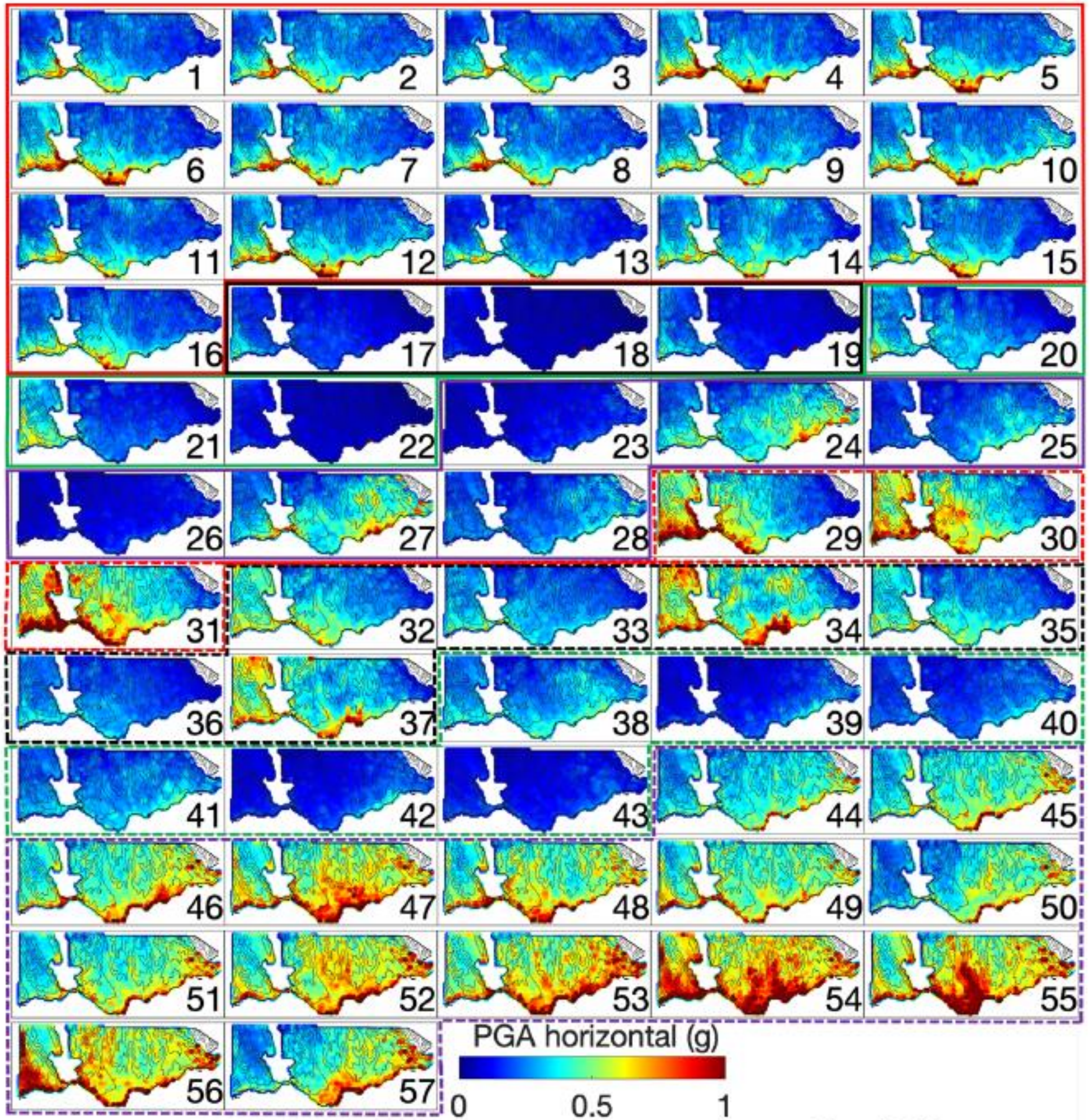


Hybrid method

Graves & Pitarka (2010)

End of digression

Ground Motion Simulation



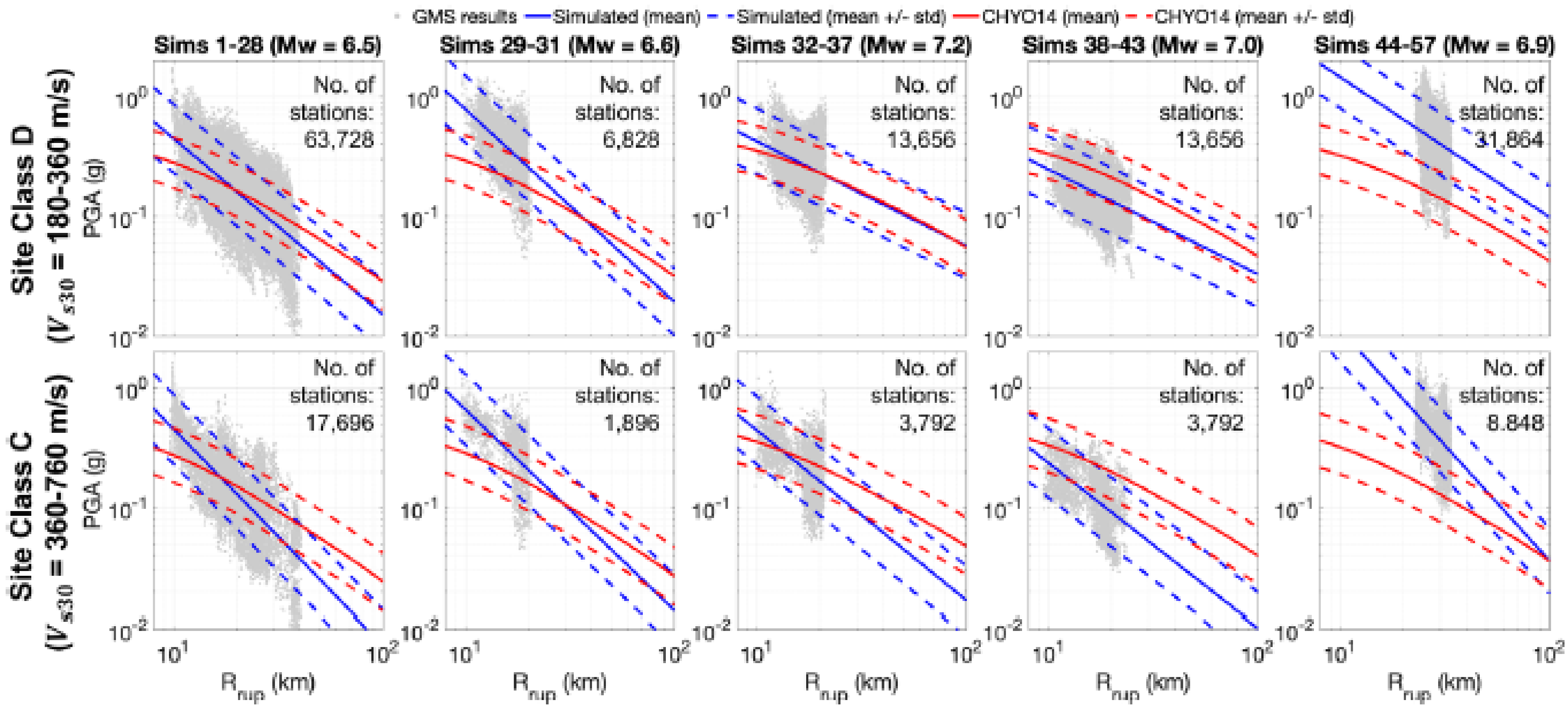
Horizontal PGA
For
57 source scenarios

Strong variability!

Zhang et al. (2022)

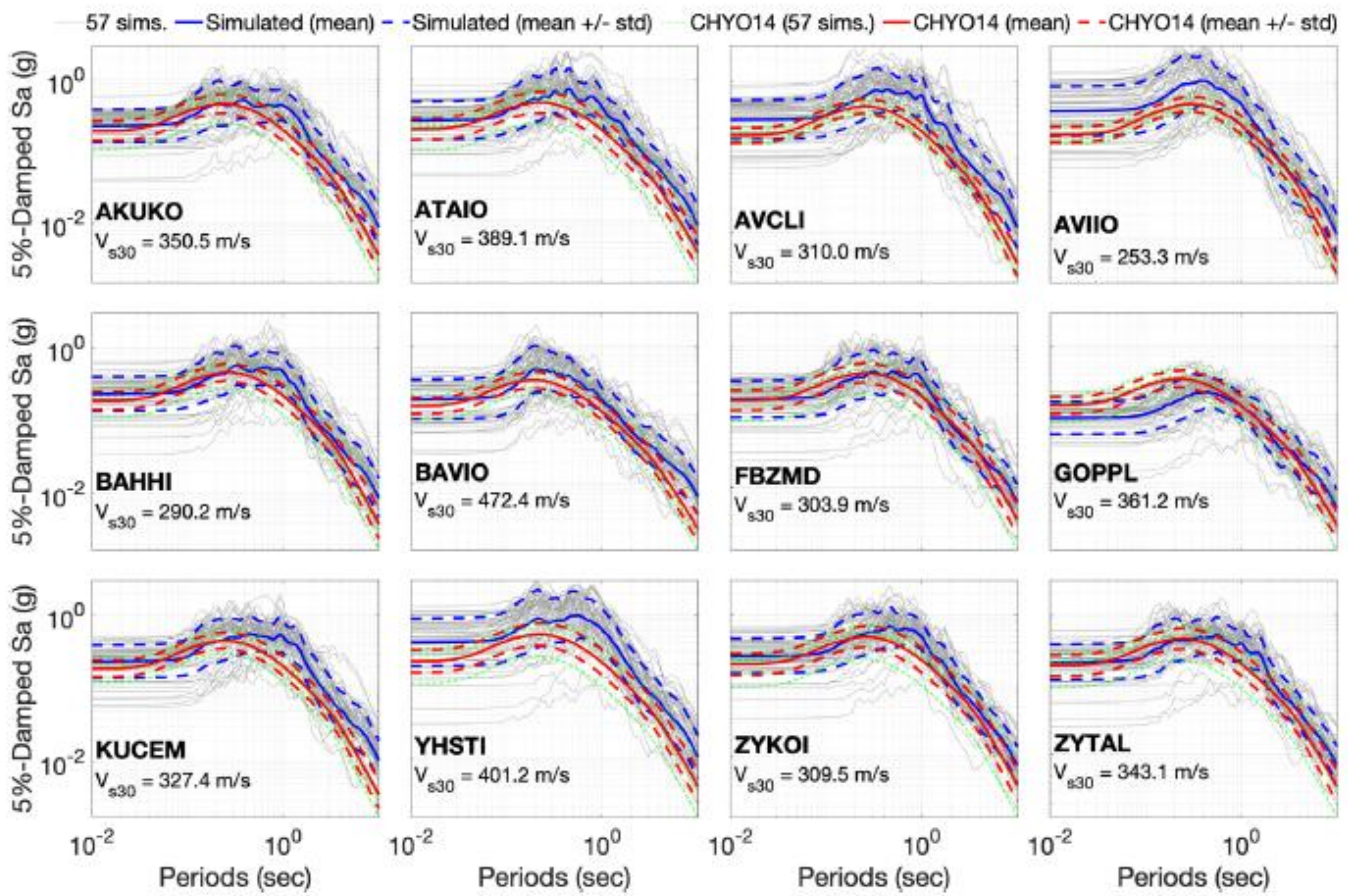
PGA for GMPE (red) and GMS (blue)

with respect to distance

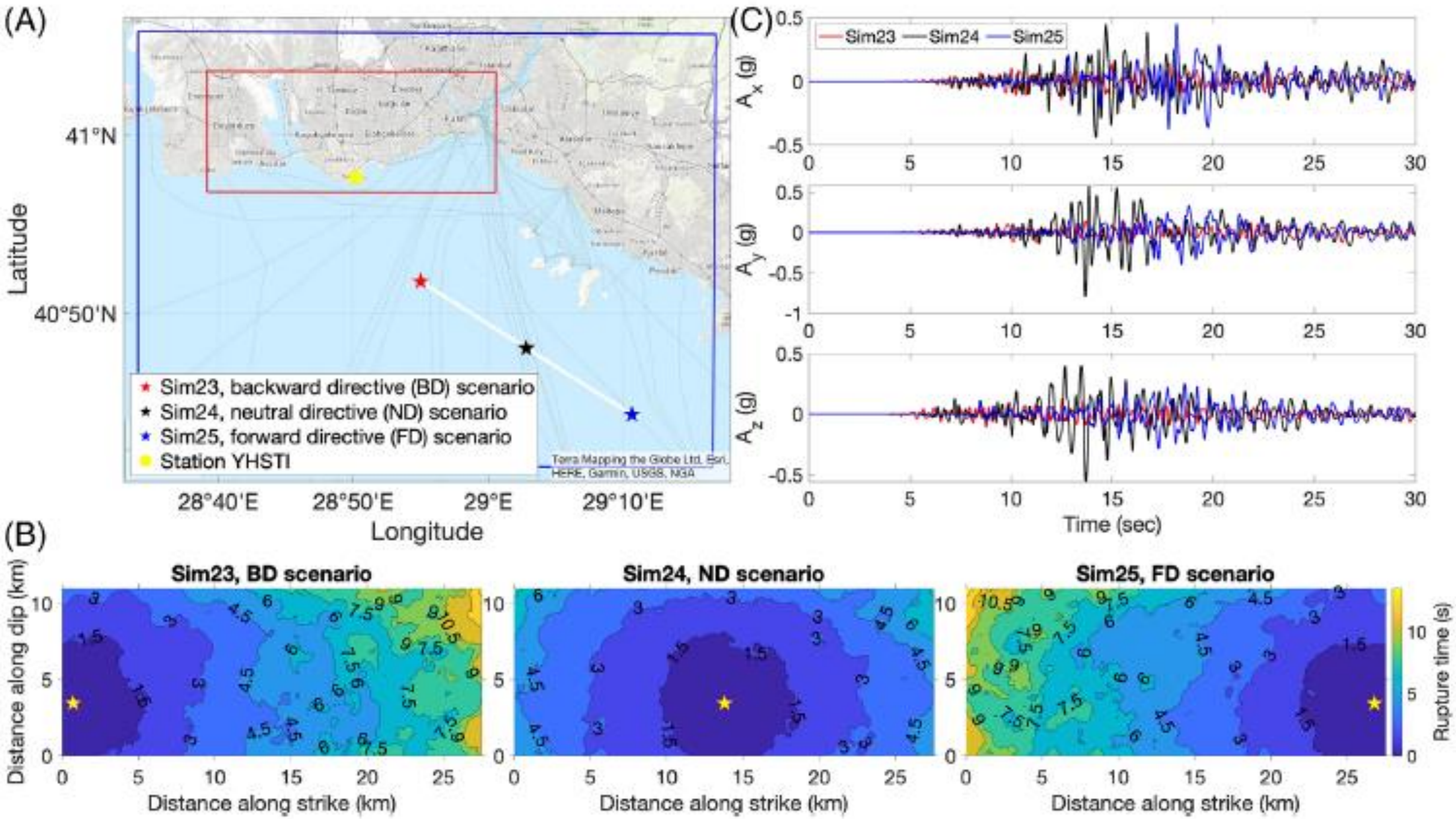


CHYO14 : GMM for Turkey (Chiou & Youngs, 2014)

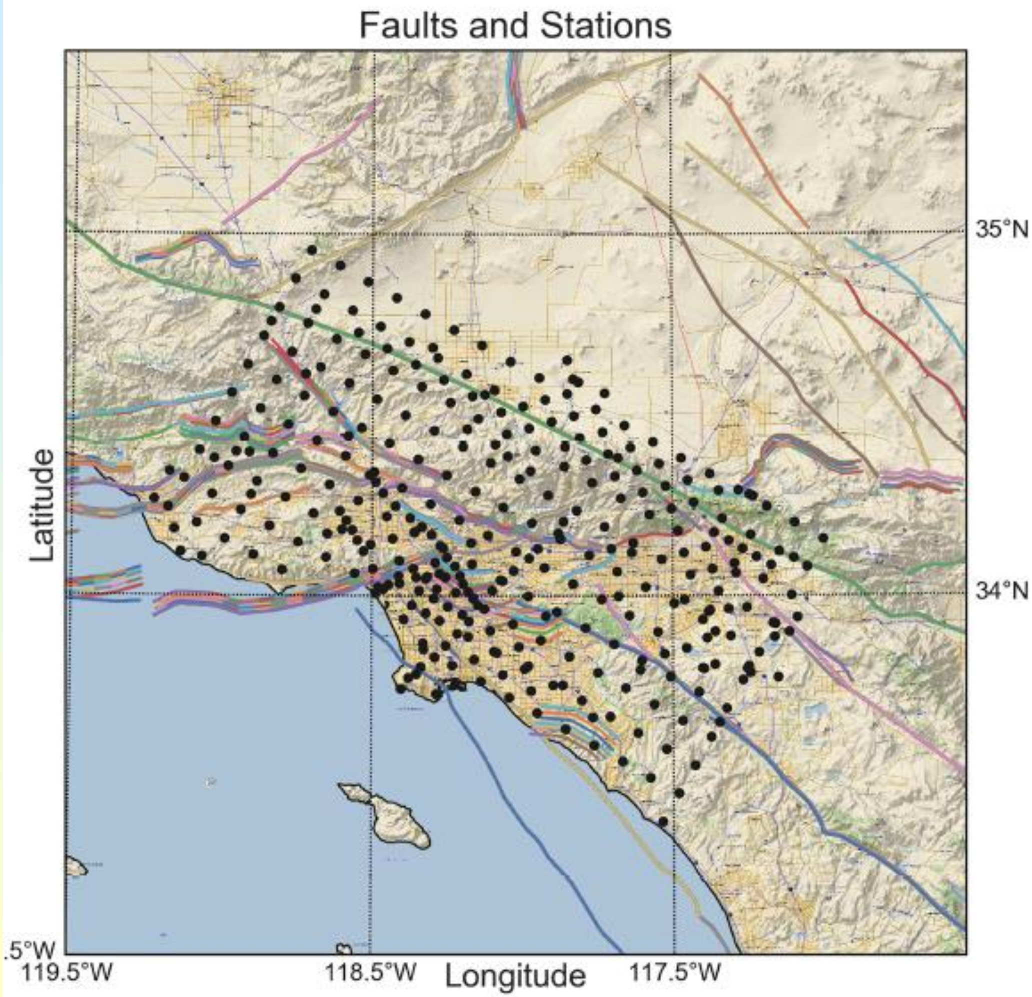
Response spectral acceleration



Three different scenarios of GMS



GMPE on synthetic data



~330 synthetic stations

~10000 fault geometries

SCEC resources

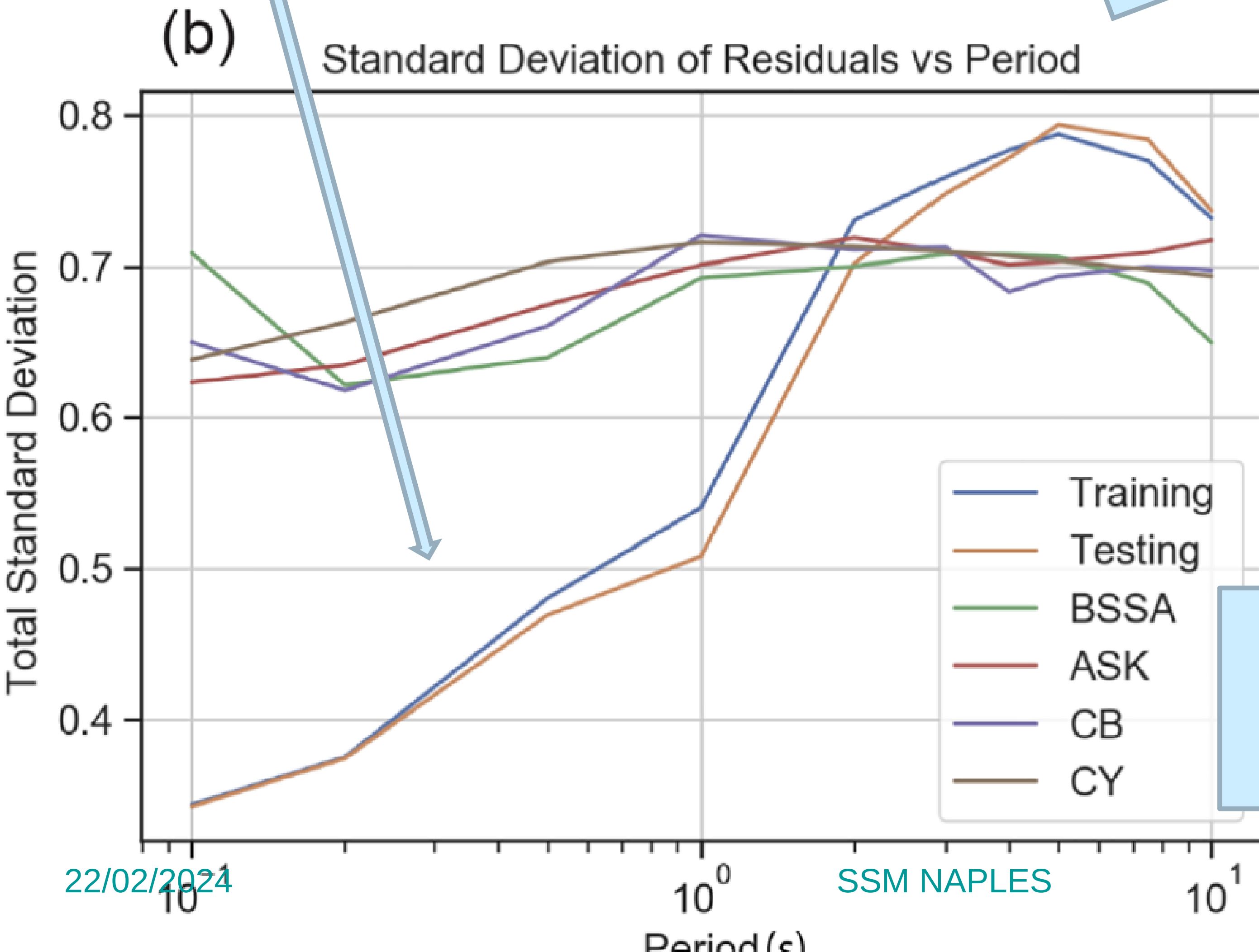
CyberShake simulations
Velocity model (CVM-S4.26.M01)
Period [0.1s-10s]

Withers et al. (2020)

GMPE on data from simulations

Better predictability. However, not enough model variations
(only large-scale velocity variations)

Less pertinent for LowFreq variability



GMPEs

Soil amplification?

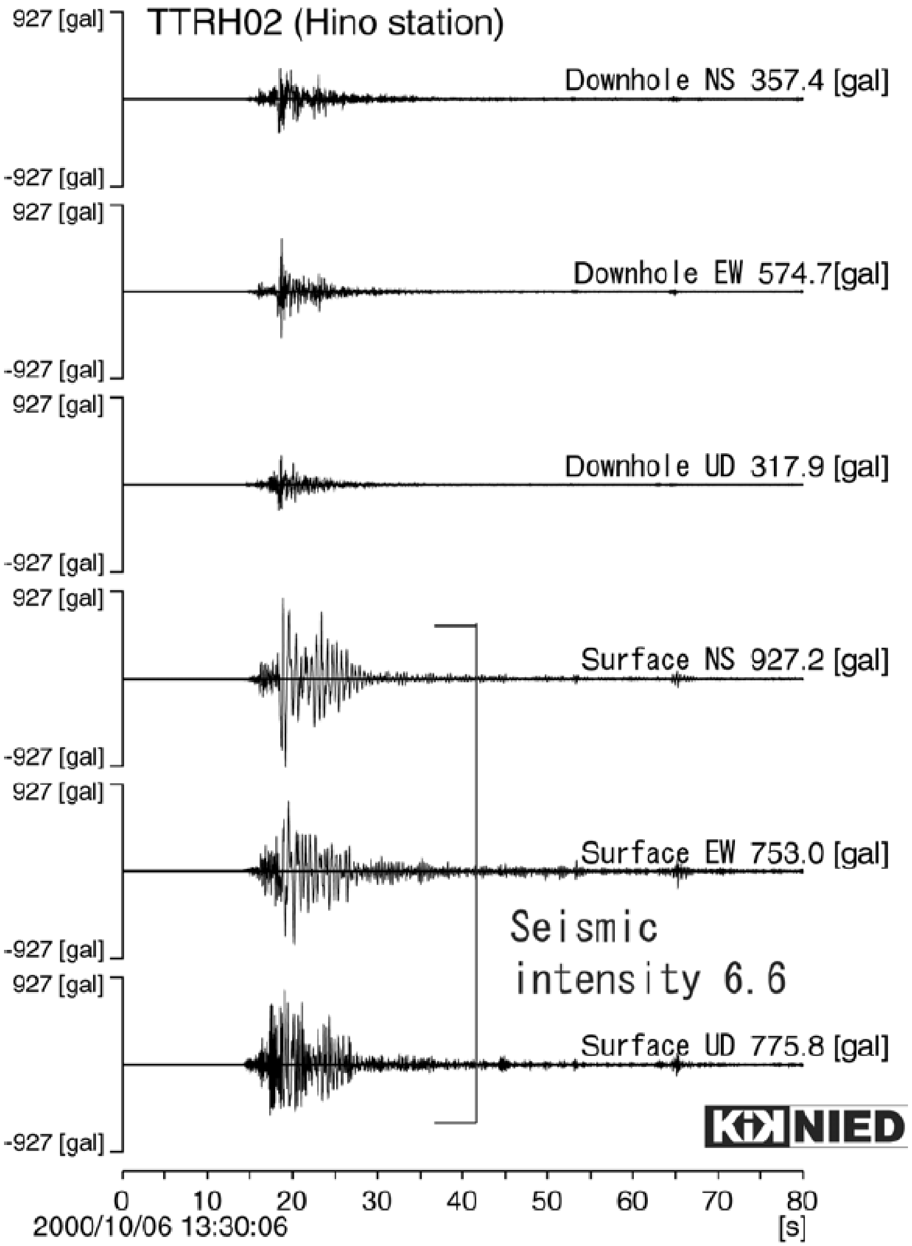
A deterministic challenge?

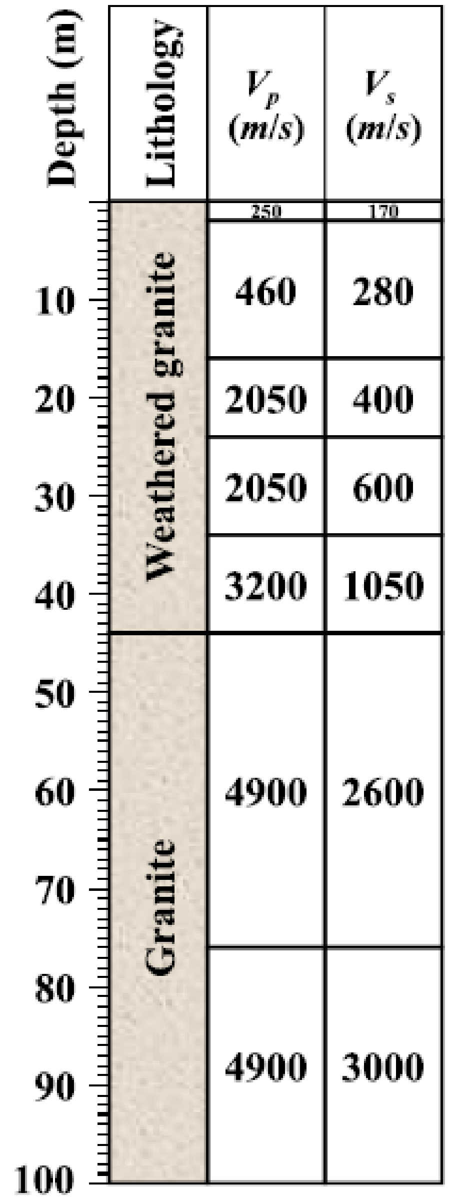
Limitations of models and parameters

- Physics-based models (Vs > 500 m/s)
- Non-linear soil behavior

Prediction of soil seismic response based on

- recorded ground motions
- synthetic ground motions





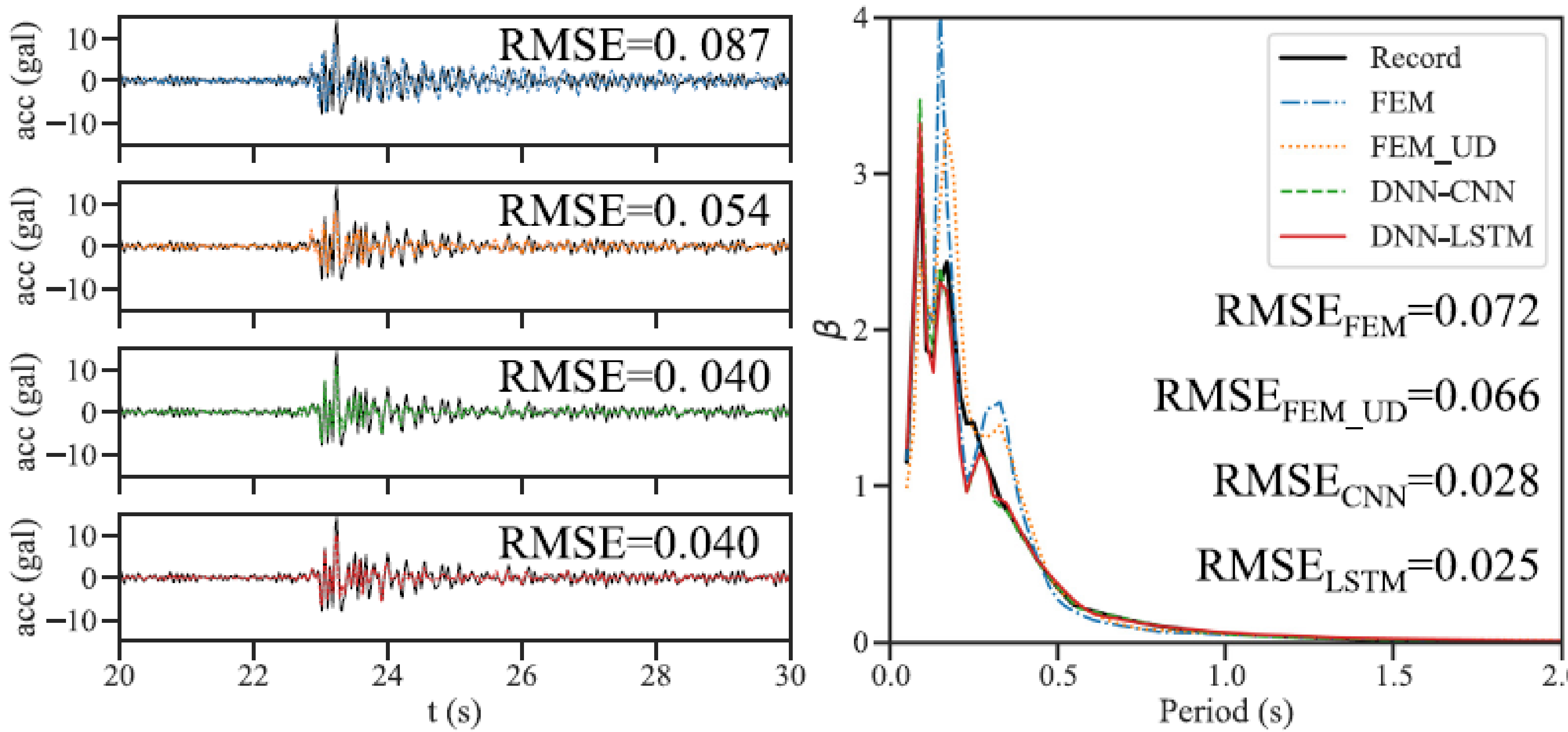
Station IBRH13

1D approximation valid

(Thompson et al., 2012)

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

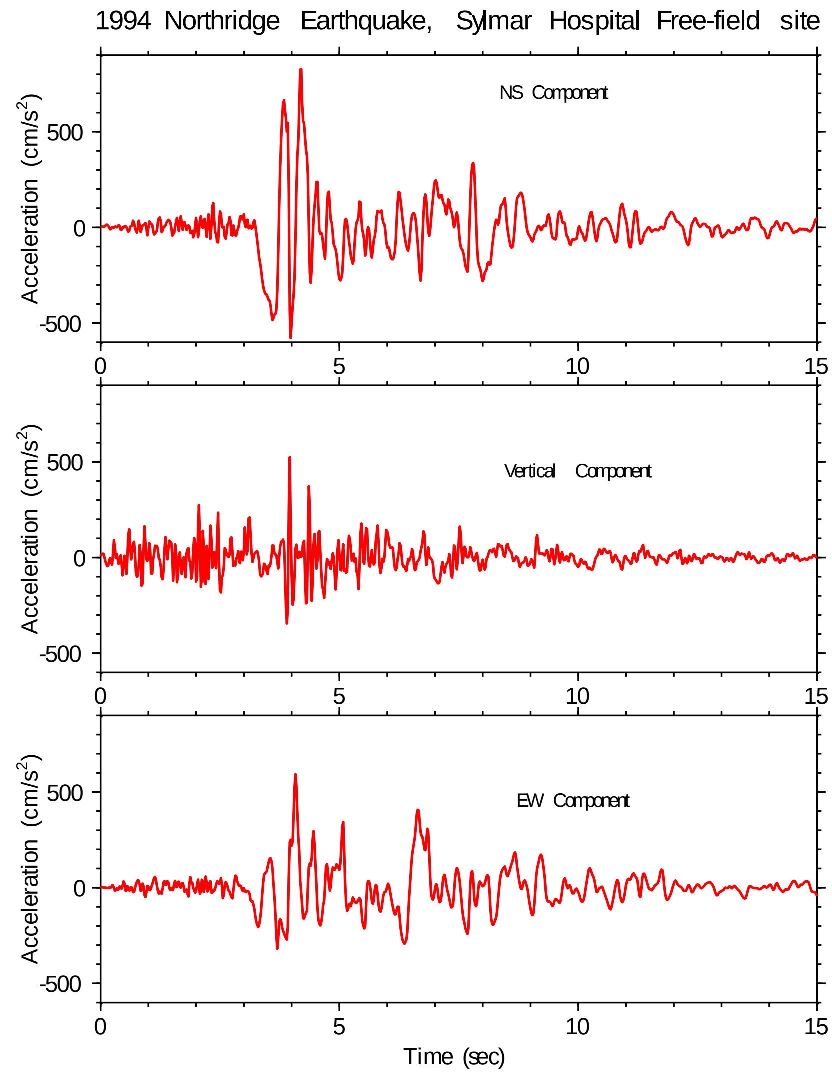
Seismogram hierarchy!
Hope for GM simulation

Body-wave phases

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

The most constrained part of ground motion prediction

Body-wave phases

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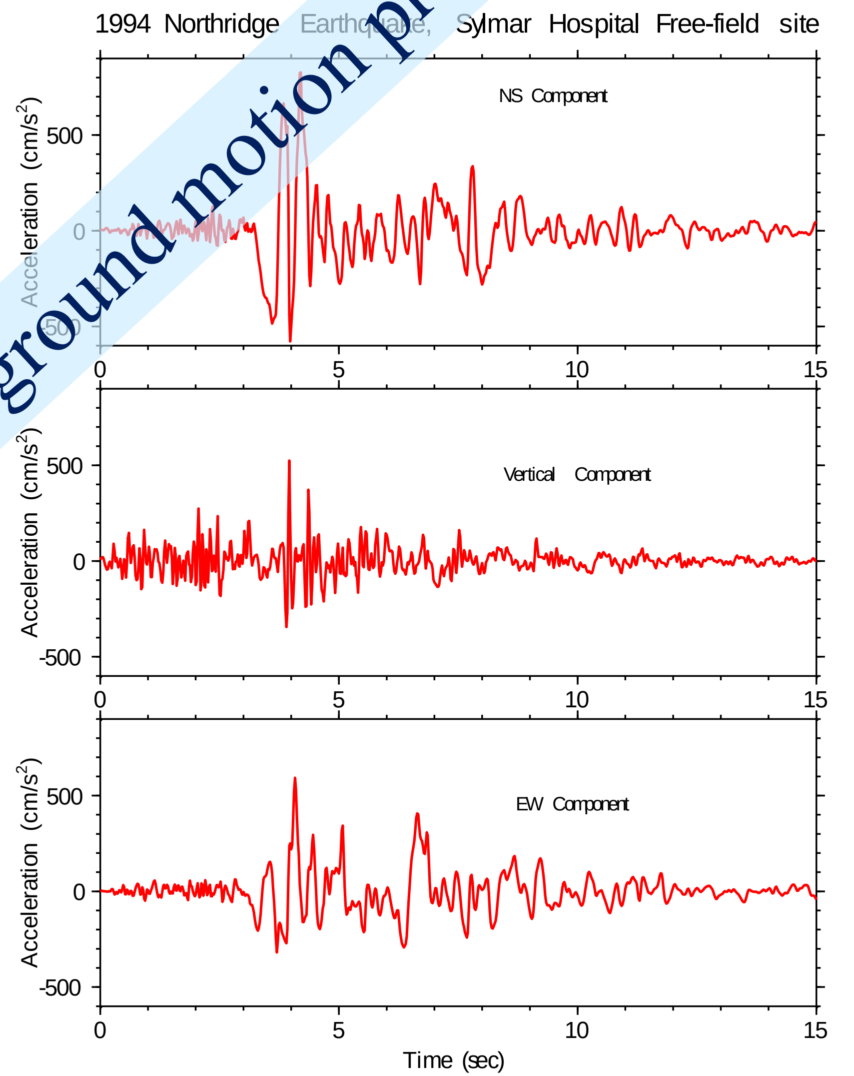


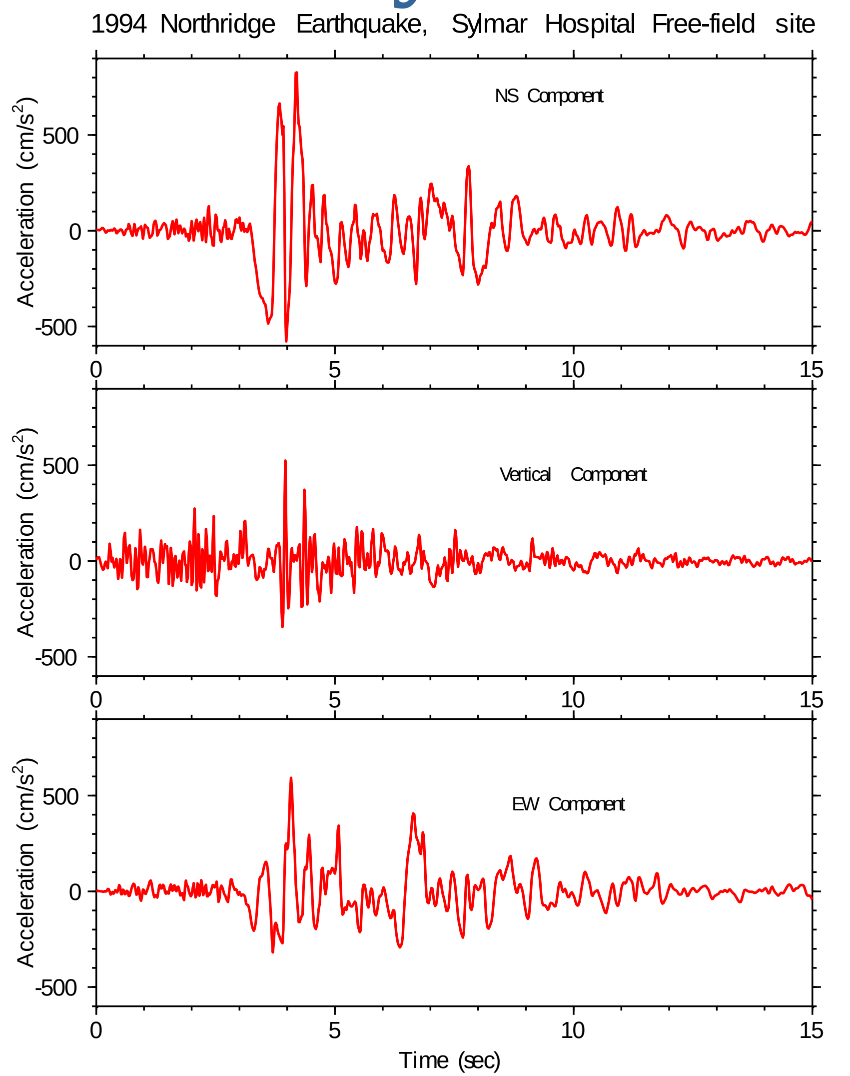
Seismogram hierarchy!

Hope for velocity model

Large-scale velocity model

Short-scale velocity model

?



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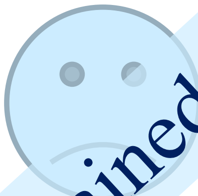
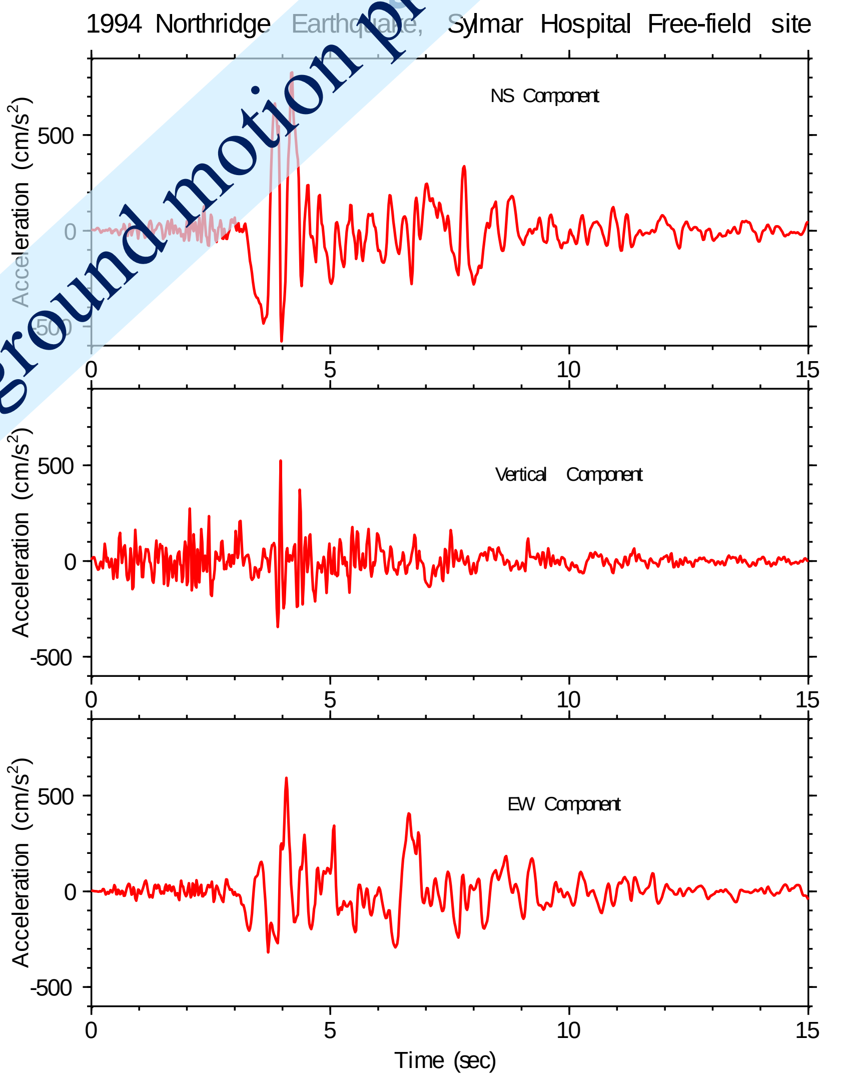


?

The most constrained part of ground motion prediction



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