Site response:

Translating ground motion simulation output into earthquake engineering input

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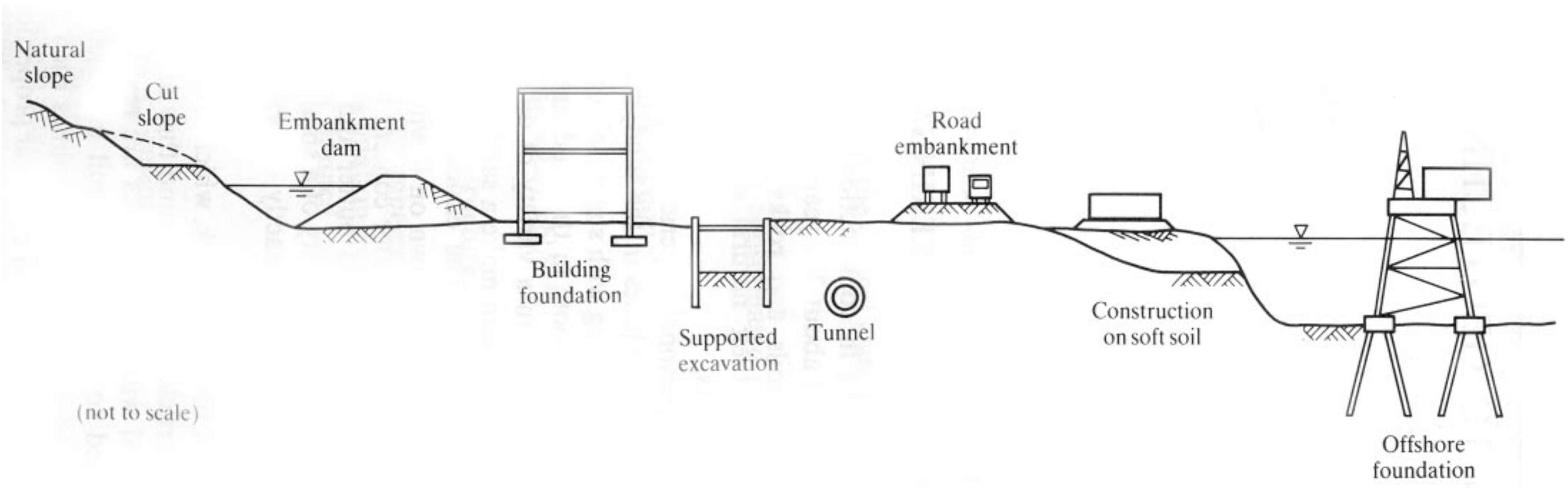
why site response?



"Virtually every structure is supported by soil or rock. Those that aren't - either fly, float, or fall over."

-Richard Handy, 1995

Observations

"The convulsion was greater along the Mississippi, as well as along the Ohio, than in the uplands. The strata in both valleys are loose. The more tenacious layers of clay and loam spread over the adjoining hills … suffered but little derangement."

- from Daniel Drake (1815) on the 1811-1812 New Madrid sequence

Observations

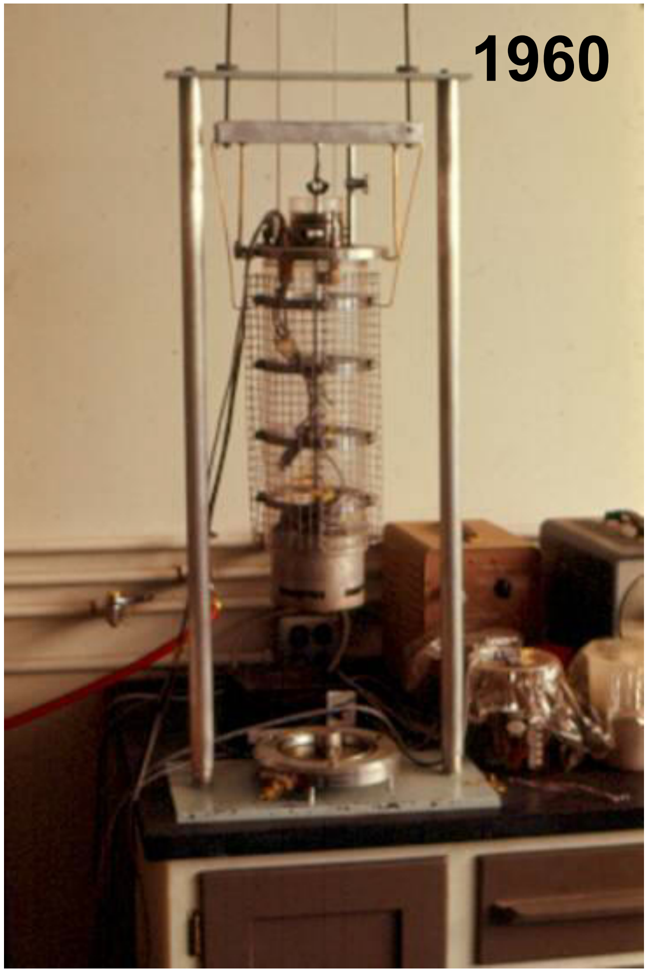
"The convulsion was greater along the Mississippi, as well as along the Ohio, than in the uplands. The strata in both valleys are loose. The more tenacious layers of clay and loam spread over the adjoining hills … suffered but little derangement."

- from Daniel Drake (1815) on the 1811-1812 New Madrid sequence

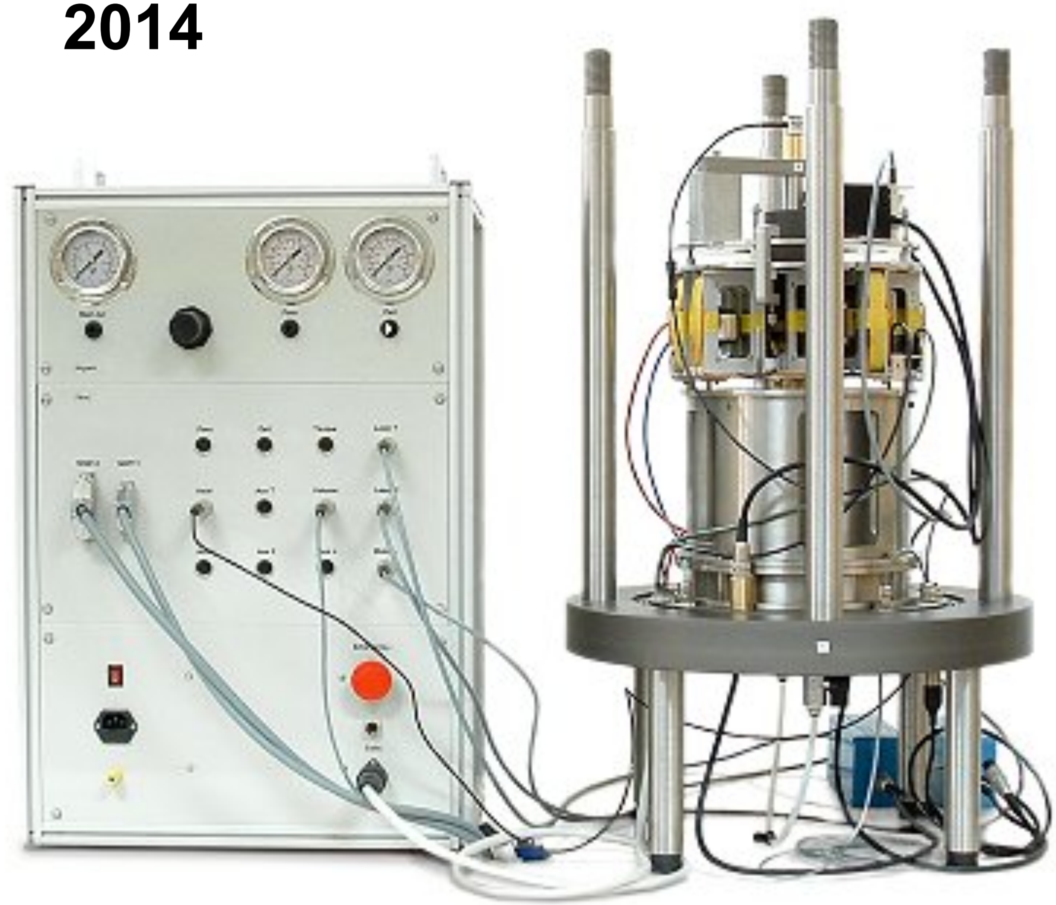
"*… a movement … must be modified while passing through media of different constitutions. Therefore, the earthquake effects will arrive to the surface with higher or lesser violence according to the state of aggregation of the terrain which conducted the movement. This seems to be, in fact, what we have observed in the Colchagua Province (of Chile) as well as in many other cases.*"

- from Del Barrio (1855)

Laboratory experiments

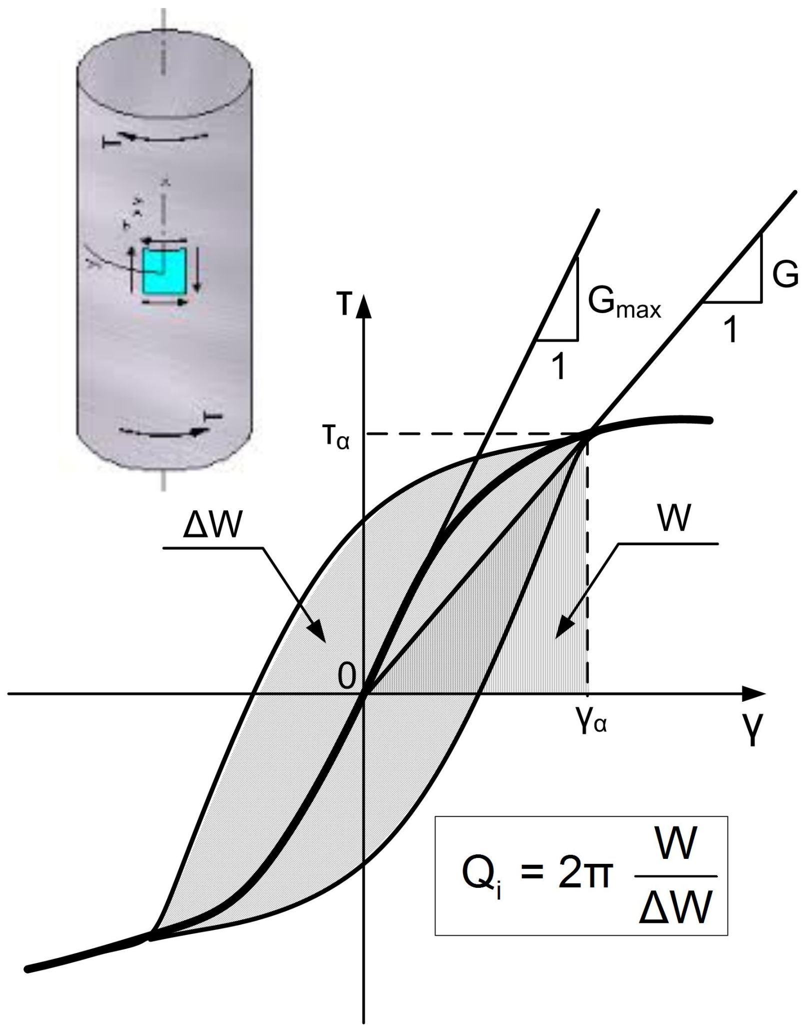


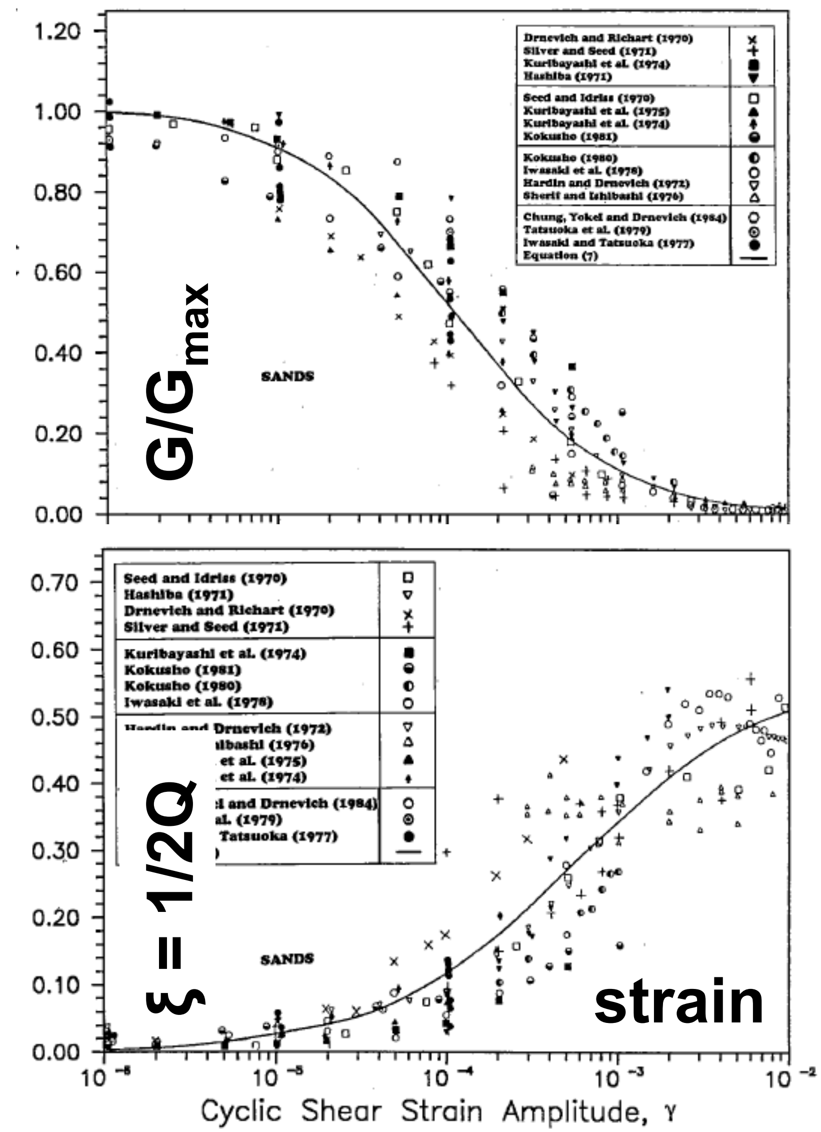
1960



2014

Soil response to cyclic loading





Geotechnical Predictive Models

15 constitutive model input and state parameters

Table I. Constant of the SANICLAY model with destructuration for Bothkennar clay.

Paramater	Description	Value
$M_c(N_c)$	Slope of the CSL on the compression side of $p-q$ plane (shape of the yield surface)	1.4 (1.2)
$m(n)$	Ratio of the slope of the CSL on the extension and on the compression side of $p-q$ plane (shape of the yield surface)	0.75 (1)
ν	Poisson's ratio	0.2
λ	Total volume change due to a change in mean stress	0.255
κ	Elastic volume change due to a change in mean stress	0.03
$x_\alpha\,(x_\beta)$	Saturation limit of anisotropy under paths with $\eta =$ const.	3.14 (1)
C	Rate of evolution of anisotropy	12
k_i	Parameter describing the rate of isotropic destructuration	0.9
k_f	Parameter describing the rate of frictional destructuration	1.3
A	Parameter describing coupling between volumetric and frictional destructuration	0.2

Table II. Initial conditions (model state variables) for undisturbed Bothkennar clay.

Variable	Description	Value
e	Void ratio	1.86
p_0^*	Defining the size of the yield surface	53
$\alpha\,(\beta)$	Orientation of the plastic potential (yield) surface	0.2(0.7)
S_i	Isotropic structuration factor	6.0
S_f	Initial frictional structuration factor	1.3

Dafalias, Y. F., Manzari, M. T., and Papadimitriou, A. G., "**SANICLAY: simple anisotropic clay plasticity model**"
International Journal for Numerical and Analytical Methods in Geomechanics, vol. 30, pp. 1231-1257, 2006.

what this lecture is NOT about

Ground failure: Surface rupture

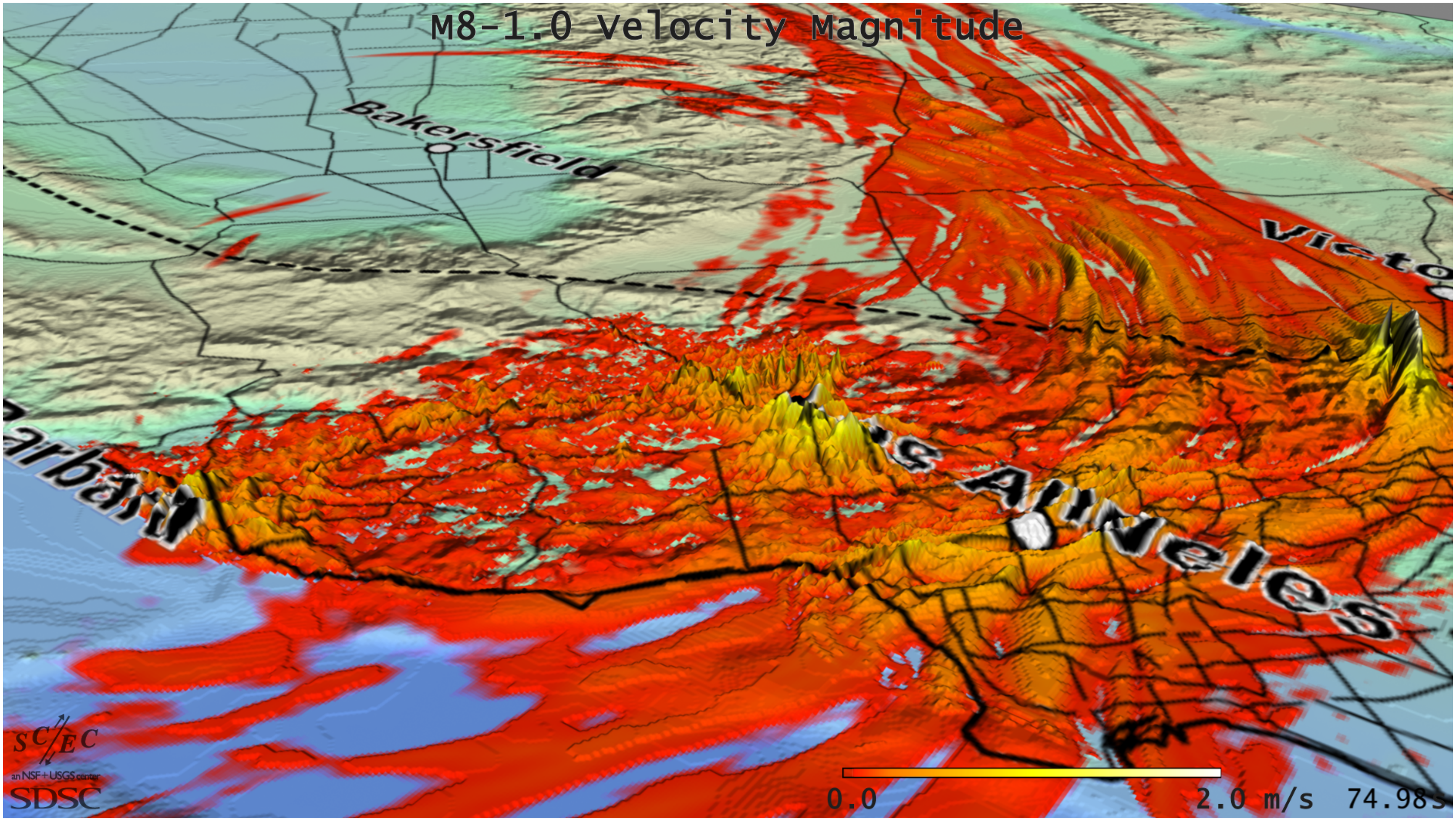
Denali, 2002

Landslides

Liquefaction

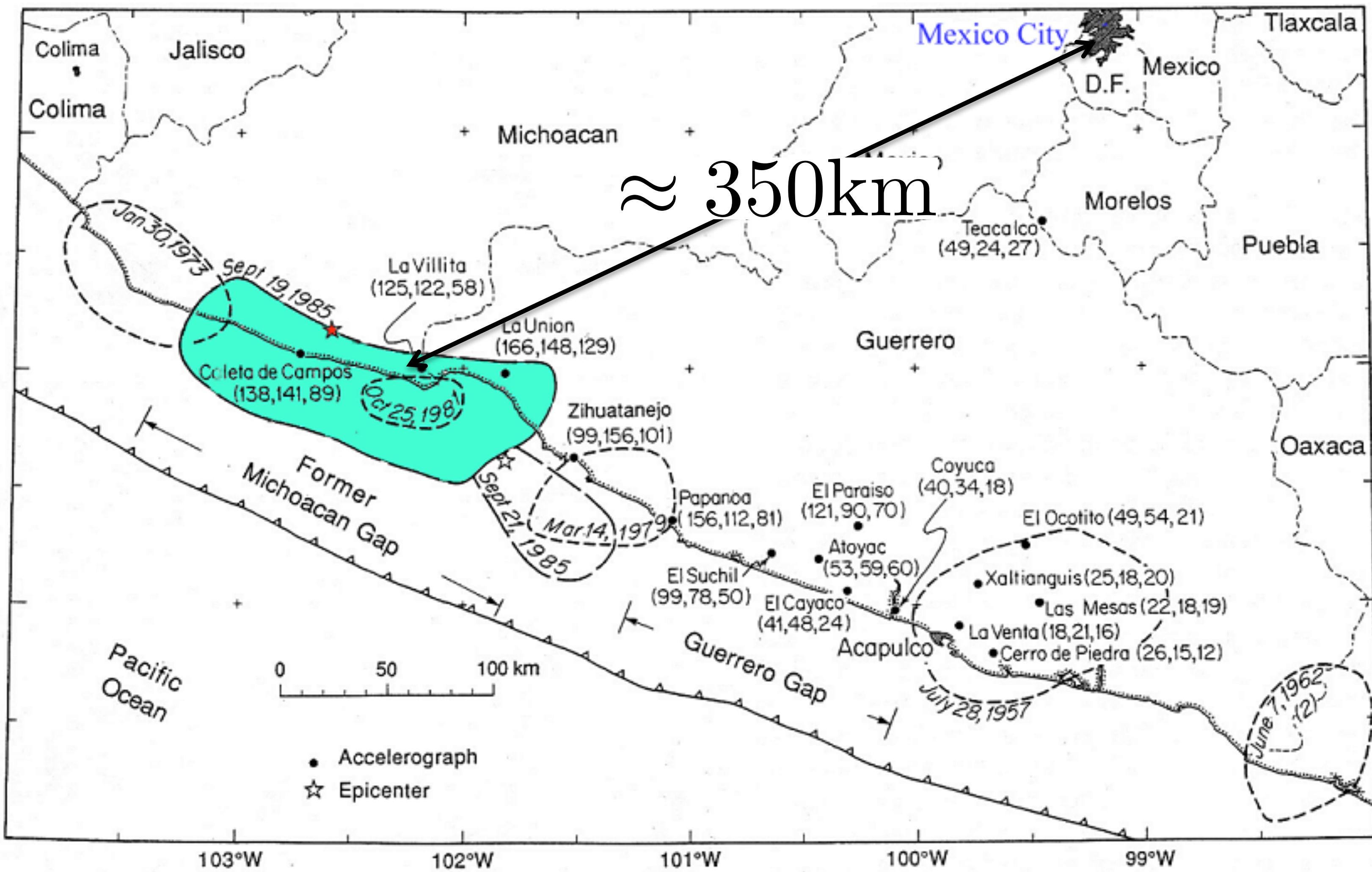
Topography effects

3D basin effects



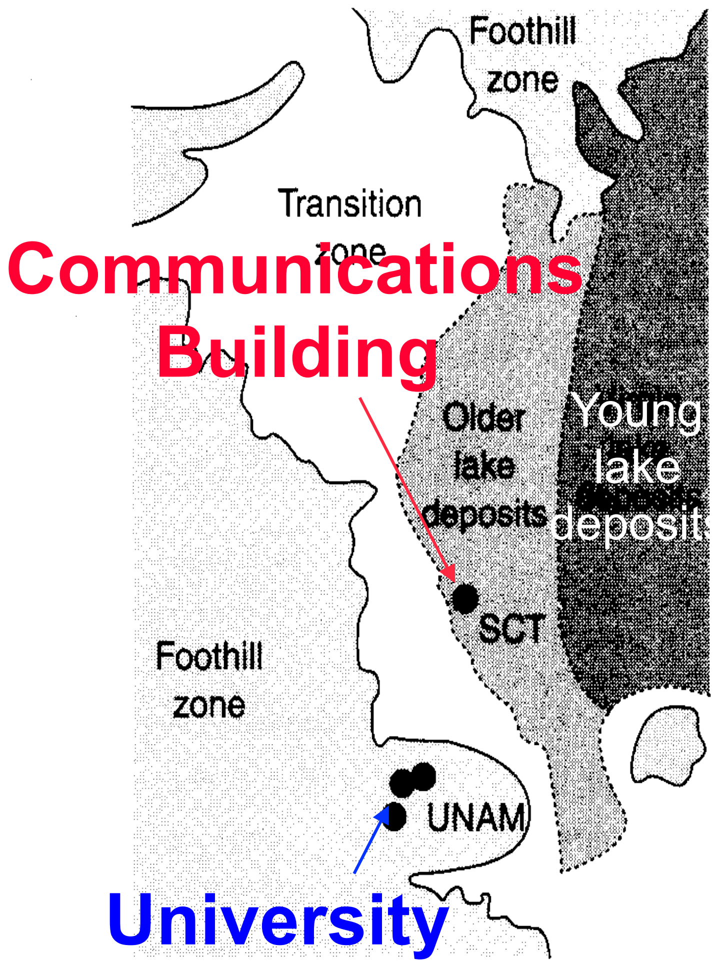
what IS this lecture about?

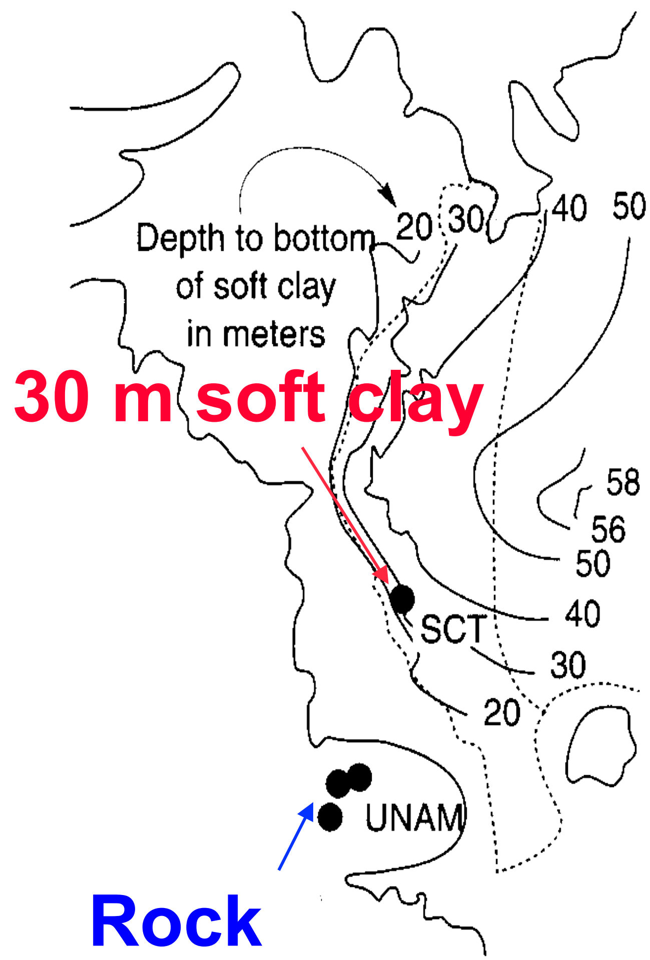
M8.1 Mexico City earthquake, 1985



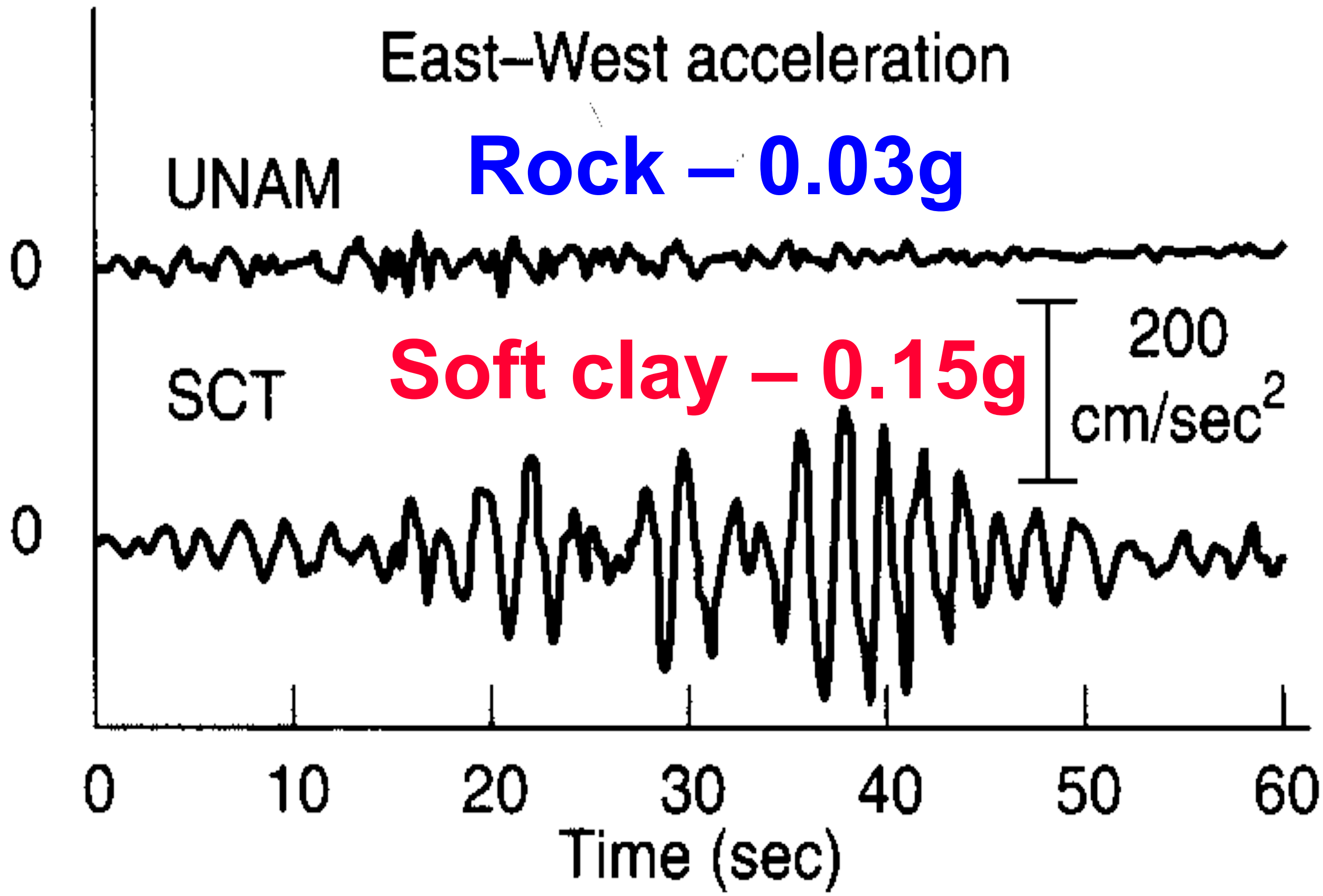
M8.1; Death toll: 9000 deaths
collapse of 371 high rise structures, **especially 10-14 story buildings**

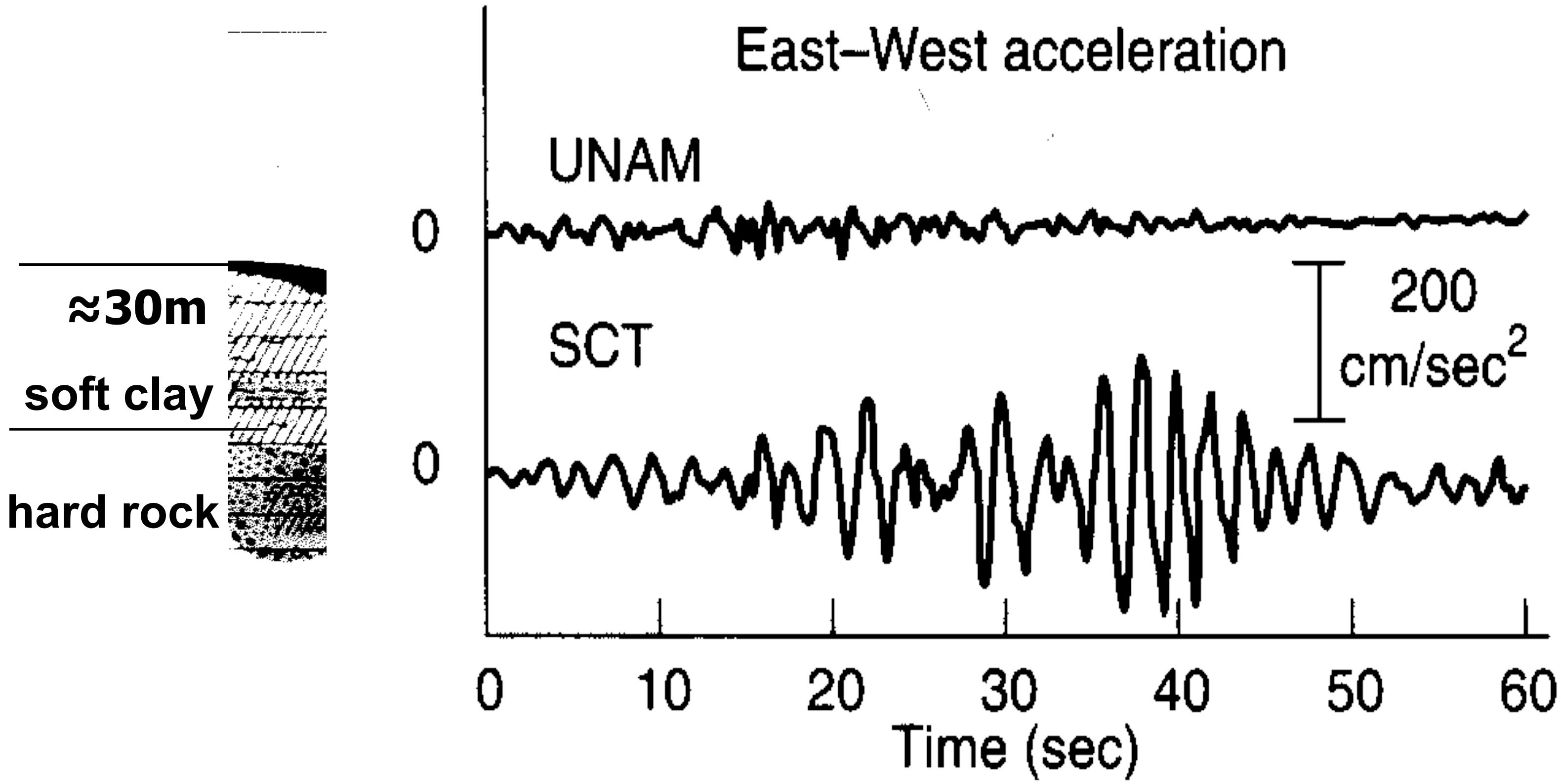
Mexico City geology





Mexico City strong motion records



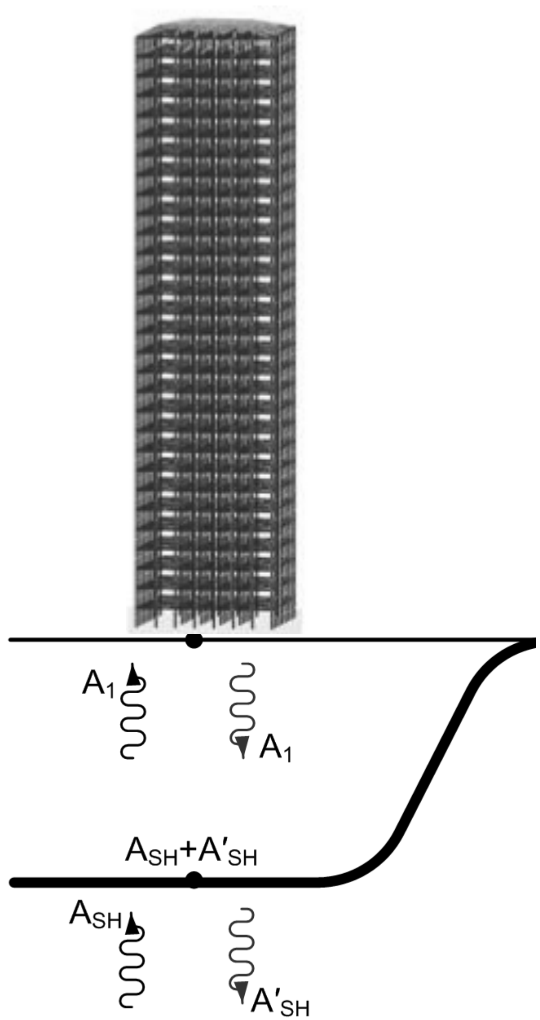


$$T_{soil}^{elastic} = \frac{4 \times H}{V_s} = \frac{4 \times 30\text{m}}{80\text{m/sec}} = 1.5\text{sec}$$

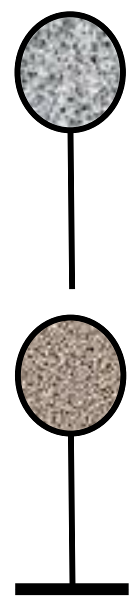
$$T_{building}^{elastic} \approx 0.1 \times \text{No. of stories} = 0.1 \times 15 = 1.5\text{sec}$$

SDOF oscillator analog

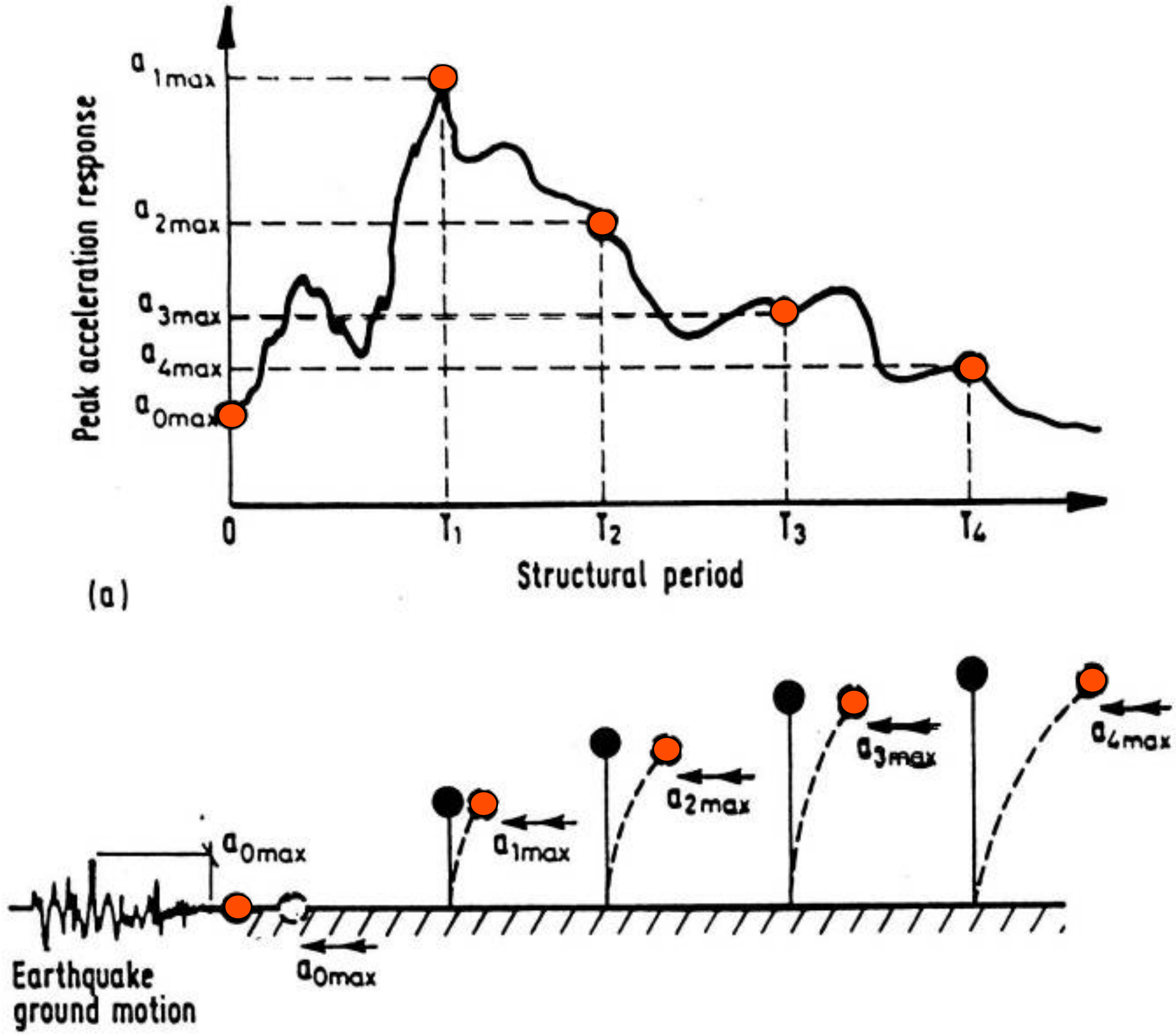
$$T = \sqrt{\frac{k}{m}}$$



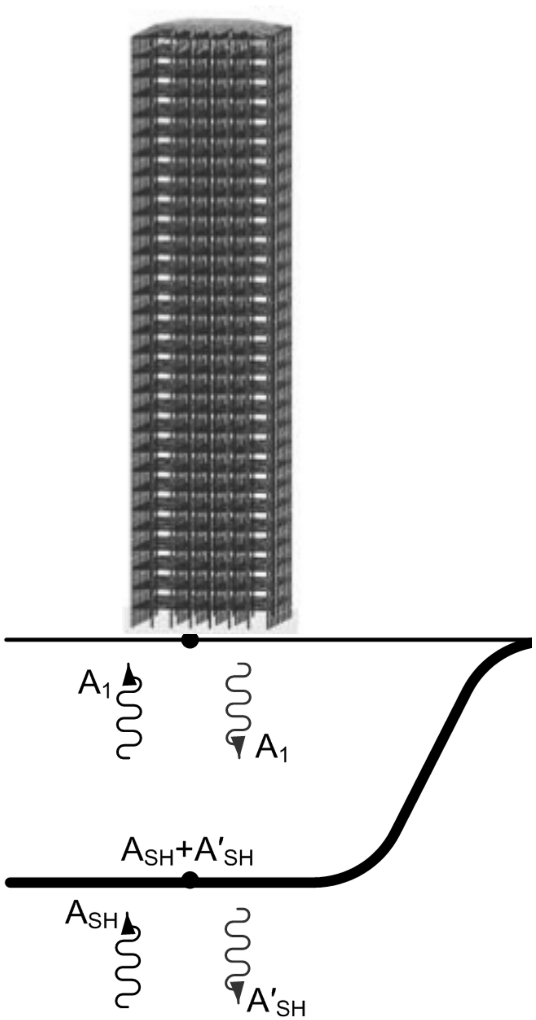
$\approx$



Response Spectrum



SDOF oscillator analog



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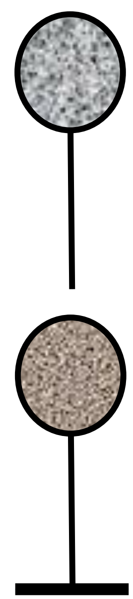
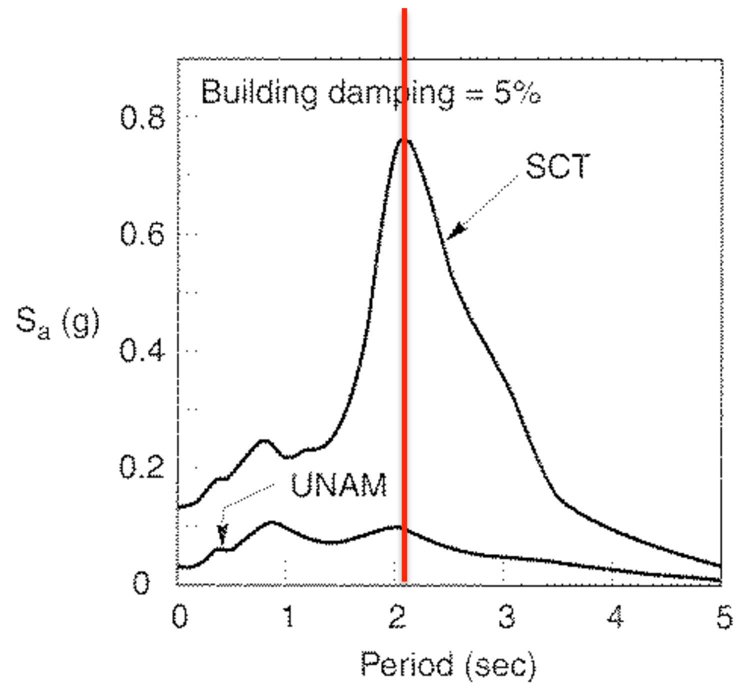


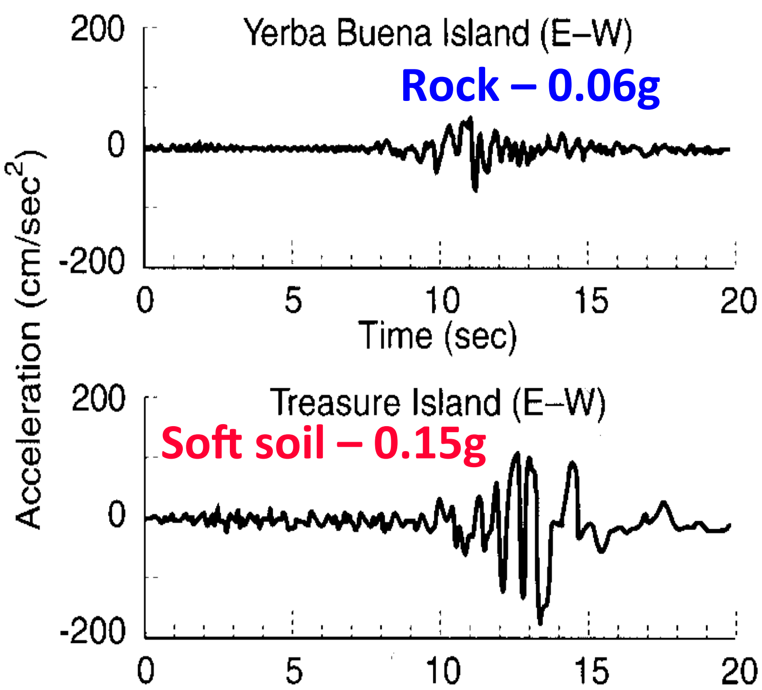
$$T_{soil}^{yielded} \approx T_{building}^{damaged}$$

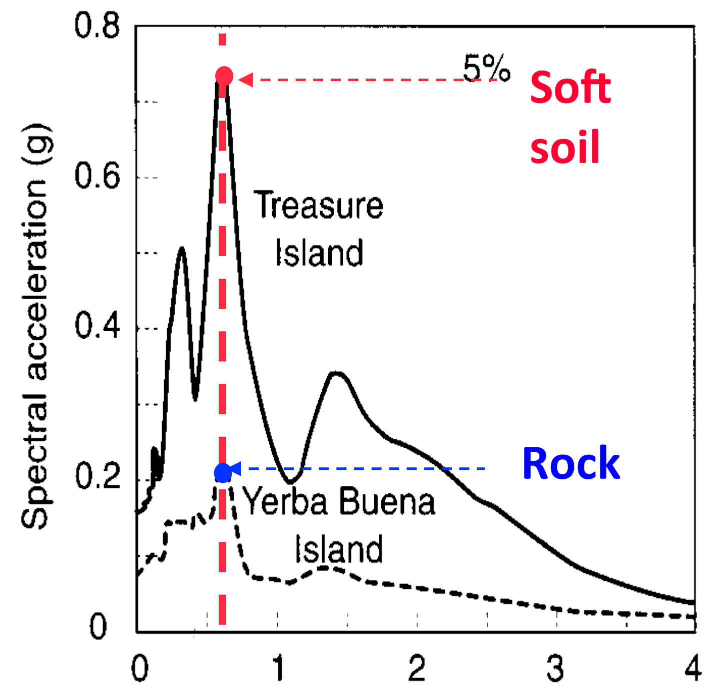


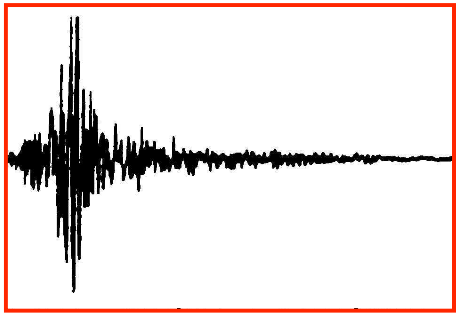
M7.1 1989 Loma Prieta earthquake

Treasure Island

Yerba Buena Island

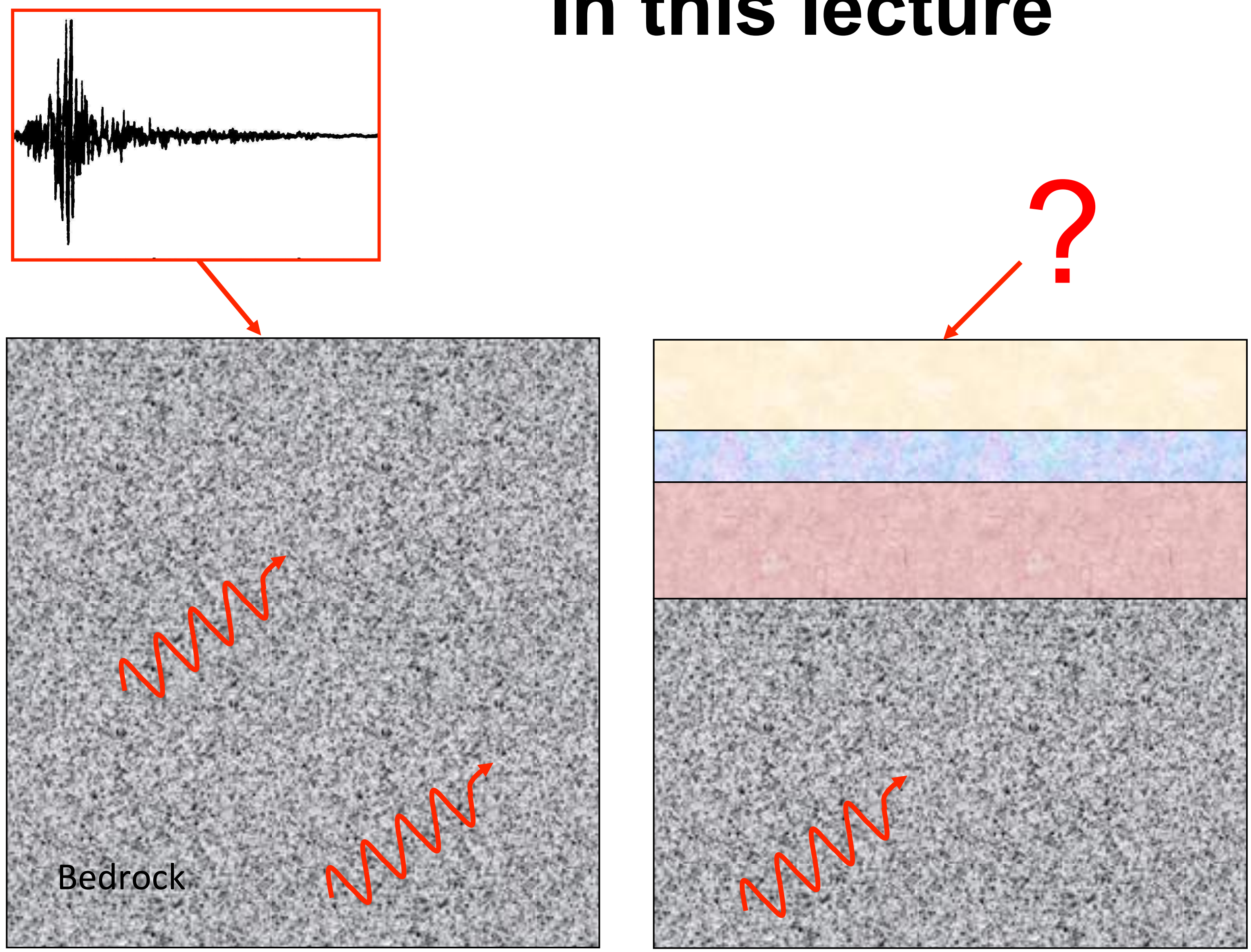




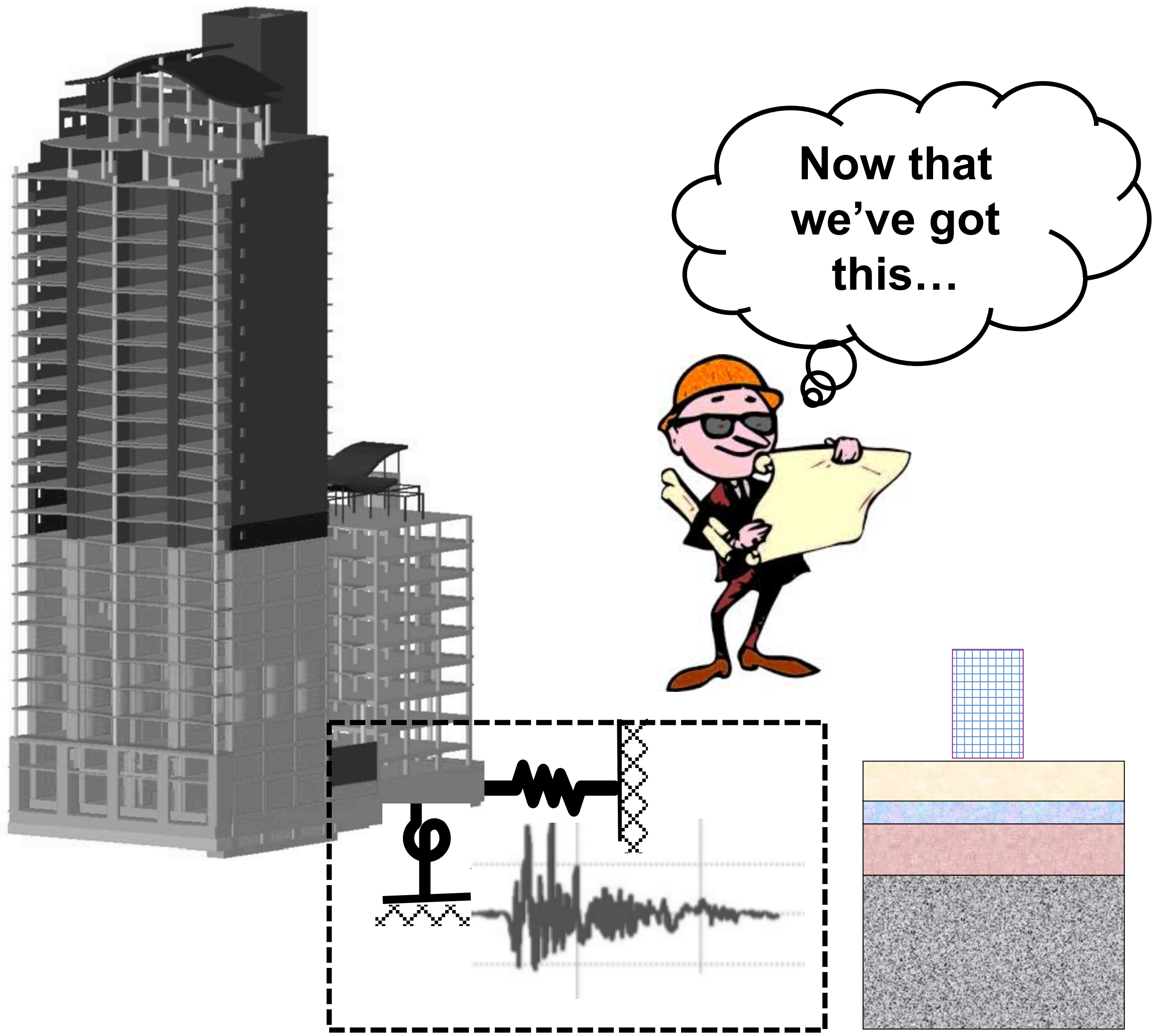


so far you have learned how we get this…

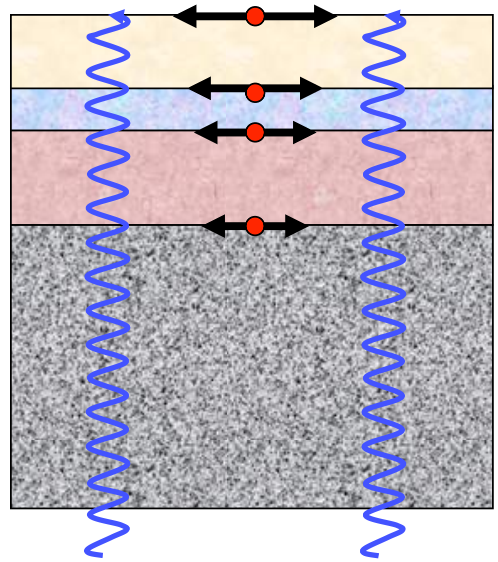
In this lecture



Structural engineer's world view…



One-dimensional site response



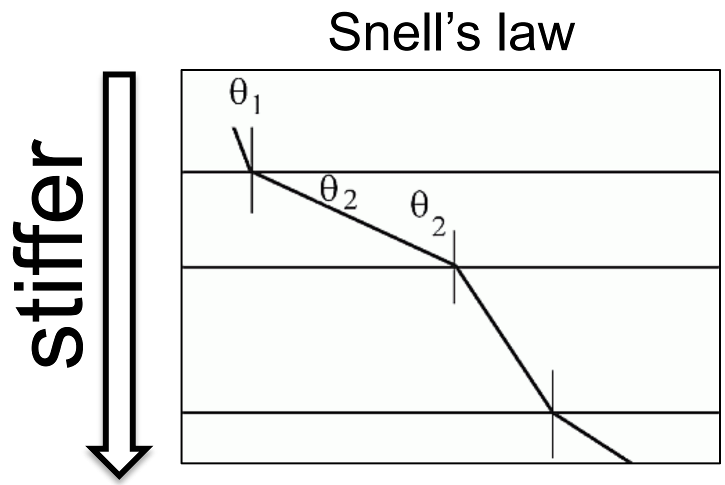
One-dimensional = one direction of propagation

Motion is identical on all perpendicular planes

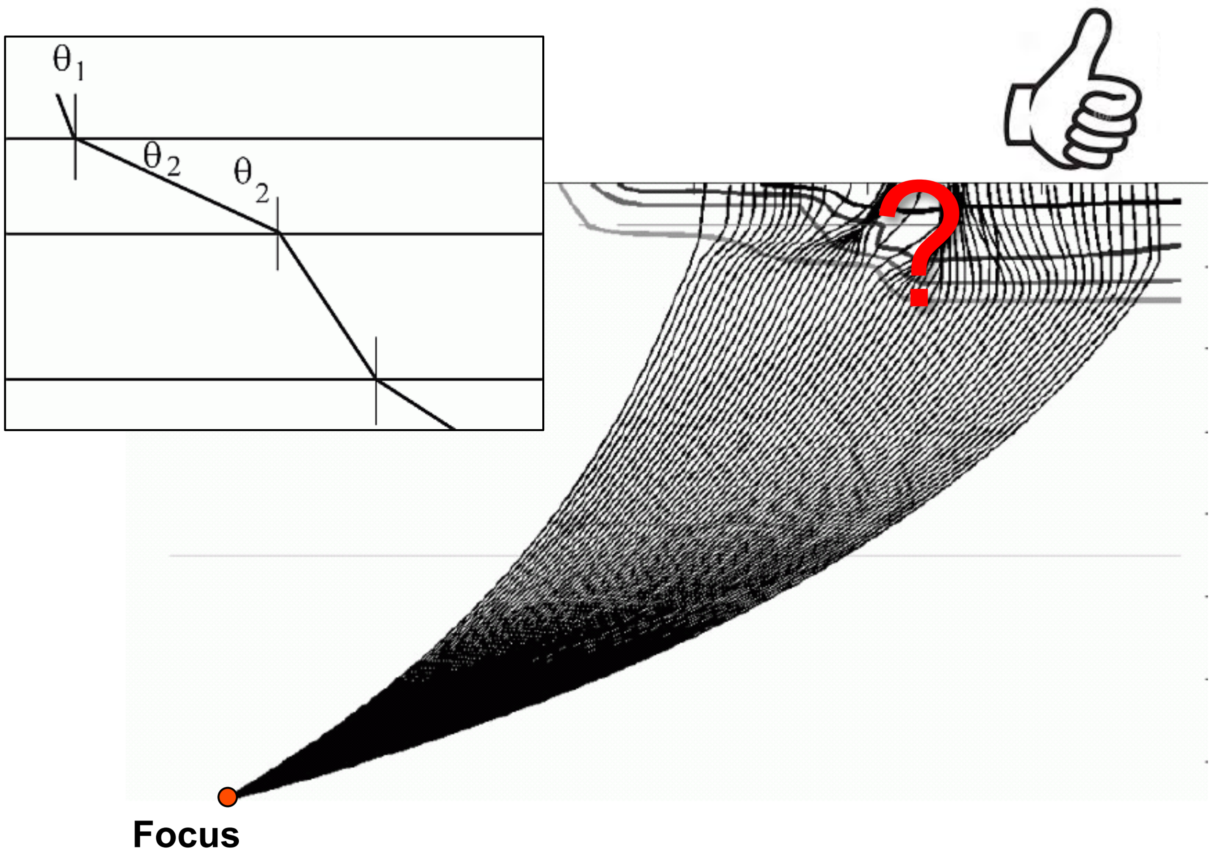
No refraction: layer boundaries parallel to particle motion

Vertically-propagating anti-plane shear (SH) waves

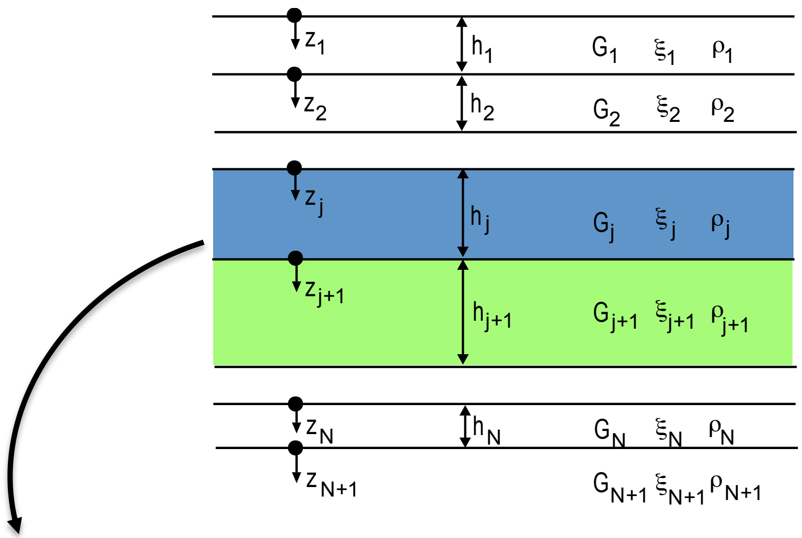
Is 1D site response a good idea?



Is 1D site response a good idea?



Linear viscoelastic site response



$$u_j(z_j, t) = (A_j e^{ik_j^* z_j} + B_j e^{-ik_j^* z_j}) e^{i\omega t}$$

Boundary conditions @ interface

No slip $$A_{j+1} + B_{j+1} = (A_j e^{ik_j^* h_j} + B_j e^{-ik_j^* h_j})$$

Equilibrium $$A_{j+1} - B_{j+1} = \frac{G_j^* k_j^*}{G_{j+1}^* k_{j+1}^*}(A_j e^{ik_j^* h_j} - B_j e^{-ik_j^* h_j})$$

Linear viscoelastic site response

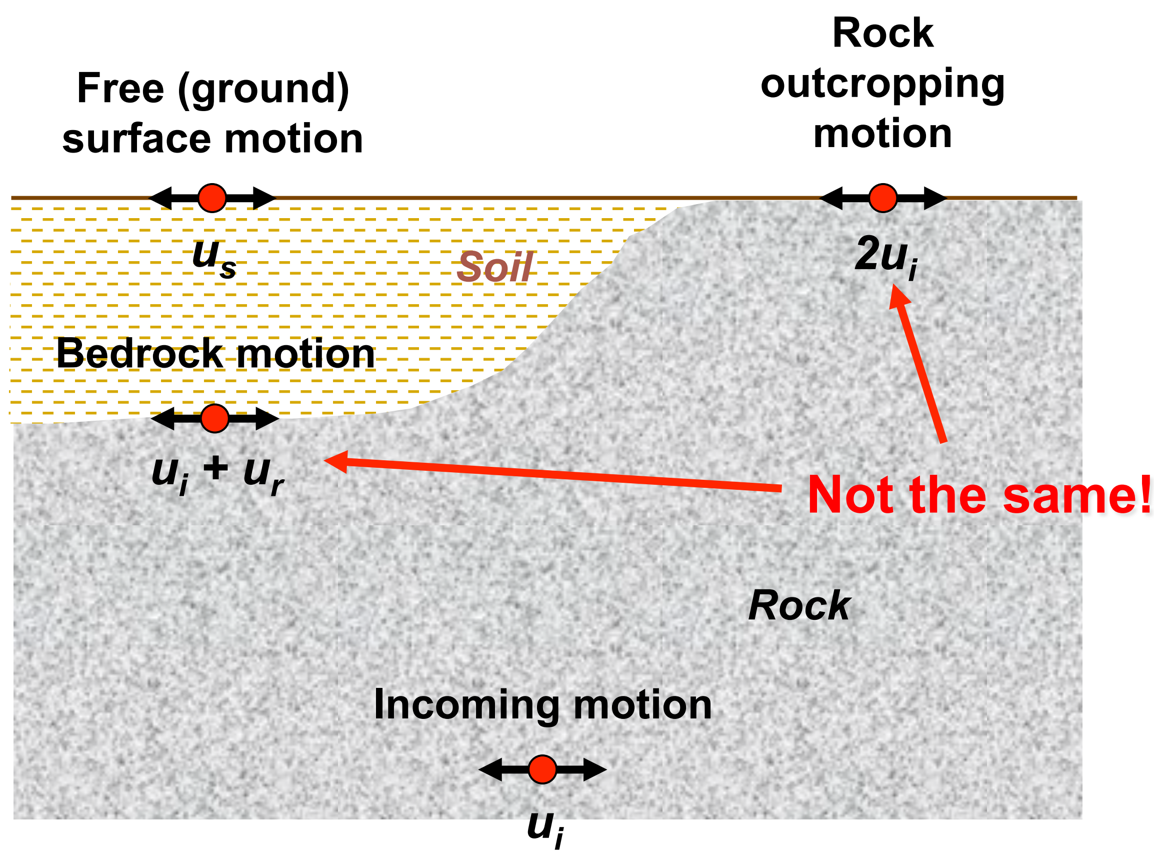
Given $$\alpha_j^* = \frac{G_j^* k_j^*}{G_{j+1}^* k_{j+1}^*}\ , A_j\ ,\ B_j$$

where $$G_j^* = G_j(1 + 2i\xi_j) = G_j(1 + i/\mathrm{Q}_j)$$

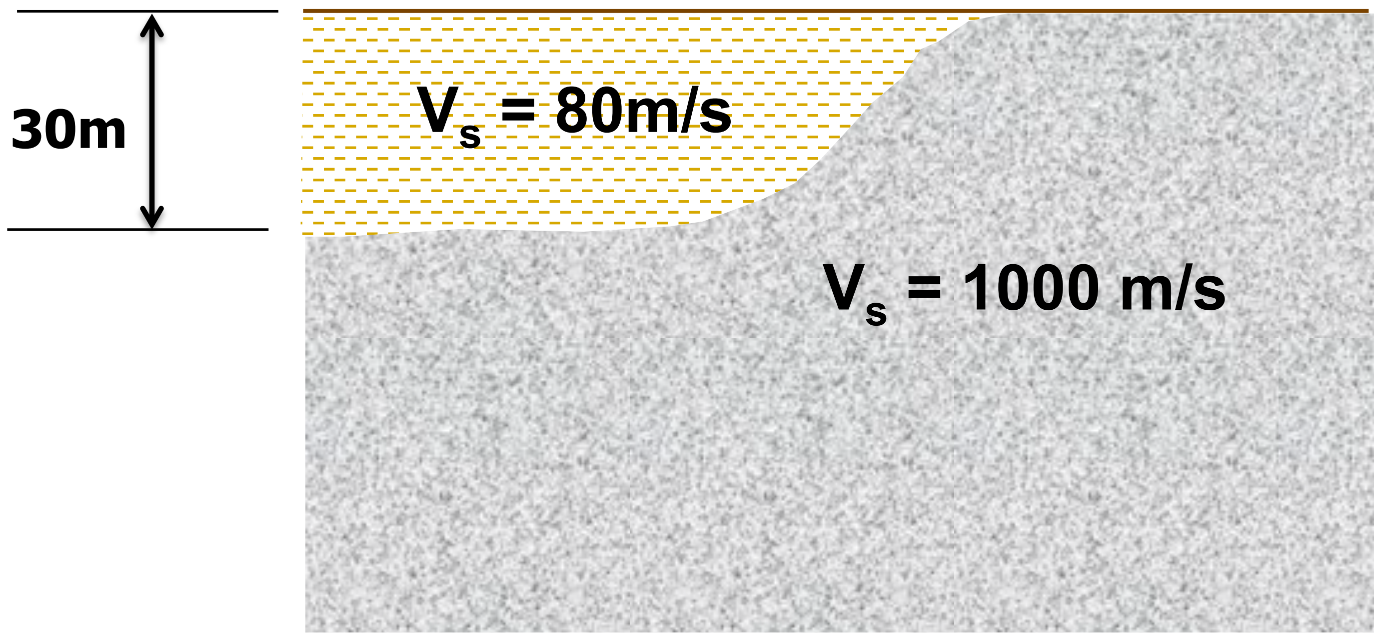
We get $$A_{j+1}\ ,\ B_{j+1}$$

$$\boxed{u_{j+1}(z_{j+1}, t) = (A_{j+1} e^{ik_{j+1}^* z_{j+1}} + B_{j+1} e^{-ik_{j+1}^* z_{j+1}}) e^{i\omega t}}$$

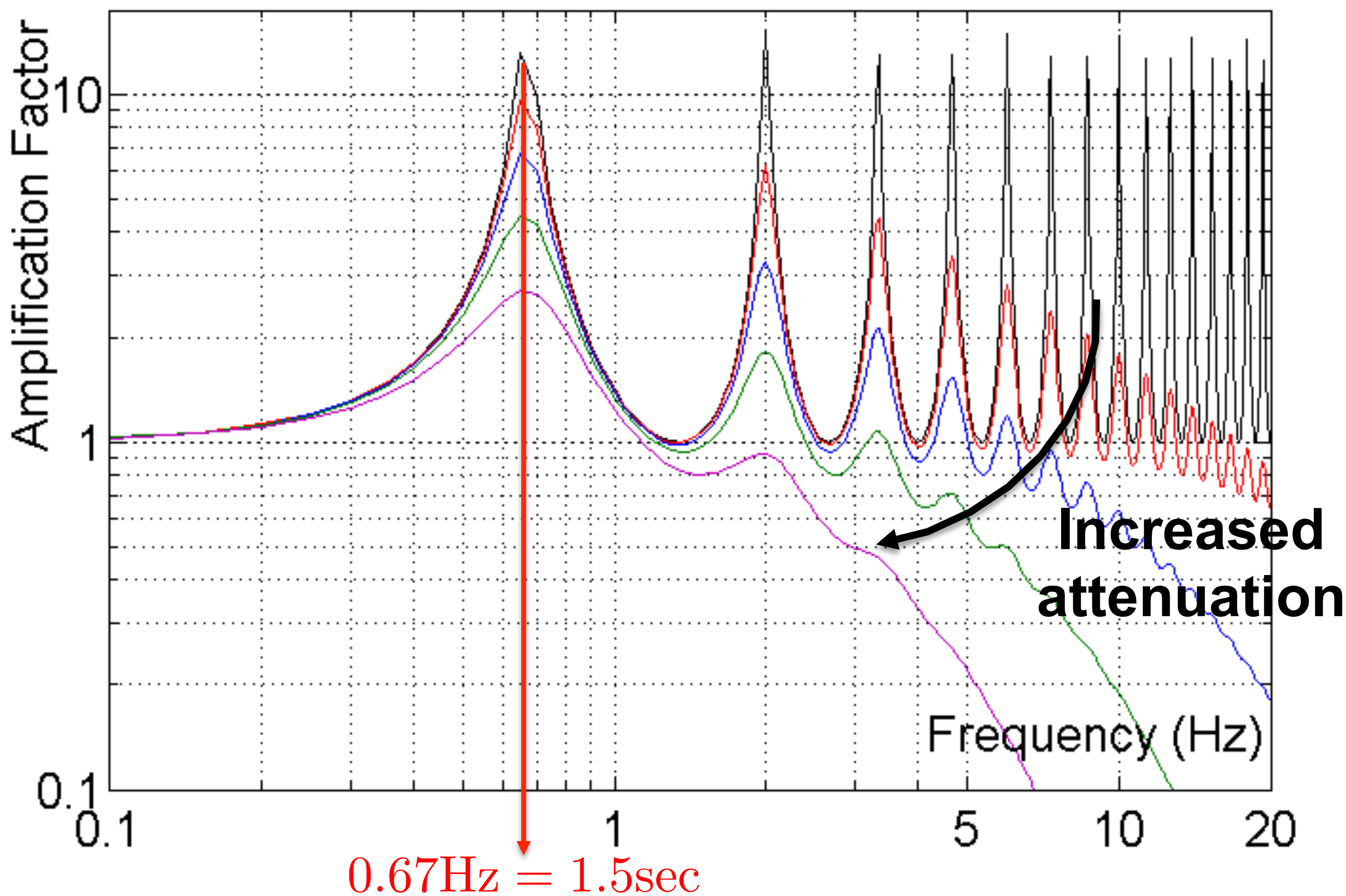
Site amplification terminology



back to Mexico City…



Surface-to-outcrop transfer function



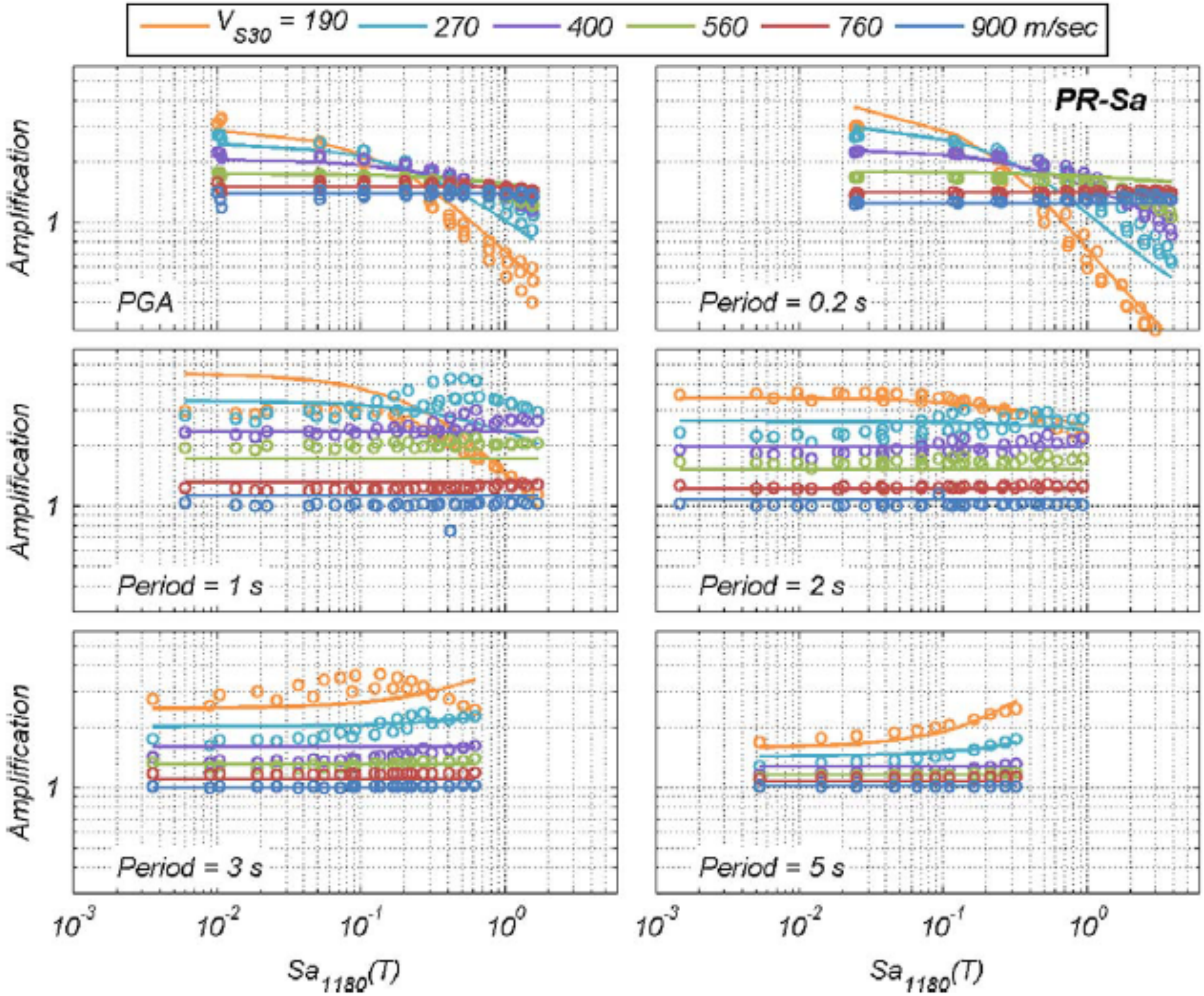
Viscoelastic site response in ground motion simulations

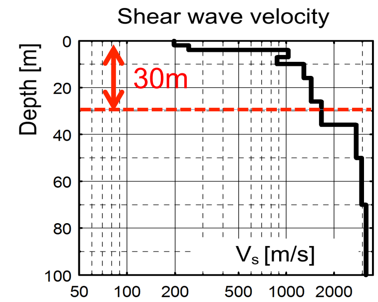
Horizontally stratified sites

Vertically propagating seismic waves

Very stiff sites or very weak motion

Empirical amplification factors

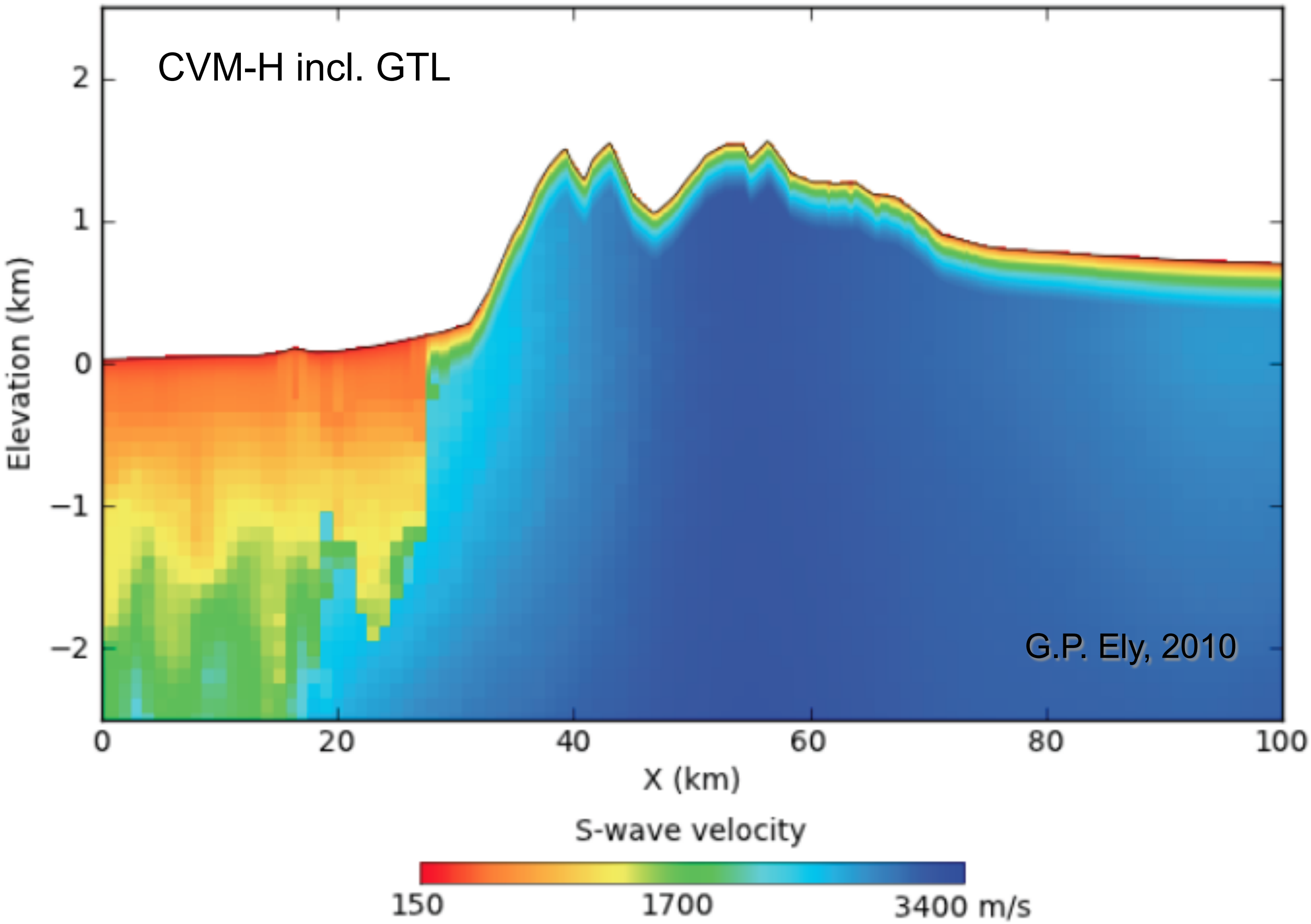




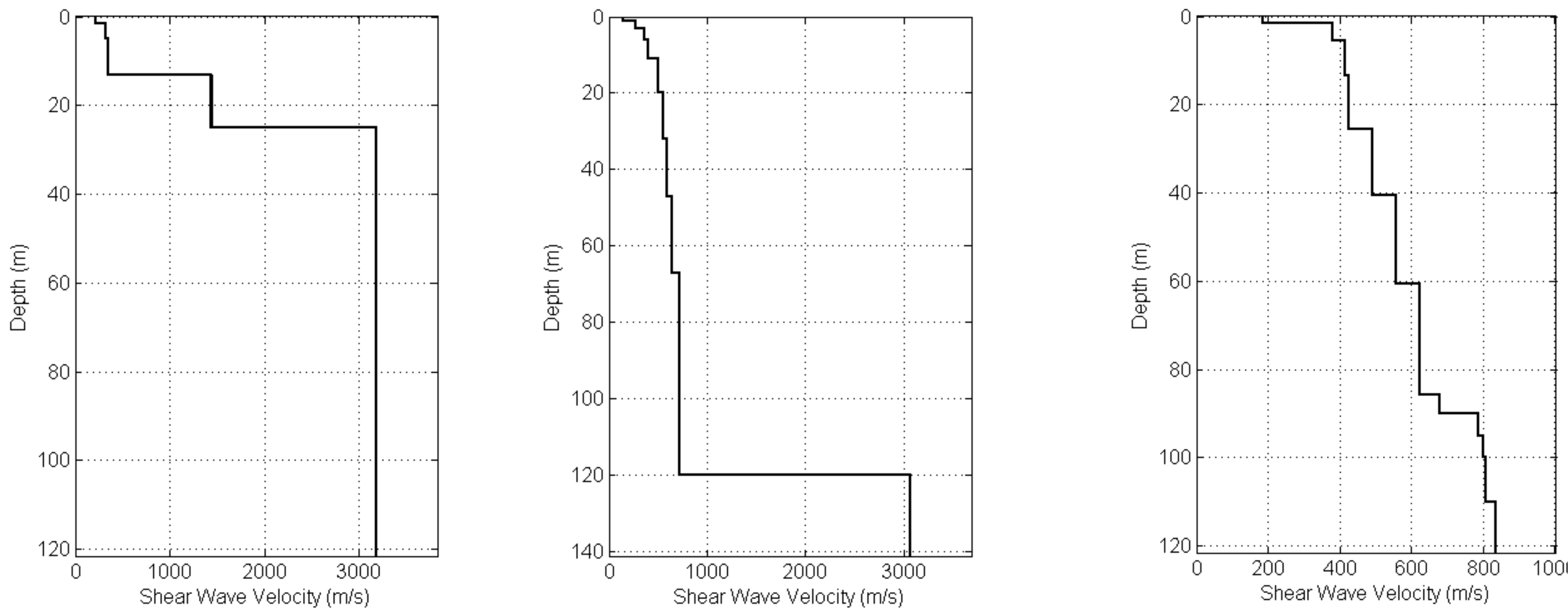
$$V_{s30} = \frac{\sum V_{si} \times t_i}{\sum t_i}$$

Kamai et al. (2014)

V_{s30}-derived Geotechnical Layer

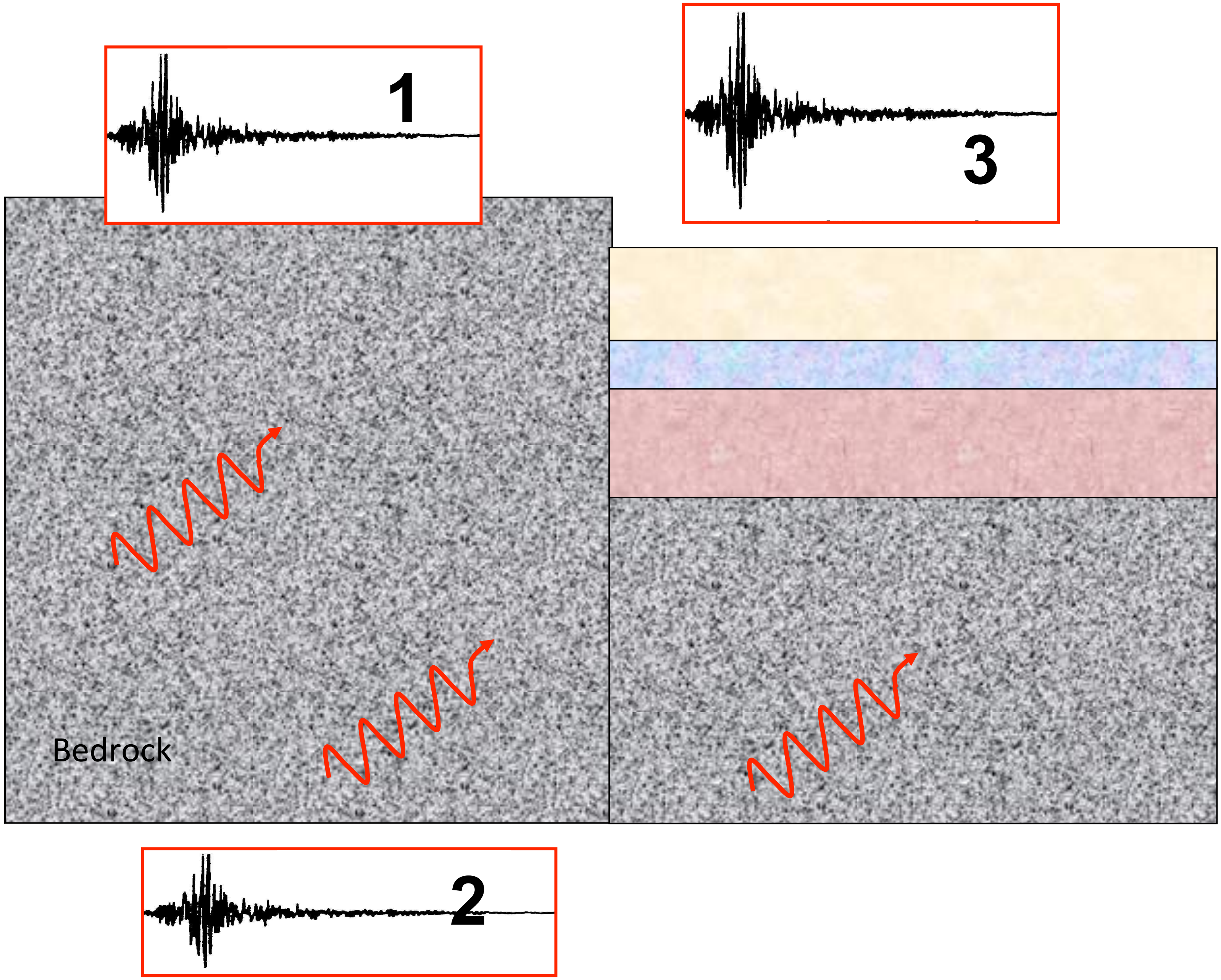


Measured site-specific velocity profile

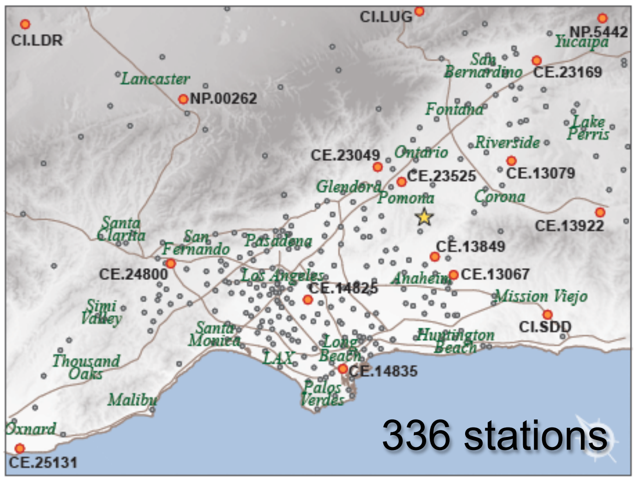


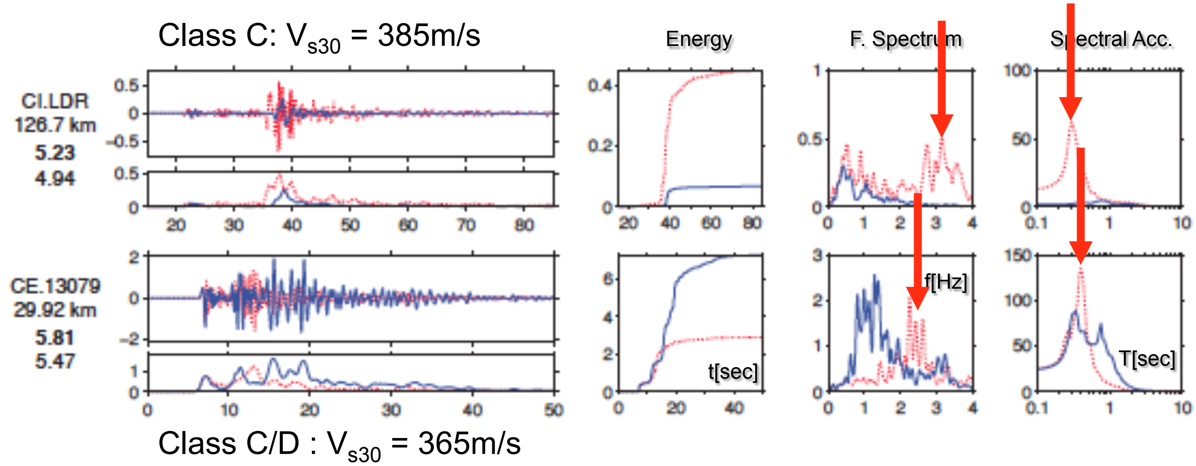
Deconvolution: Remove rock outcrop signature

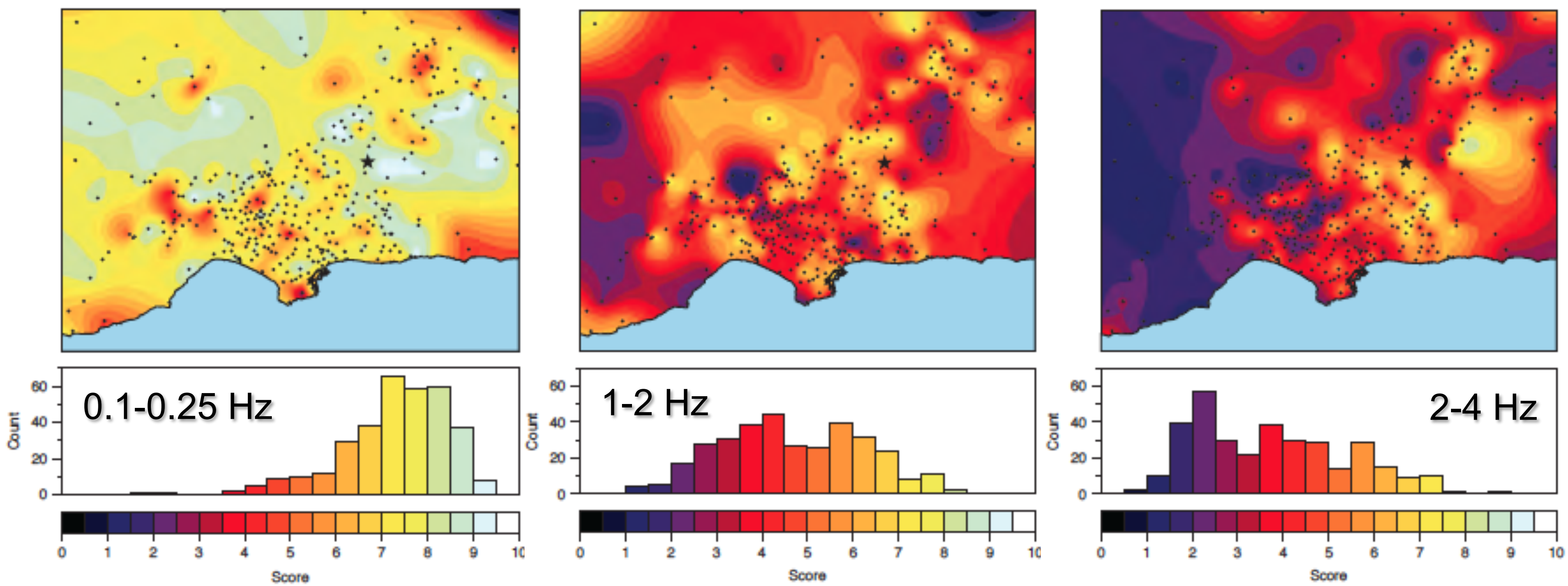
1D incident wave propagation: Add site (-specific) response


1
3
Bedrock
2

Broadband [0.1-4Hz] simulation validation: Chino Hills

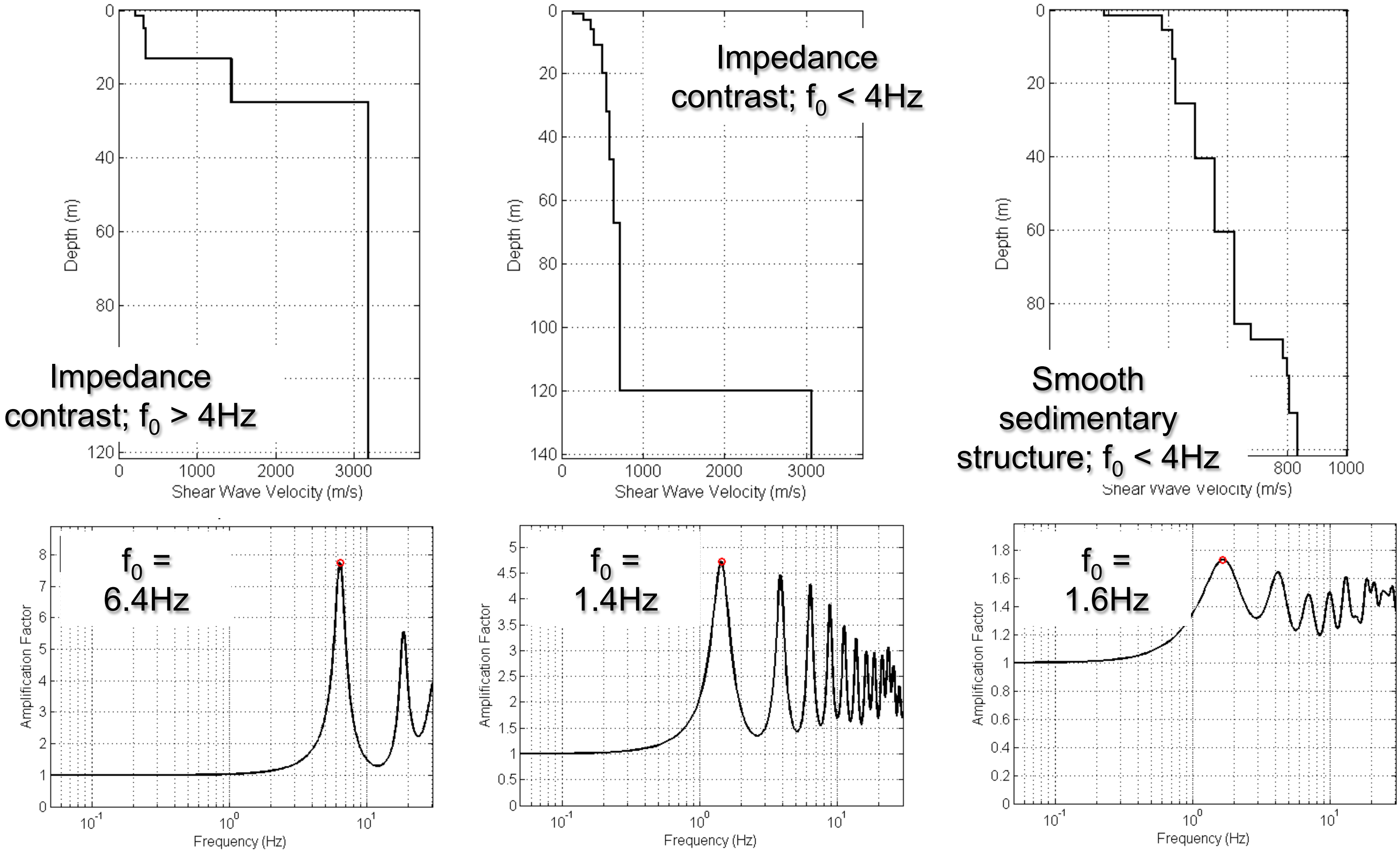






Taborda & Bielak (2013)

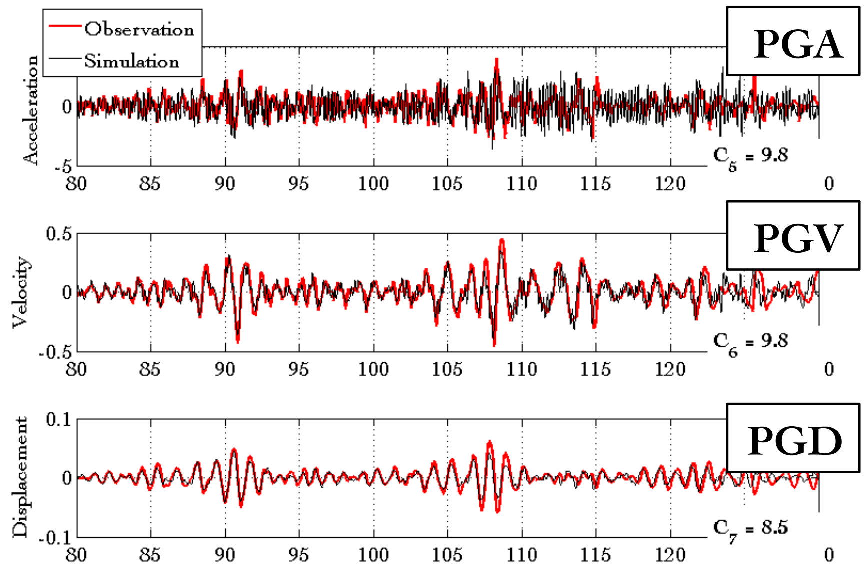
Measured site-specific velocity profile

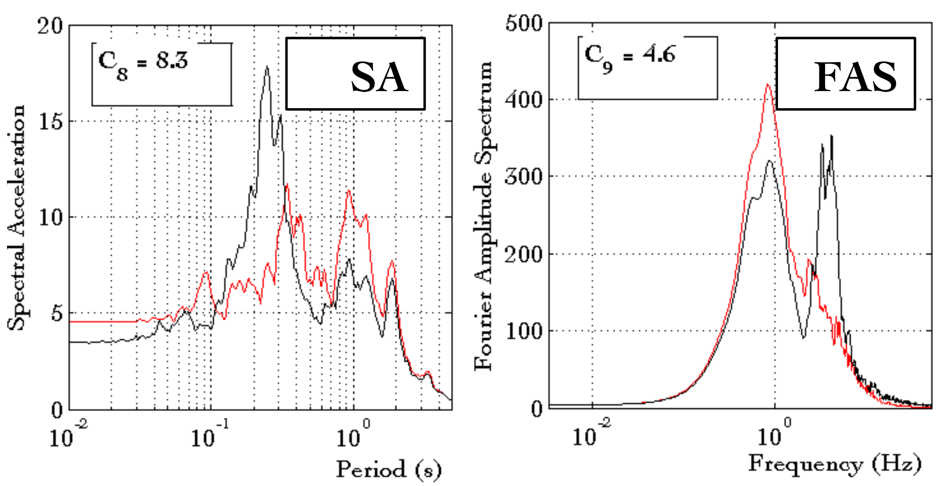


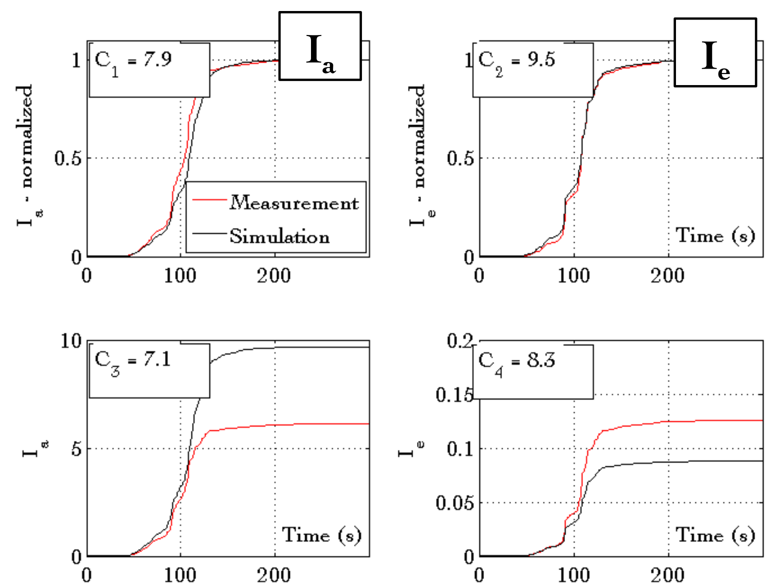
Goodness-of-fit (GOF) criteria

GOF CRITERIA:

1. **Peak amplitude**: acceleration (**PGA**); velocity (**PGV**); and displacement (**PGD**)
2. **Spectral acceleration (SA)**
3. **Fourier amplitude spectrum (FAS)**
4. **Arias intensity**: absolute and rate (**I_a**)
5. **Energy intensity**: absolute and rate (**I_e**)



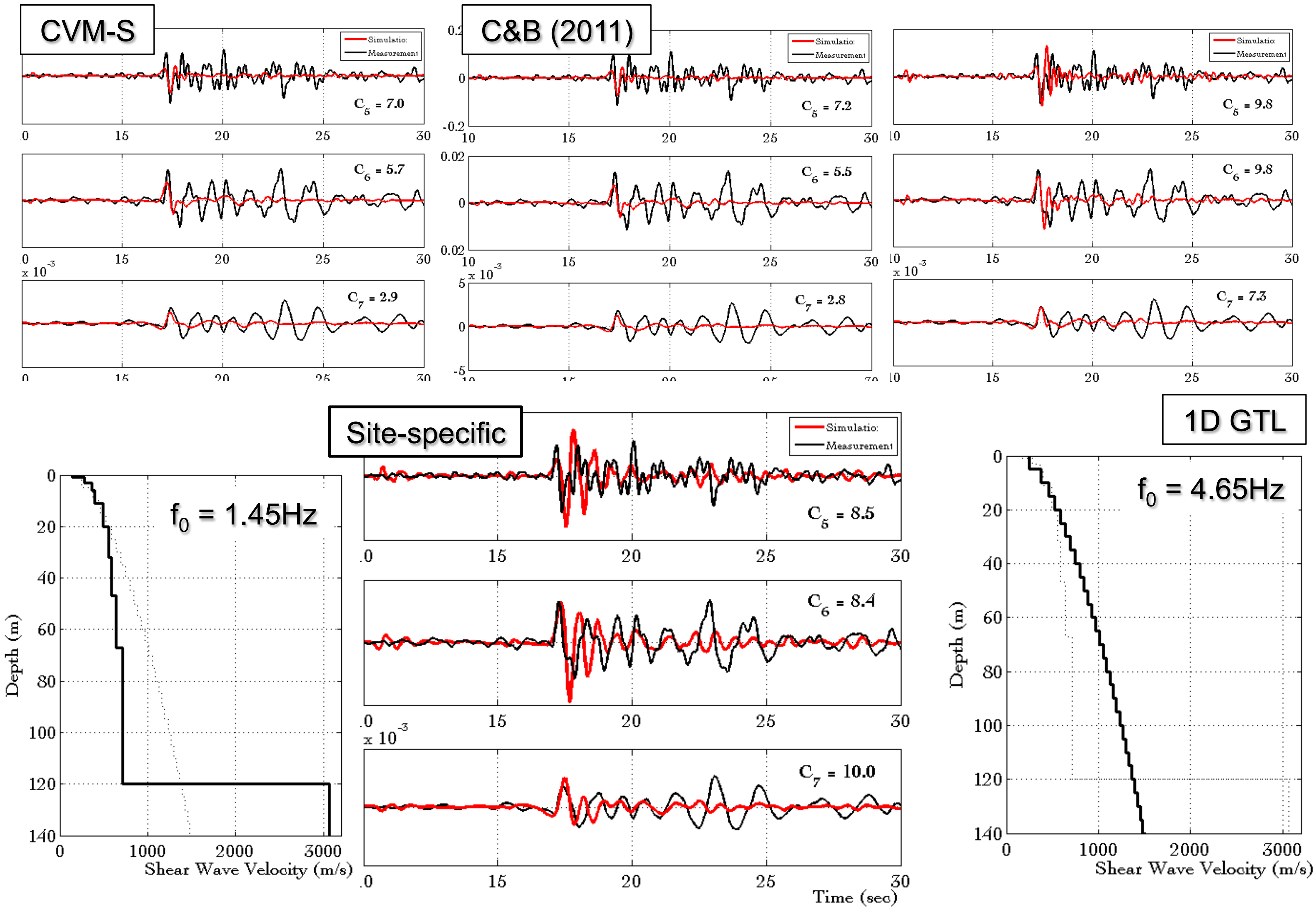




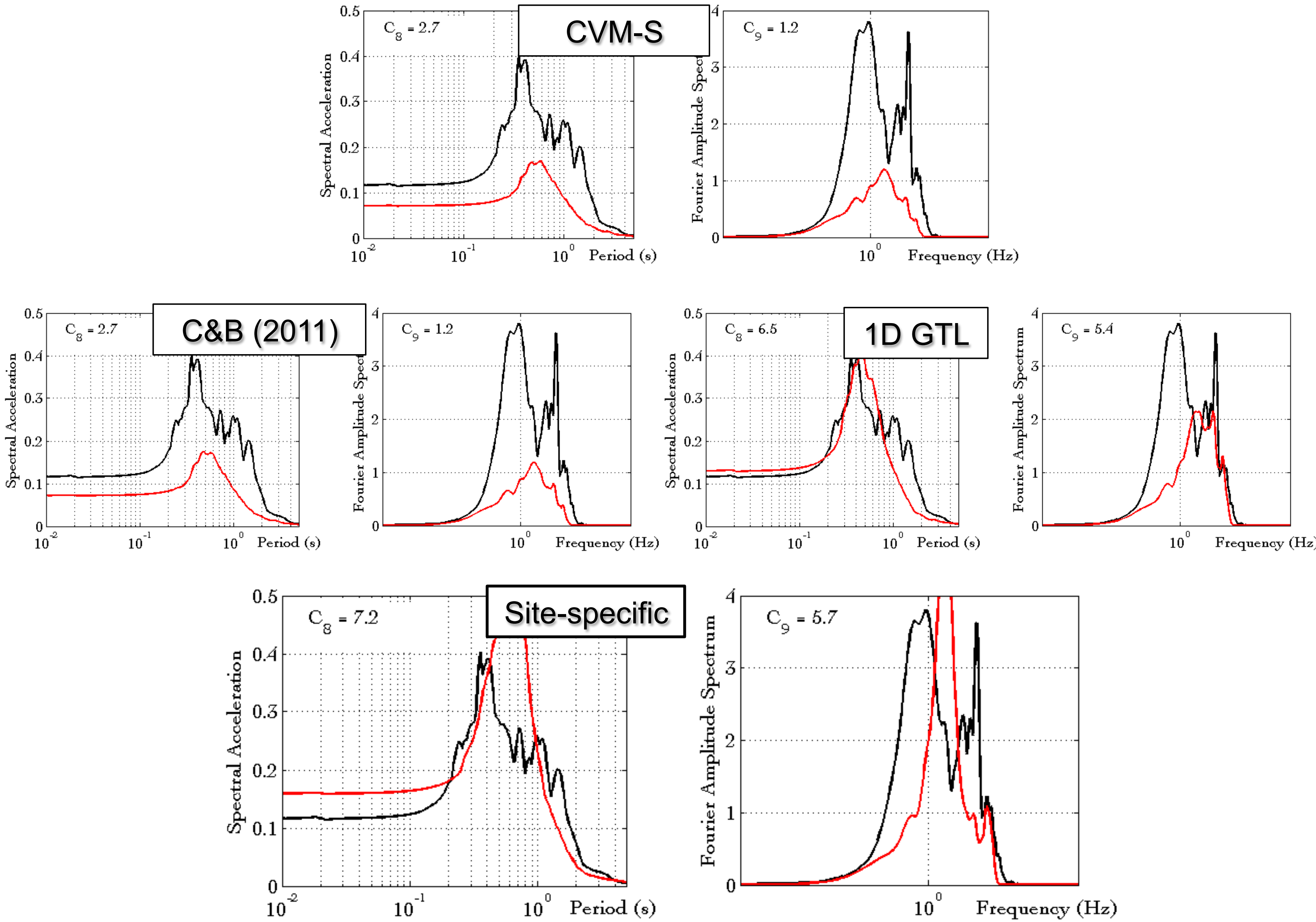
GOF = 8.2

[0-10] = [Poor – Excellent]

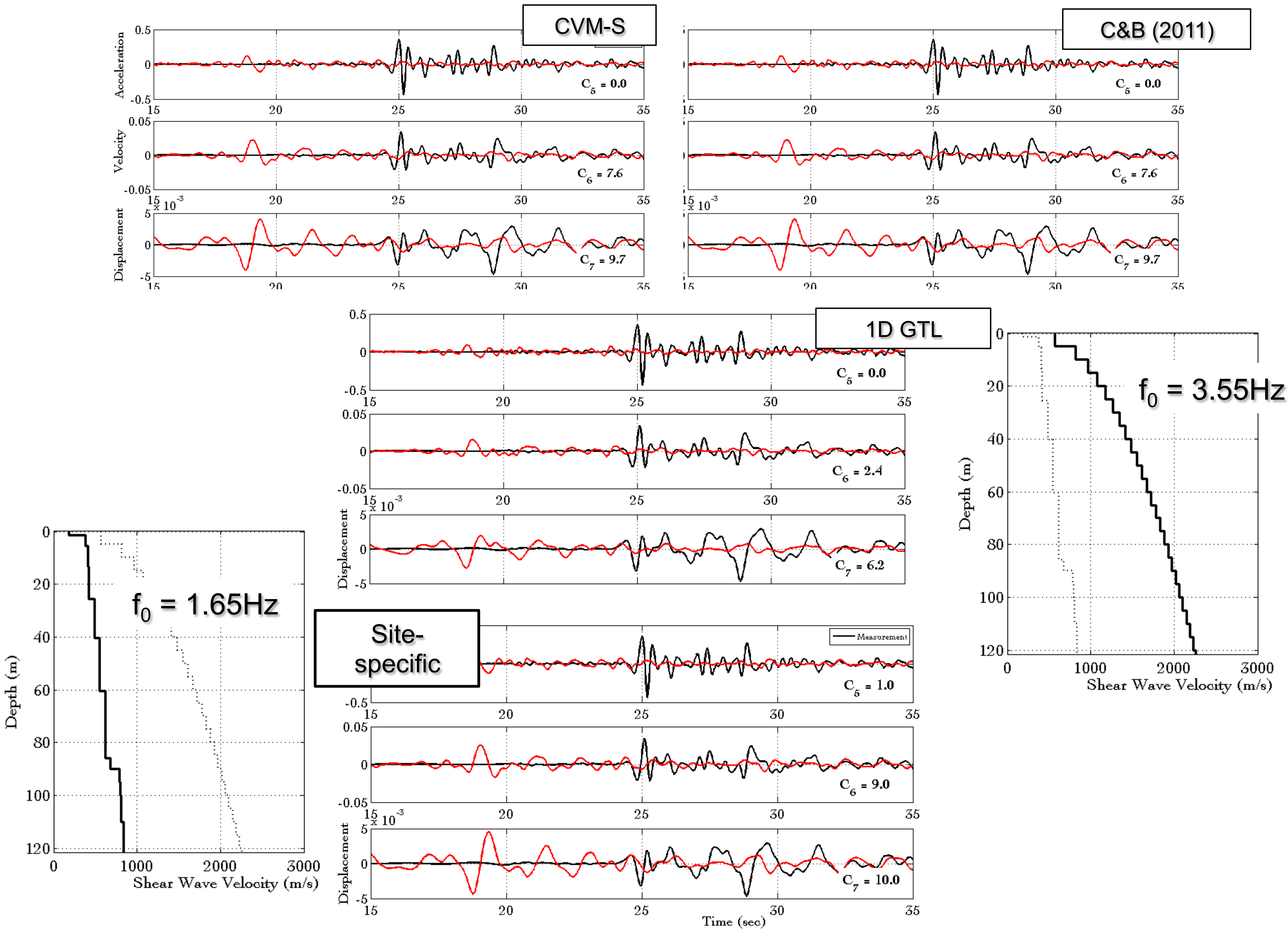
Strong impedance contrast ($V_{s,30}$=425 m/s): Time Domain



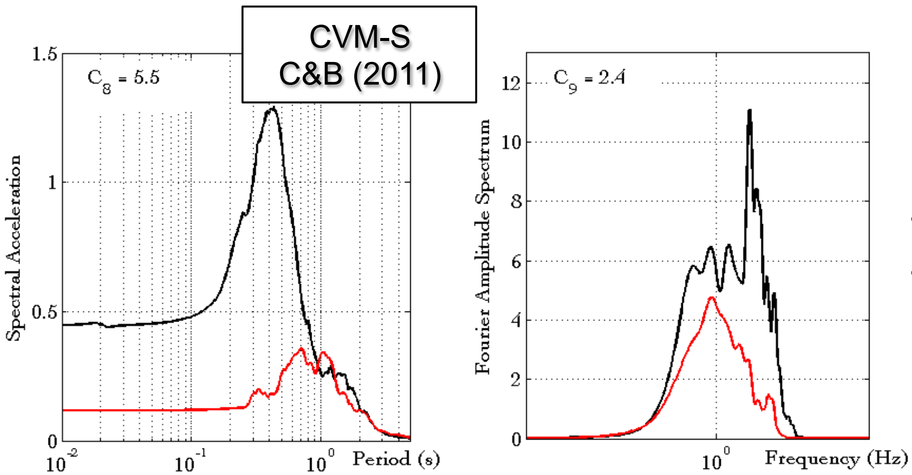
Strong impedance contrast ($V_{s,30}$=425 m/s): Frequency Domain

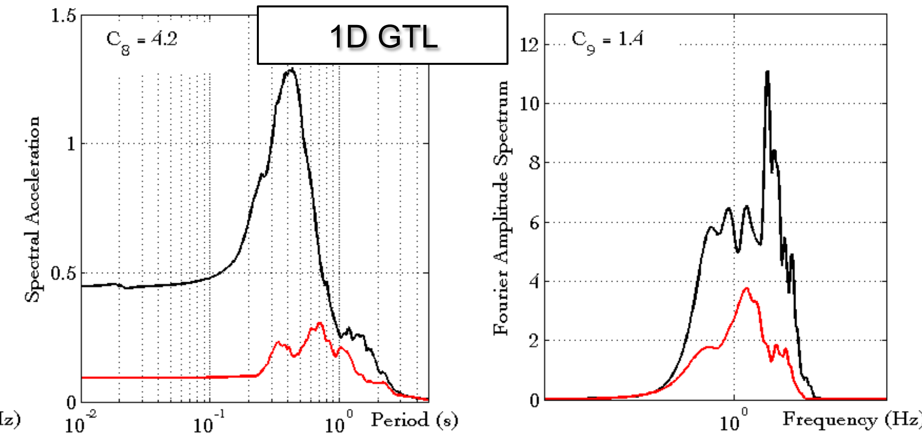


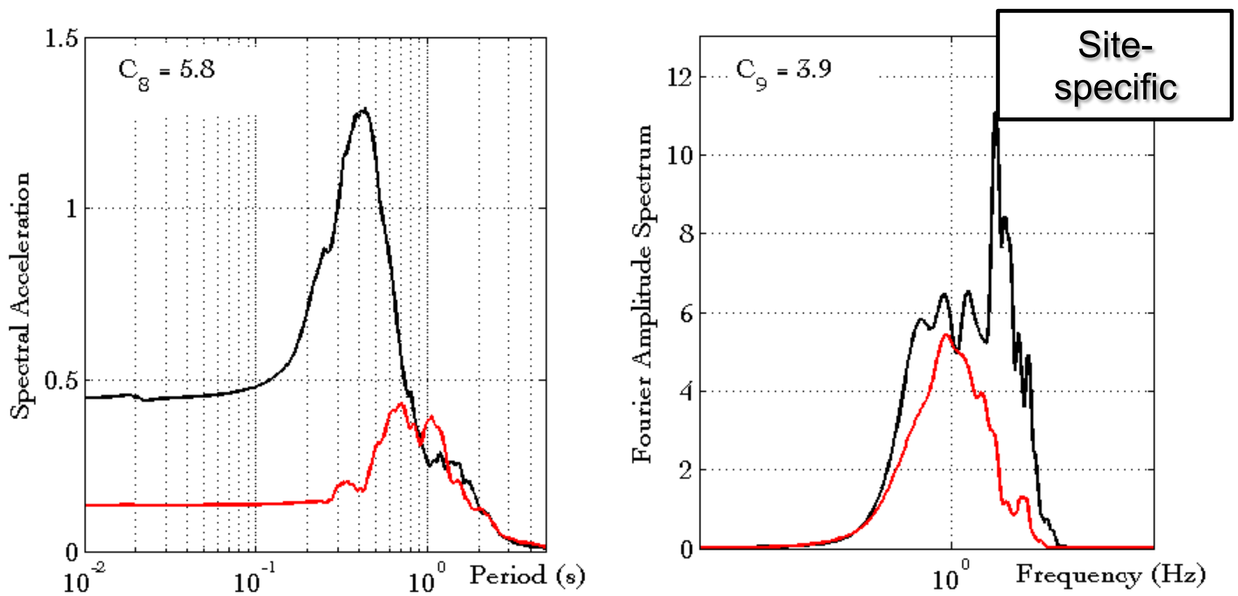
Smooth velocity profile ($V_{s,30}$=400 m/s) -- Time Domain



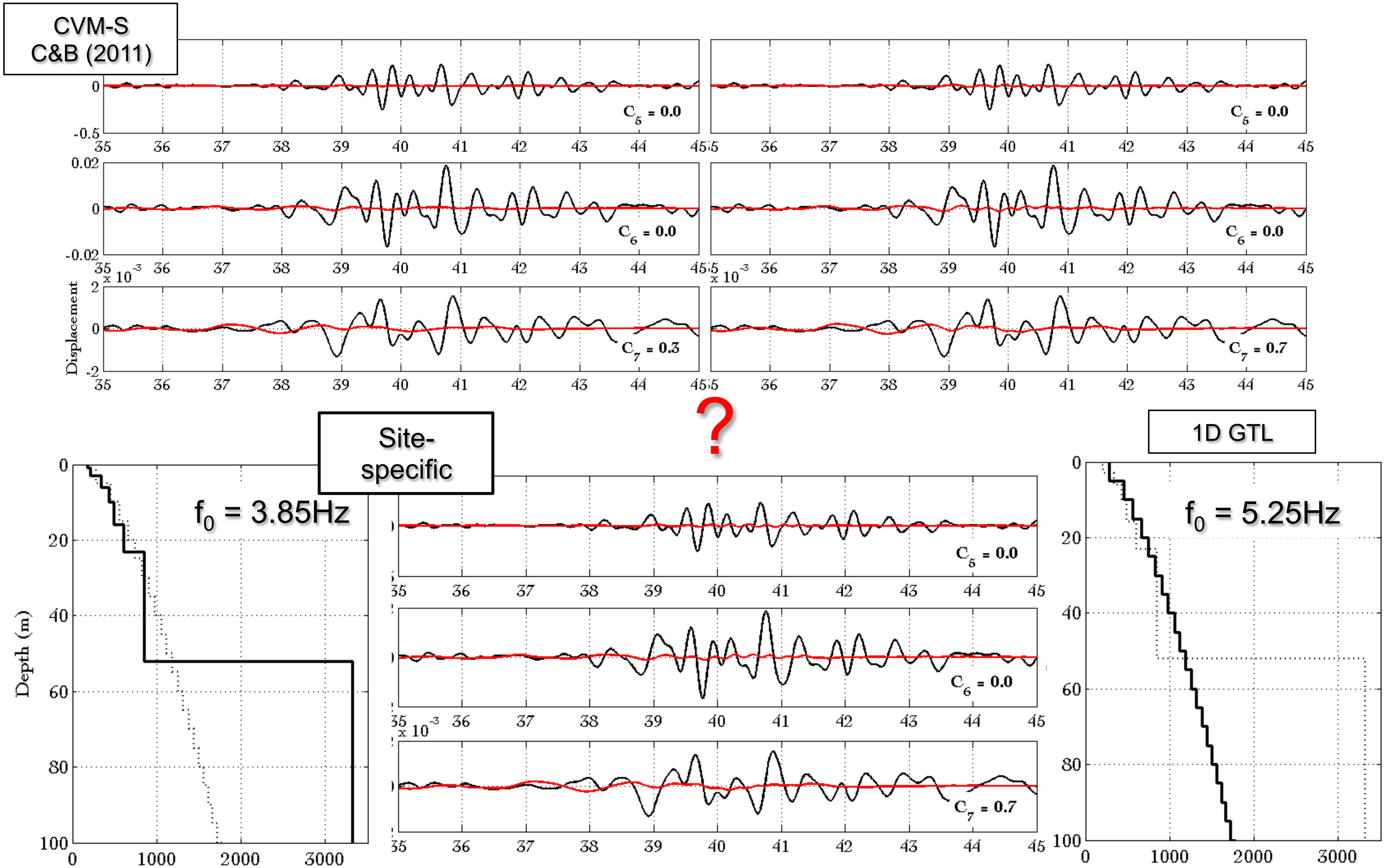
Smooth velocity profile ($V_{s,30}$=400 m/s) -- Frequency Domain



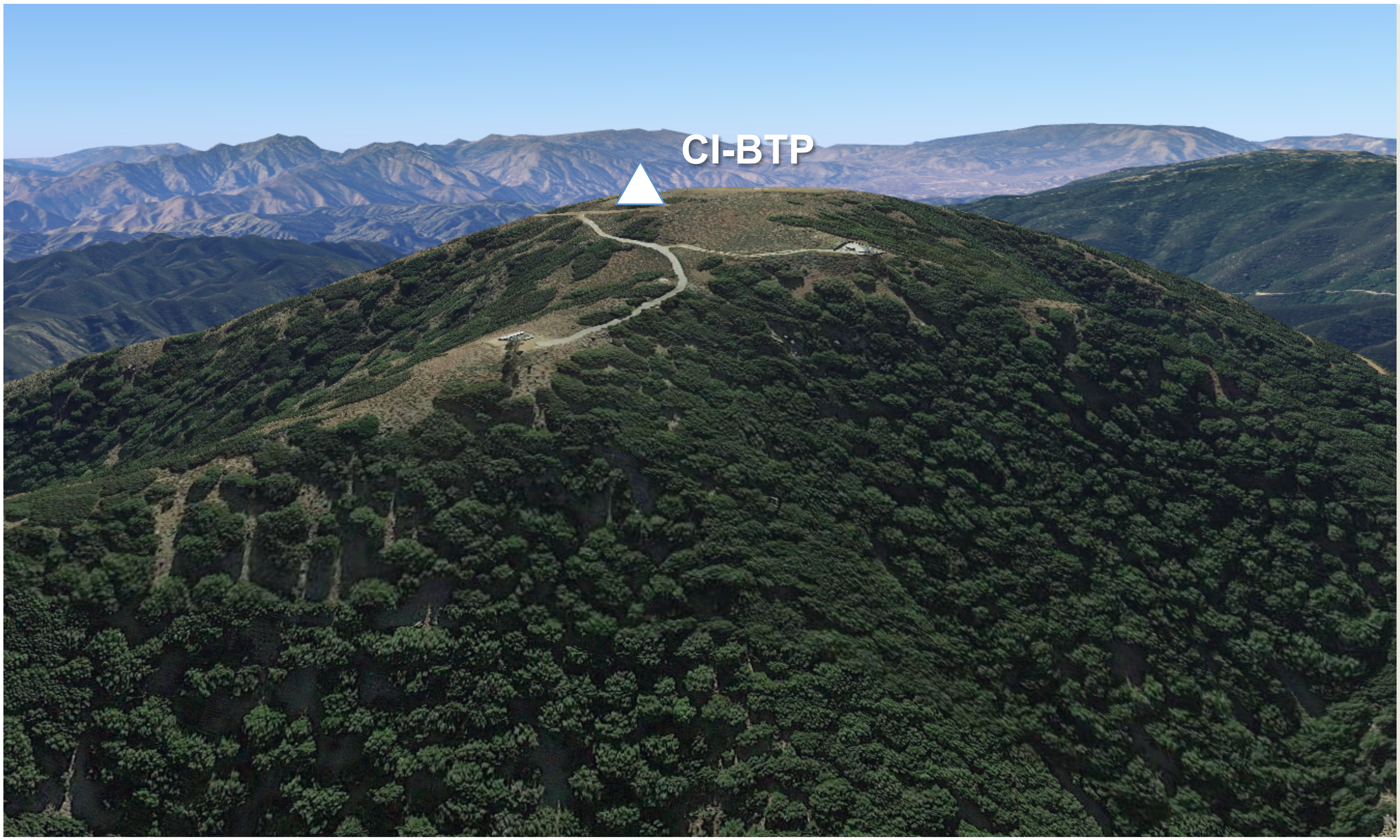




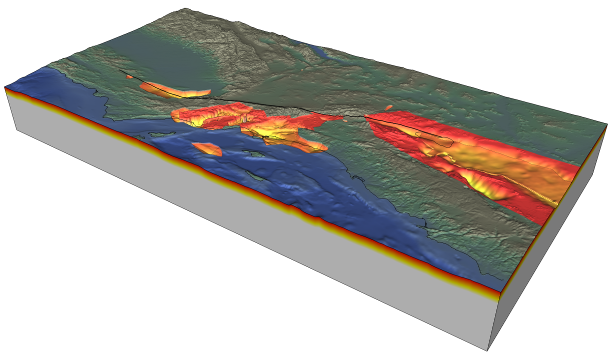
Strong impedance contrast ($V_{s,30}$=460 m/s): Time Domain

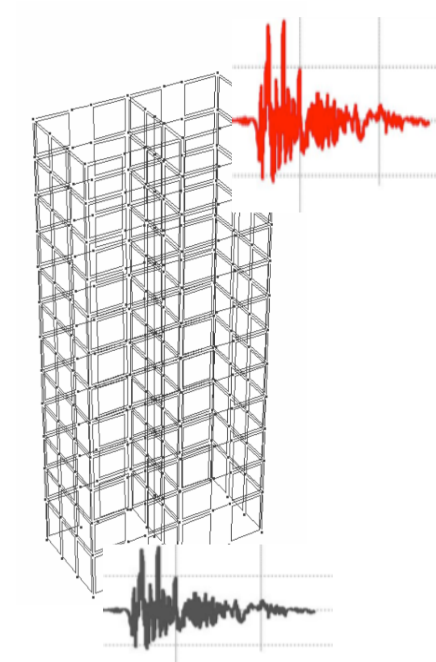


Soil-topography coupling effects?



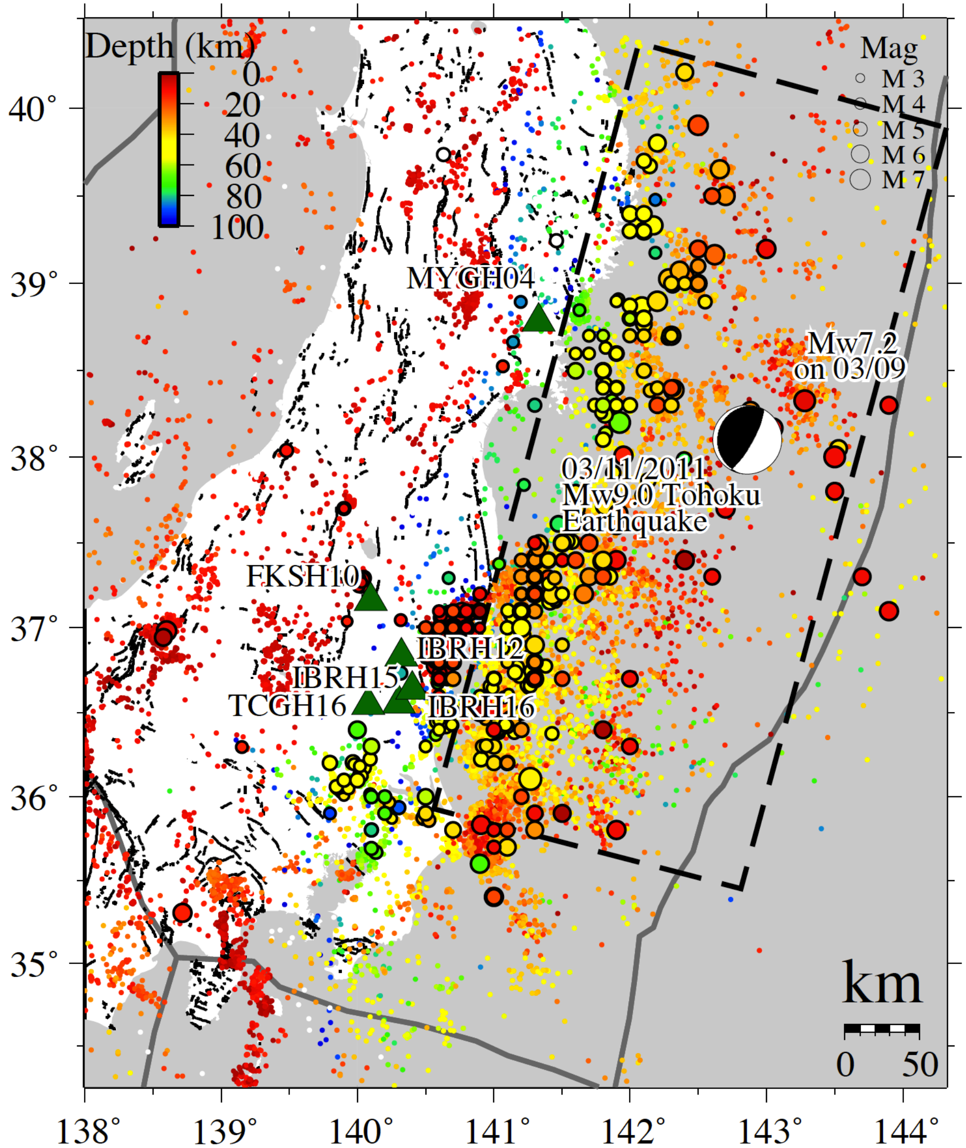
Is site response input motion & time independent?

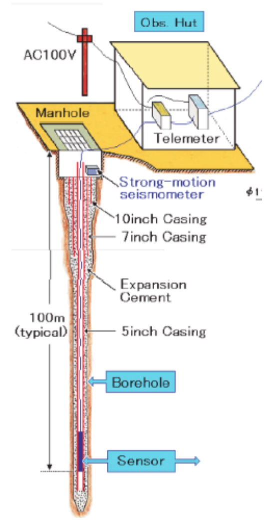




Earthquake Simulations → **Site response** → 3D Nonlinear Structural Response

The M9.0 2011 March 11 Tohoku Earthquake



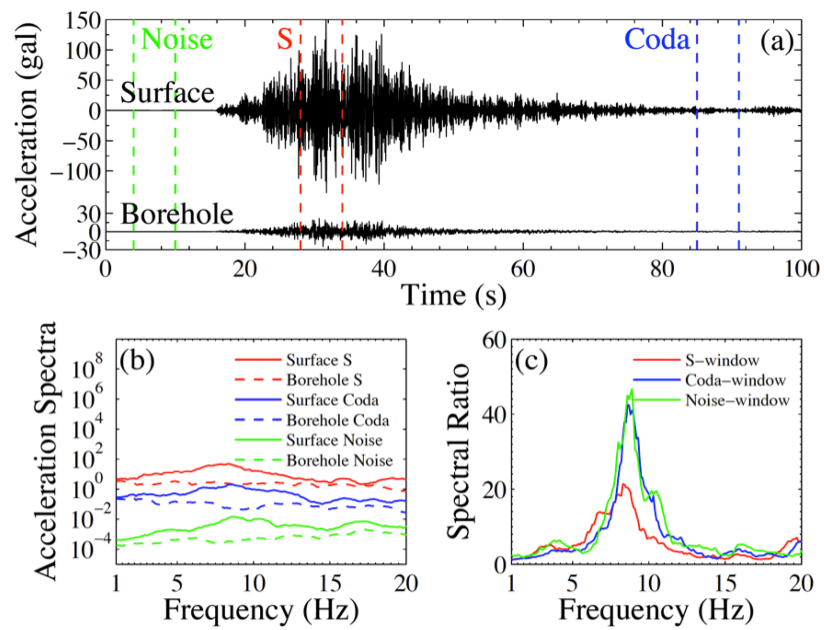


NIED

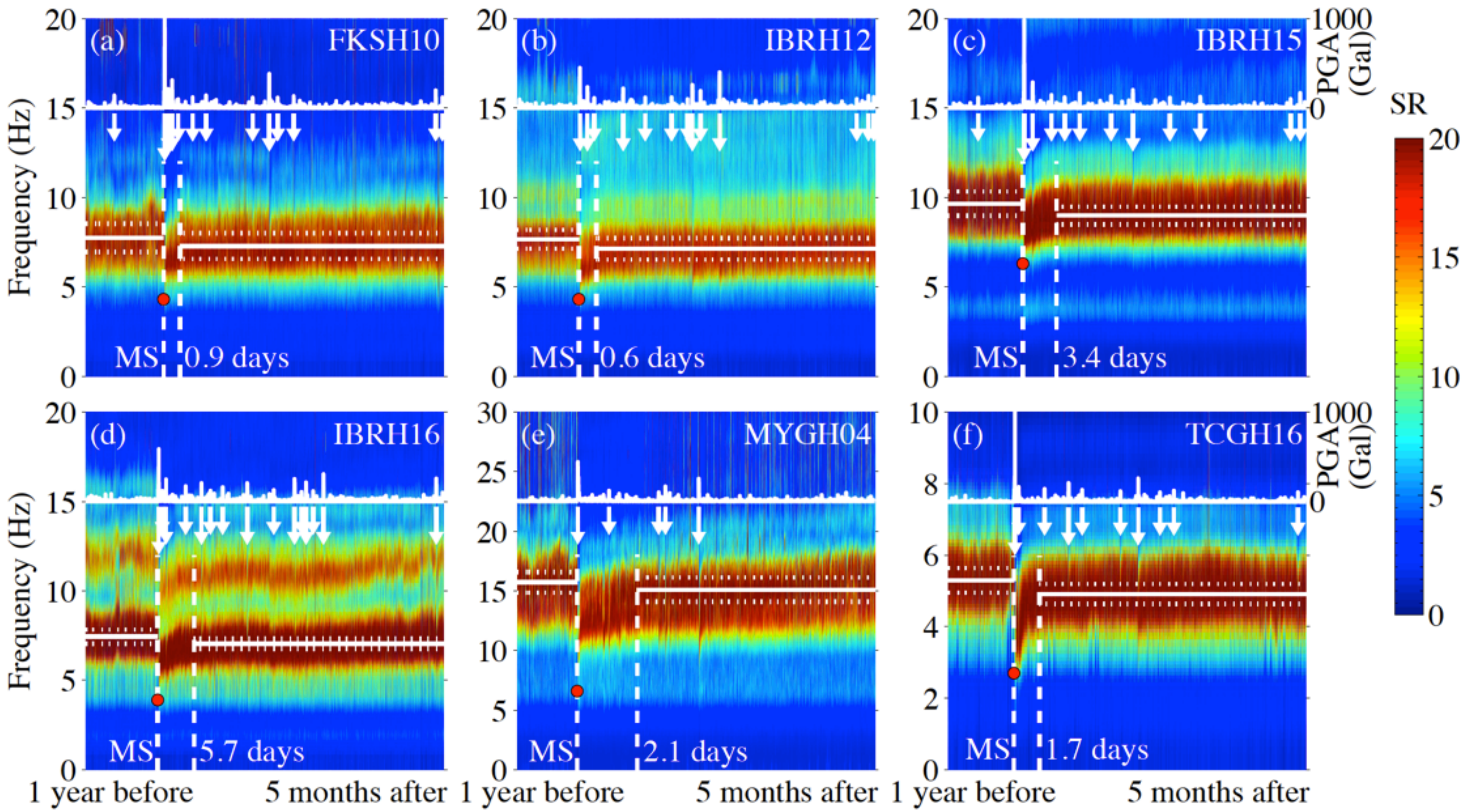
http://www.bosai.go.jp/e/

K-Net 1034 stations

KIK-Net 660 arrays

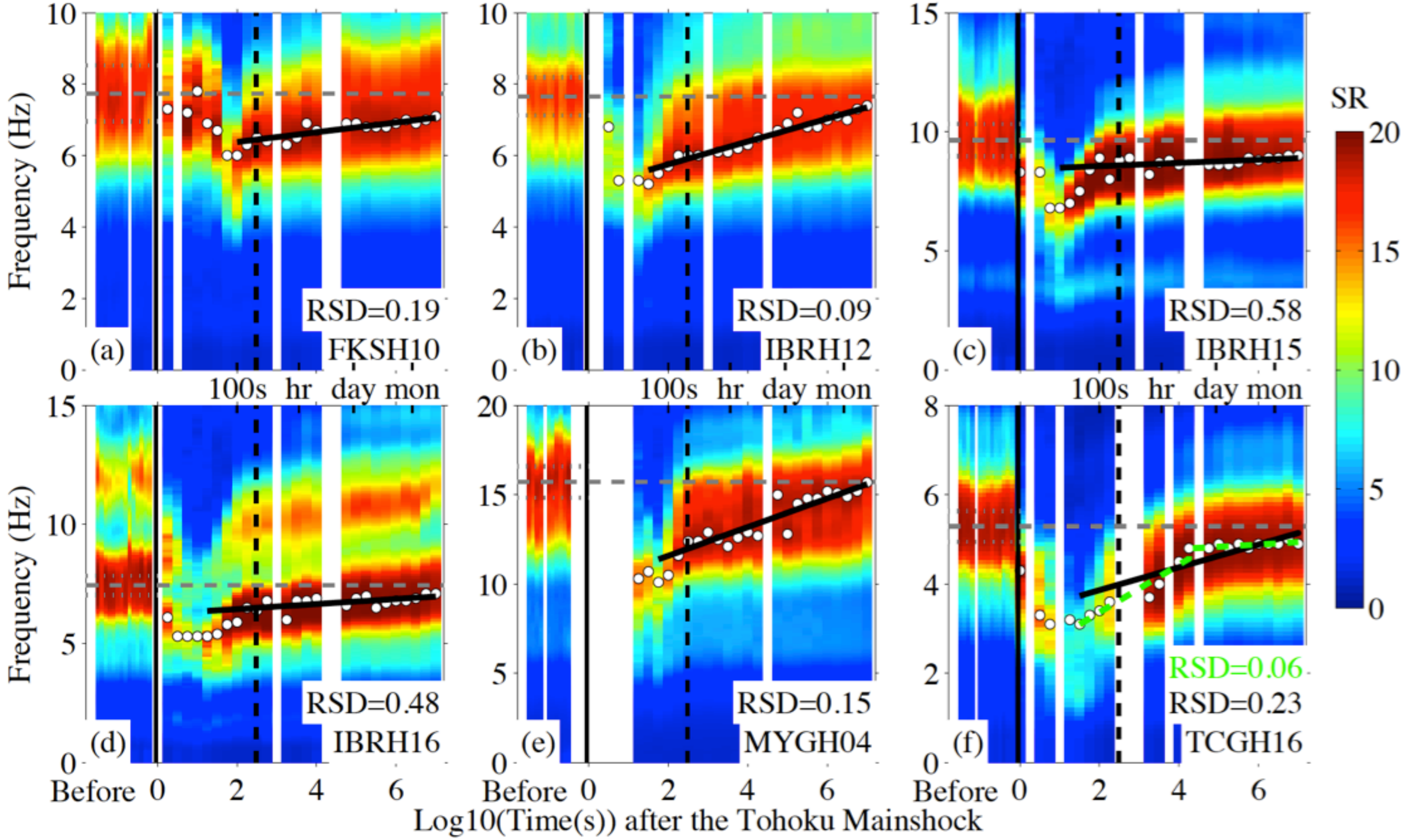


Nonlinear sediment response



Peng, Wu & Assimaki (2012)

Nonlinear sediment response



Peng, Wu & Assimaki (2012)

Nonlinear site response
in ground motion simulations

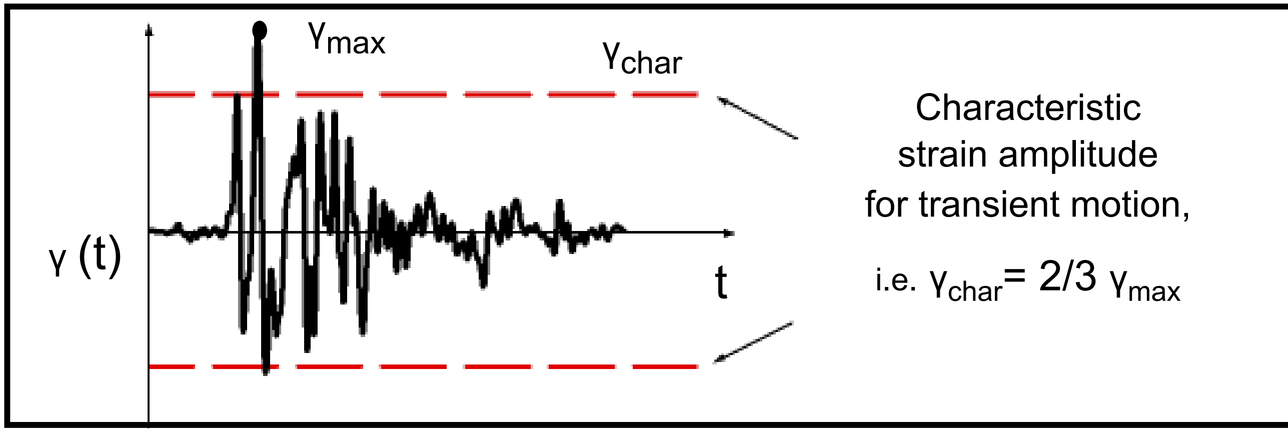
Horizontally stratified sites

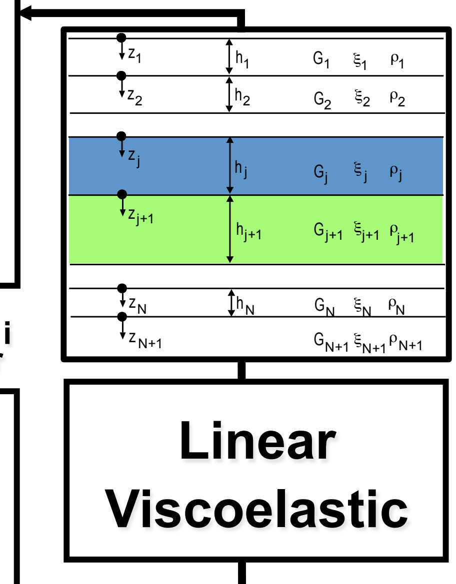
Vertically propagating seismic waves

Cohesive (plastic) soils: No liquefaction

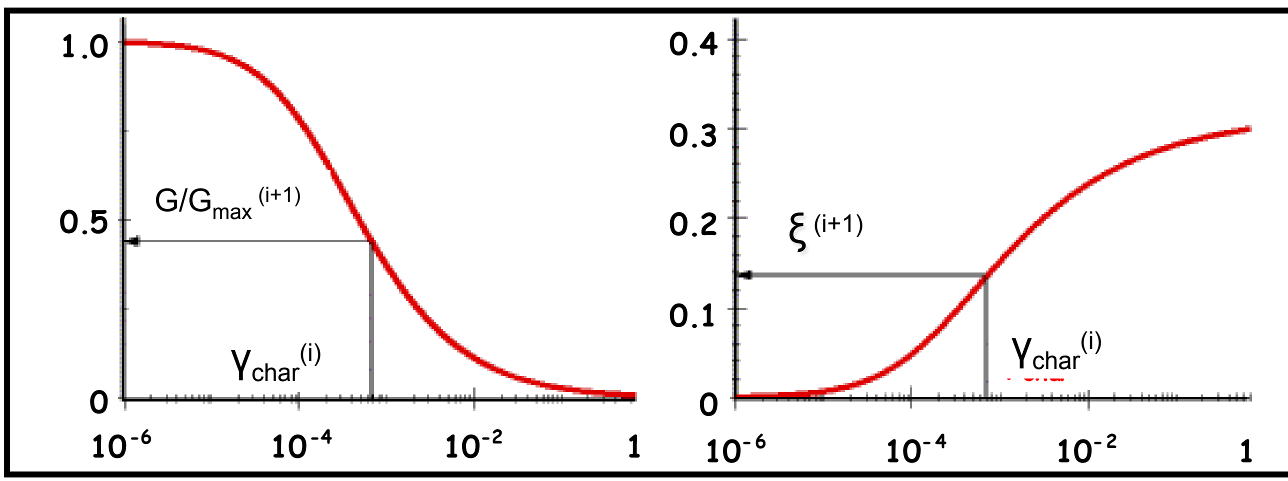
Equivalent Linear Response

Iteration *i* : Estimate characteristic level of strain γ_{char}^{i}



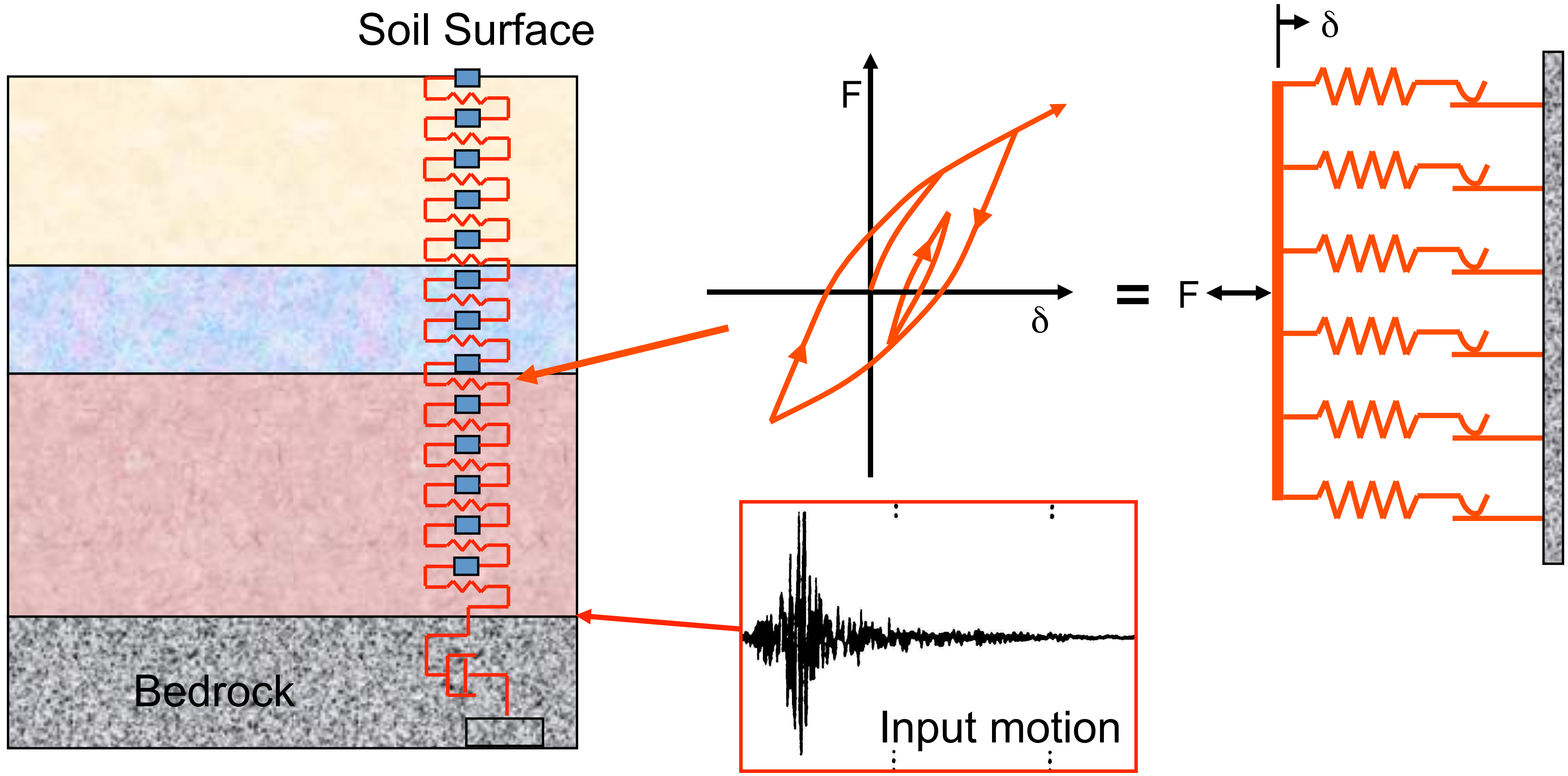


Iteration *i* +1: Select G/G_{max} and ξ consistent with γ_{char}^{i}



(Schnabel et al, 1972)

Nonlinear Site Response



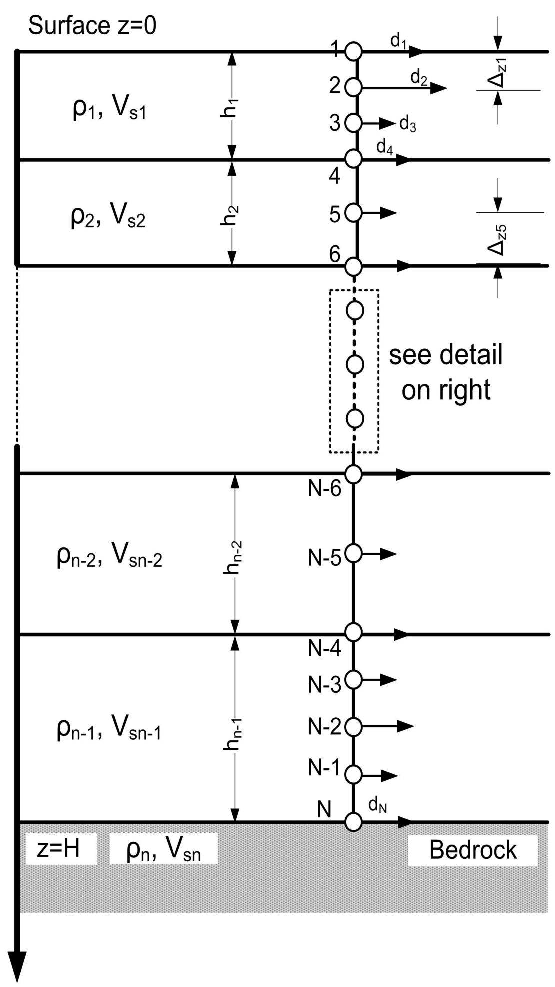
Few input parameters for nonlinear soil model
Computationally efficient
Damping calibration to avoid high frequency overdamping

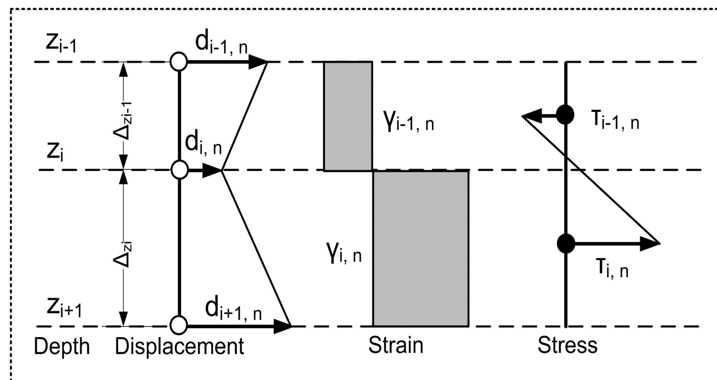
slide by Steve Kramer (UW)

SeismoSoil: 1D total-stress nonlinear analysis

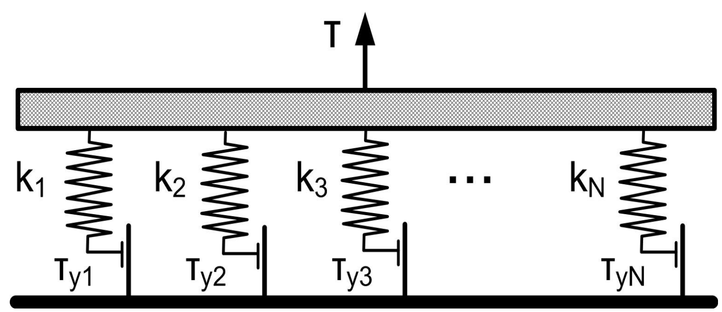
Numerical formulation: Finite differences, PML boundary conditions

Small-stain damping (ξ): SLS in parallel (Liu & Archuleta, 2006)



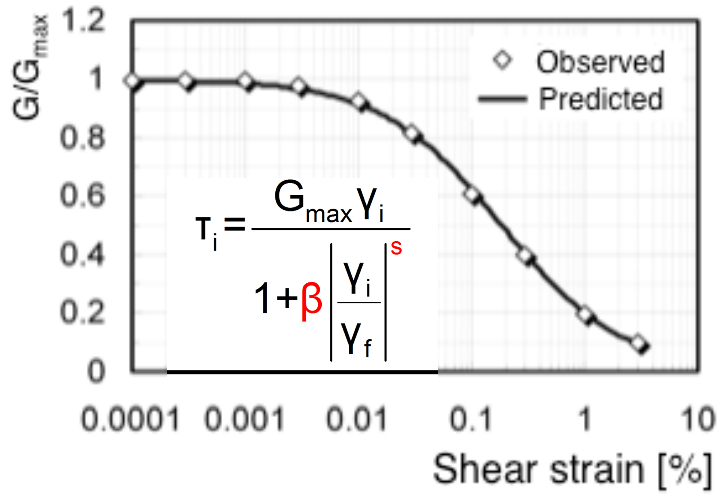


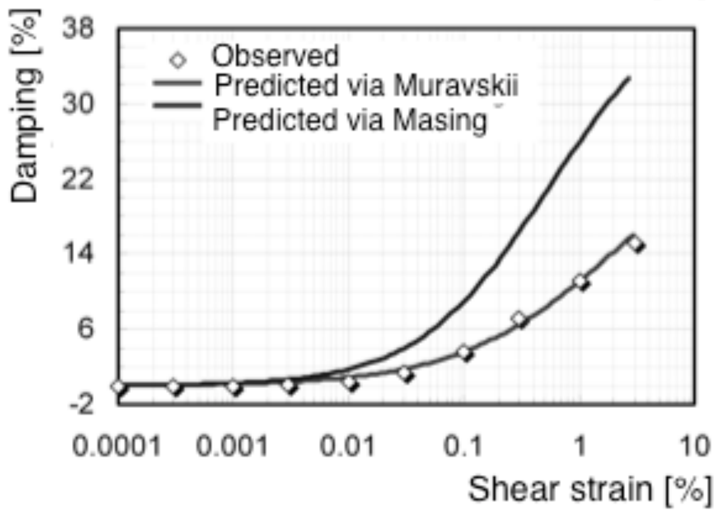
Elastoplastic springs in parallel
Iwan (1967)



Monotonic and Hysteretic Components

Monotonic loading

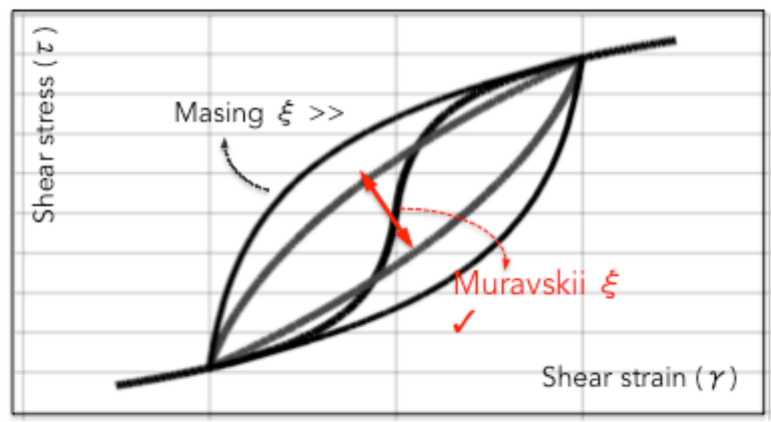




Modified Muravskii hysteretic law

U-R scaled and translated replicas of backbone

2x parameters for modulus and damping



Realistic damping predictions

Same input parameters as equivalent linear

Automatic calibration using genetic algorithms

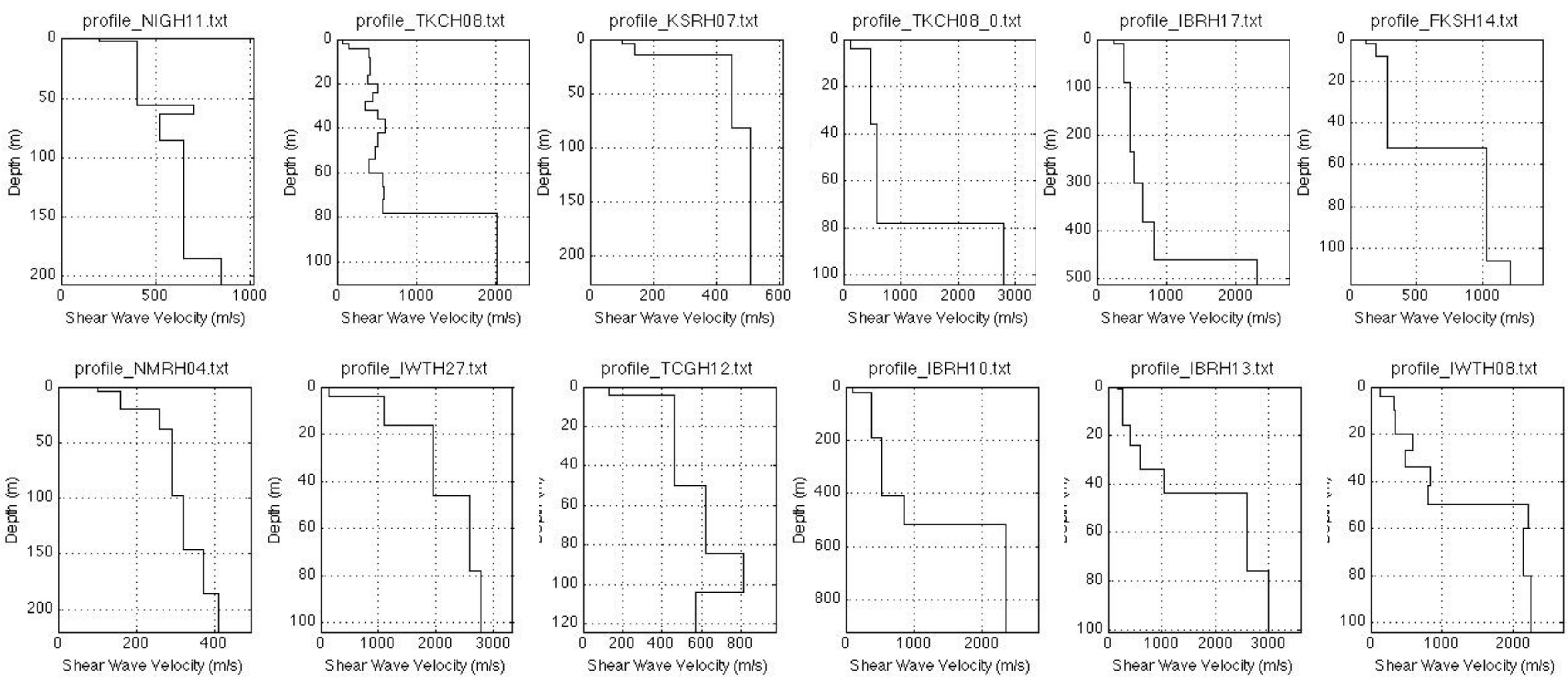
(Li & Assimaki, 2009)

Let’s compare the model performance

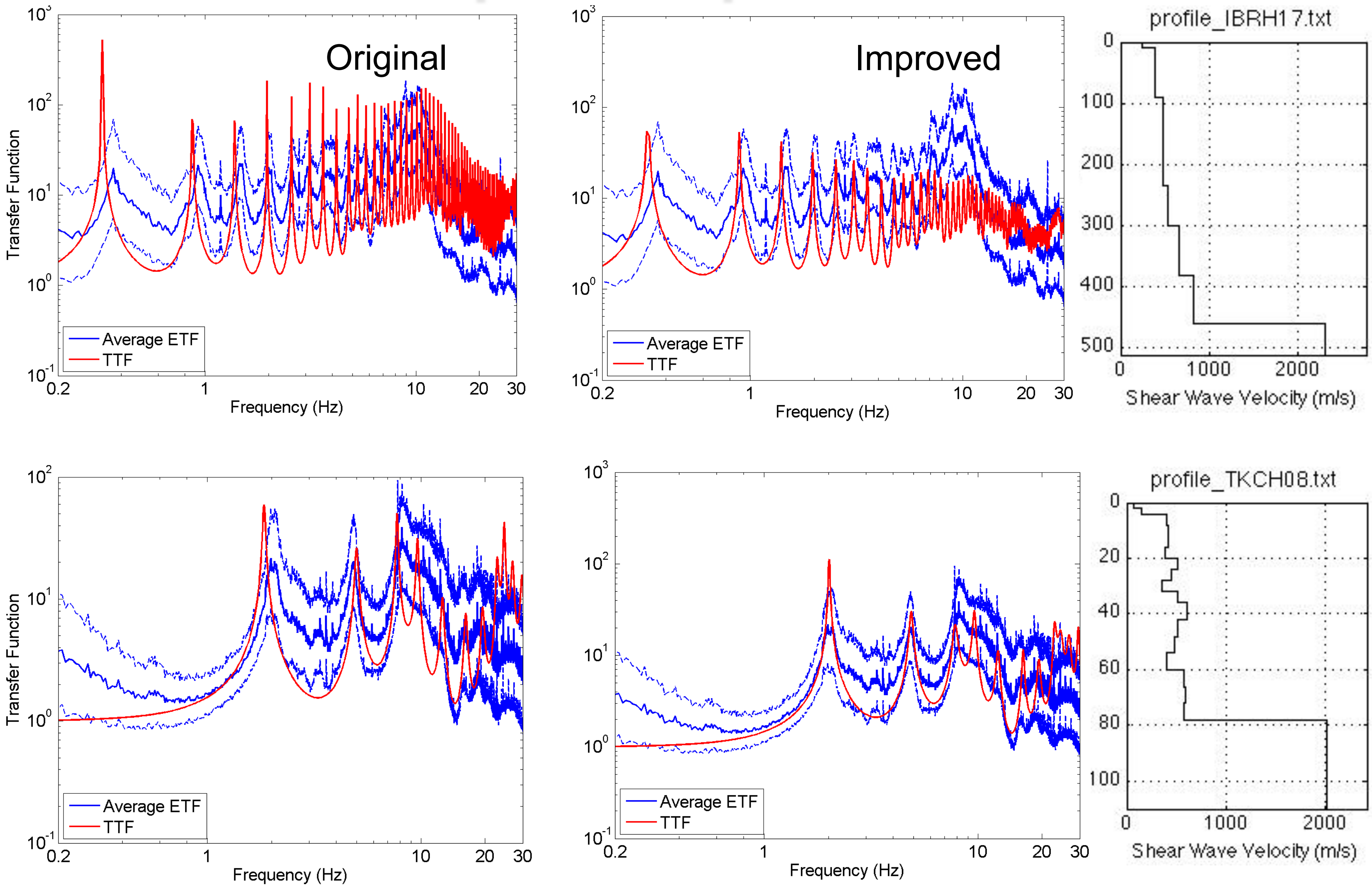
KIK-Net strong motion stations

Site selection according to 1D site response taxonomy proposed Thompson et al (2012)

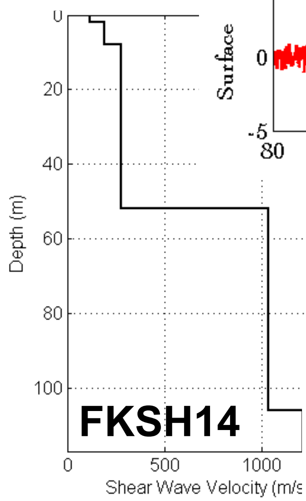
Attenuation (Q) and density from ground motion *inversion* of downhole array recordings

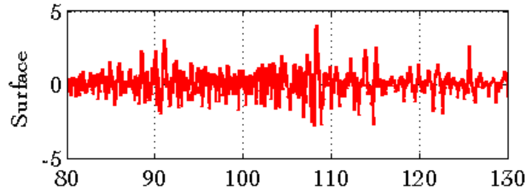


Soil profile optimization



Goodness-of-fit criteria

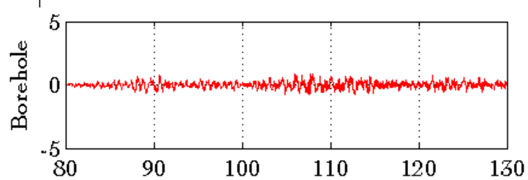


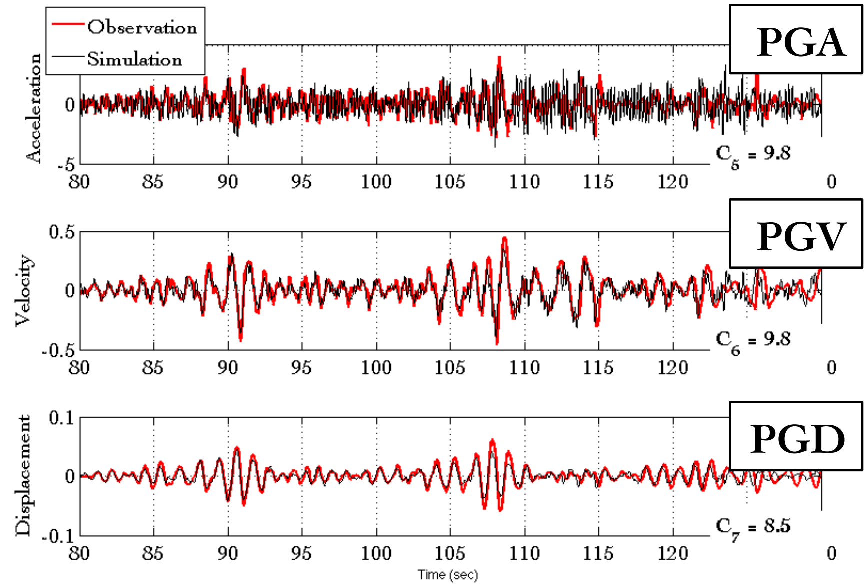


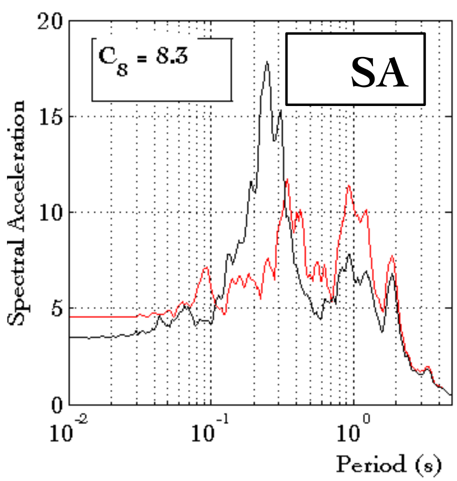
Tohoku 2011 mainshock

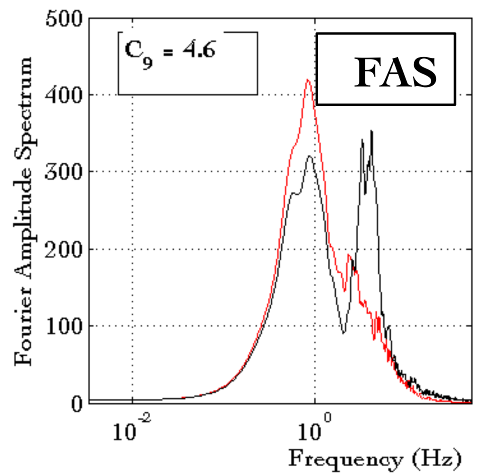
Nonlinear model

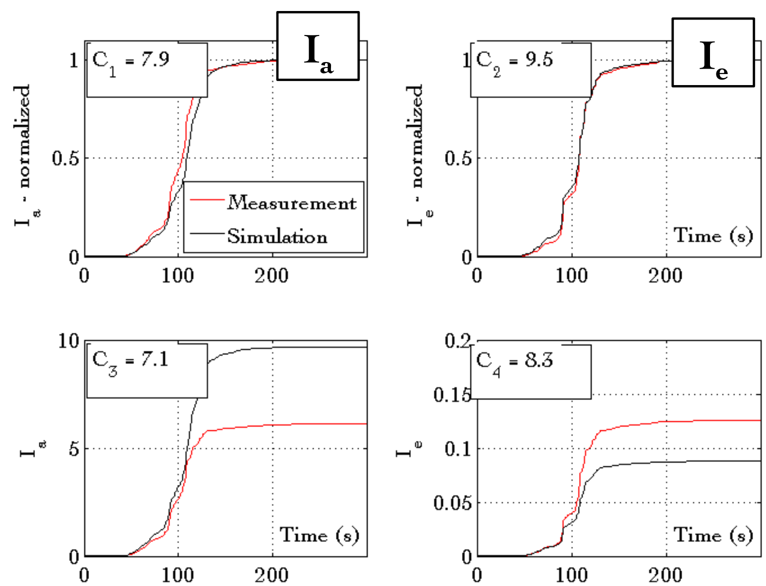
GOF = 8.2







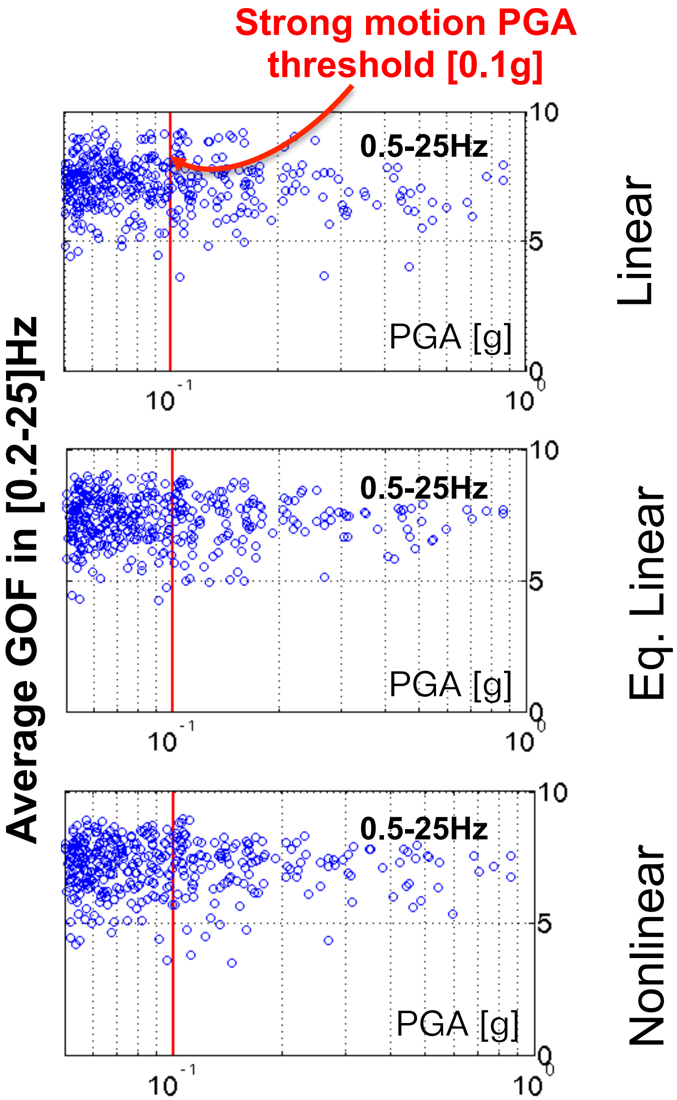




Anderson, 2004

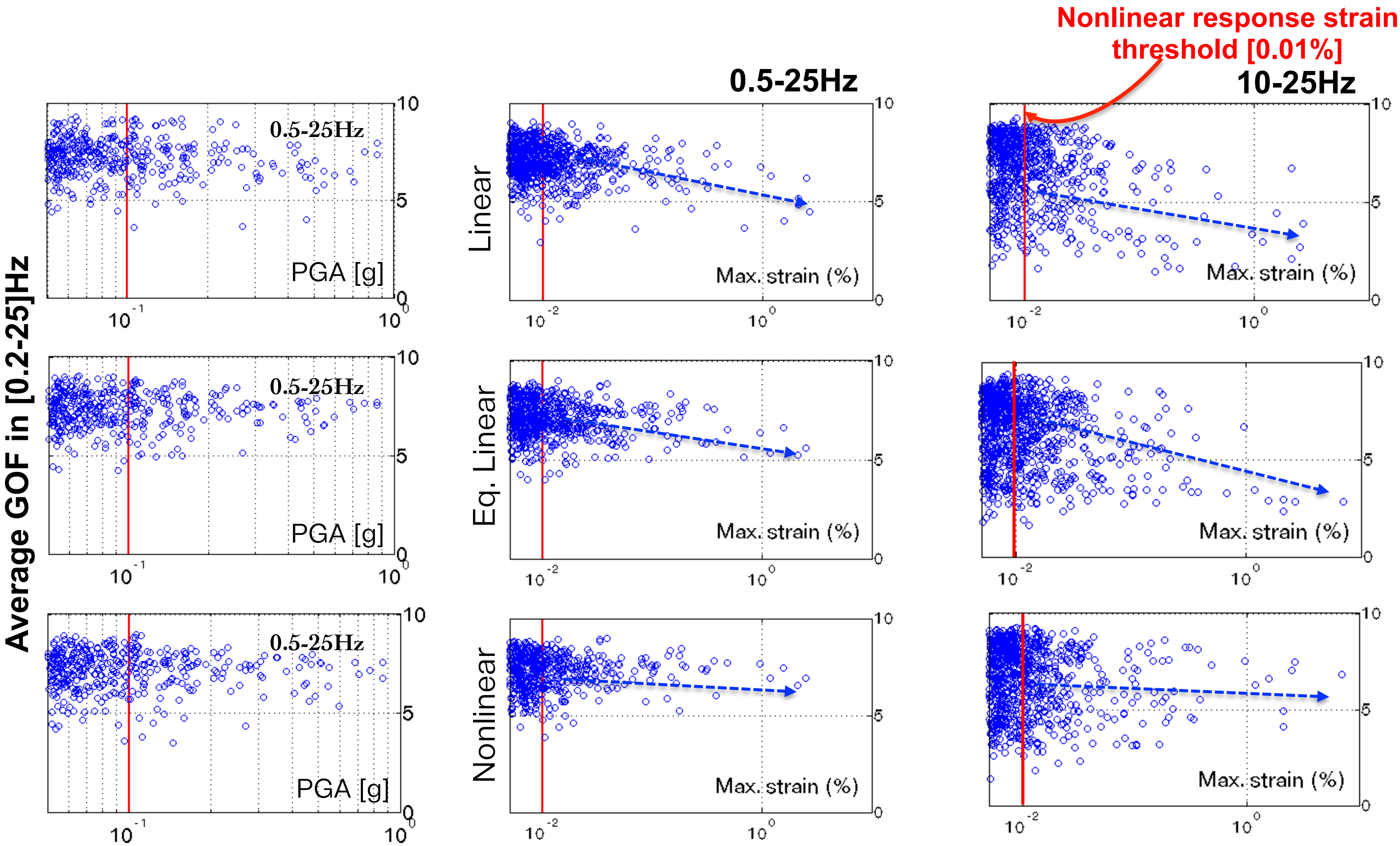
[0-10] = [Poor – Excellent]

Simulations vs. observations



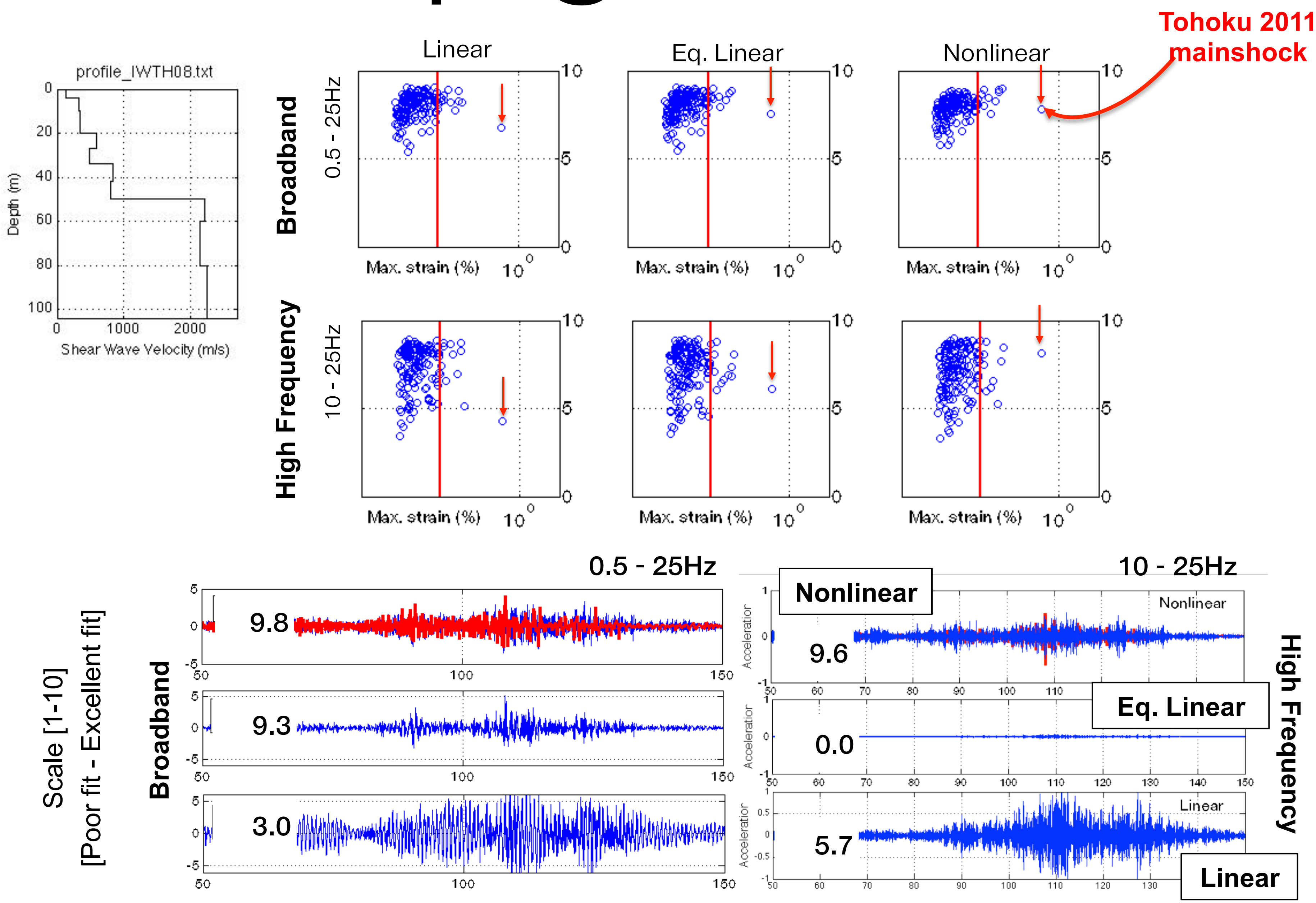
No apparent difference of <u>GOF vs. PGA</u>

Simulations vs. observations

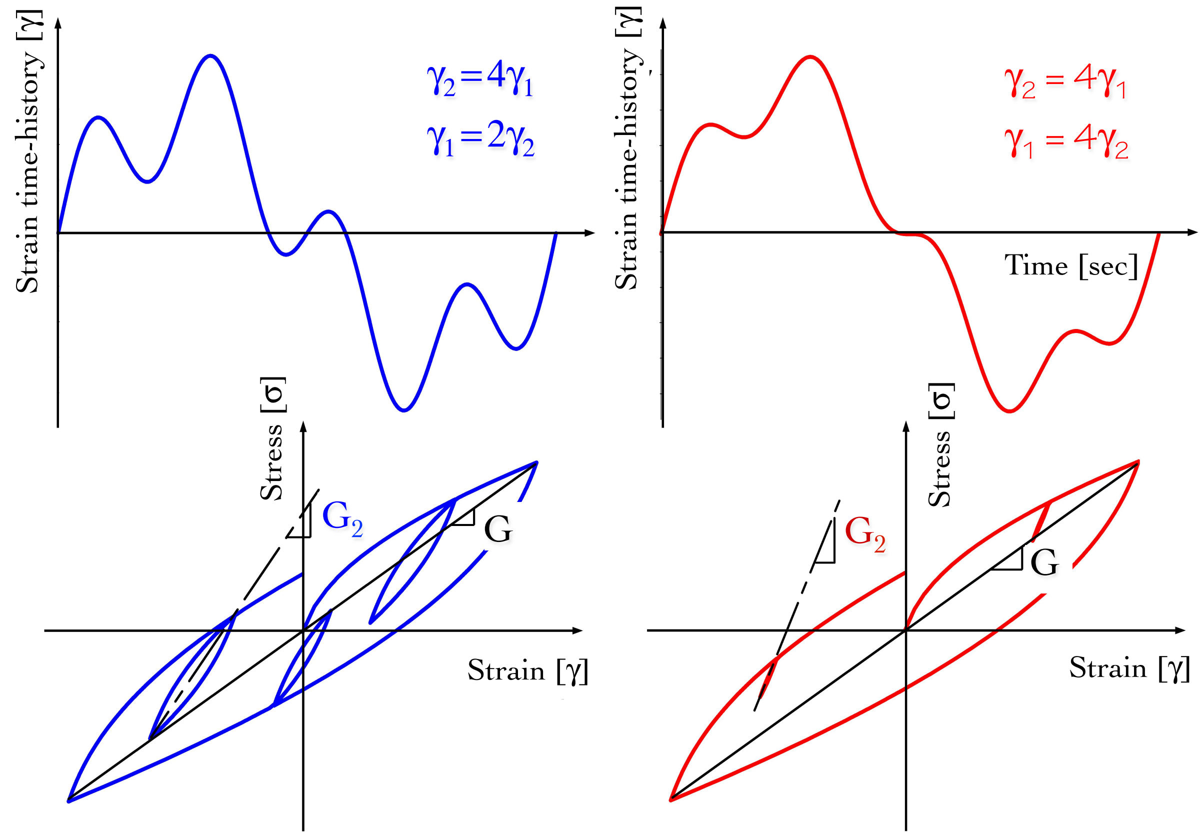


Nonlinear model performance clear for GOF vs. strain particularly in the high frequency range [10-25Hz]

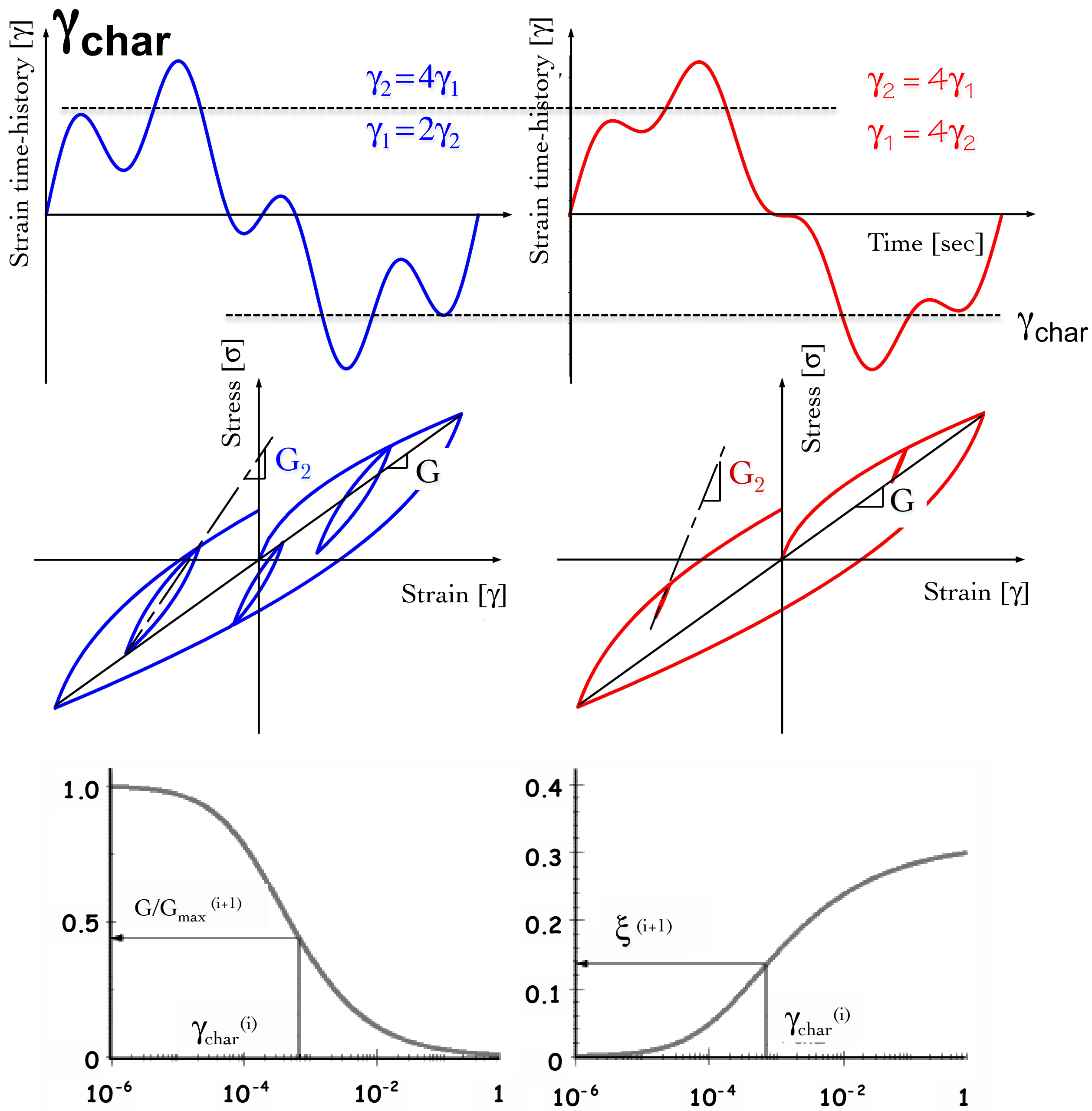
Example @ station IWTH08



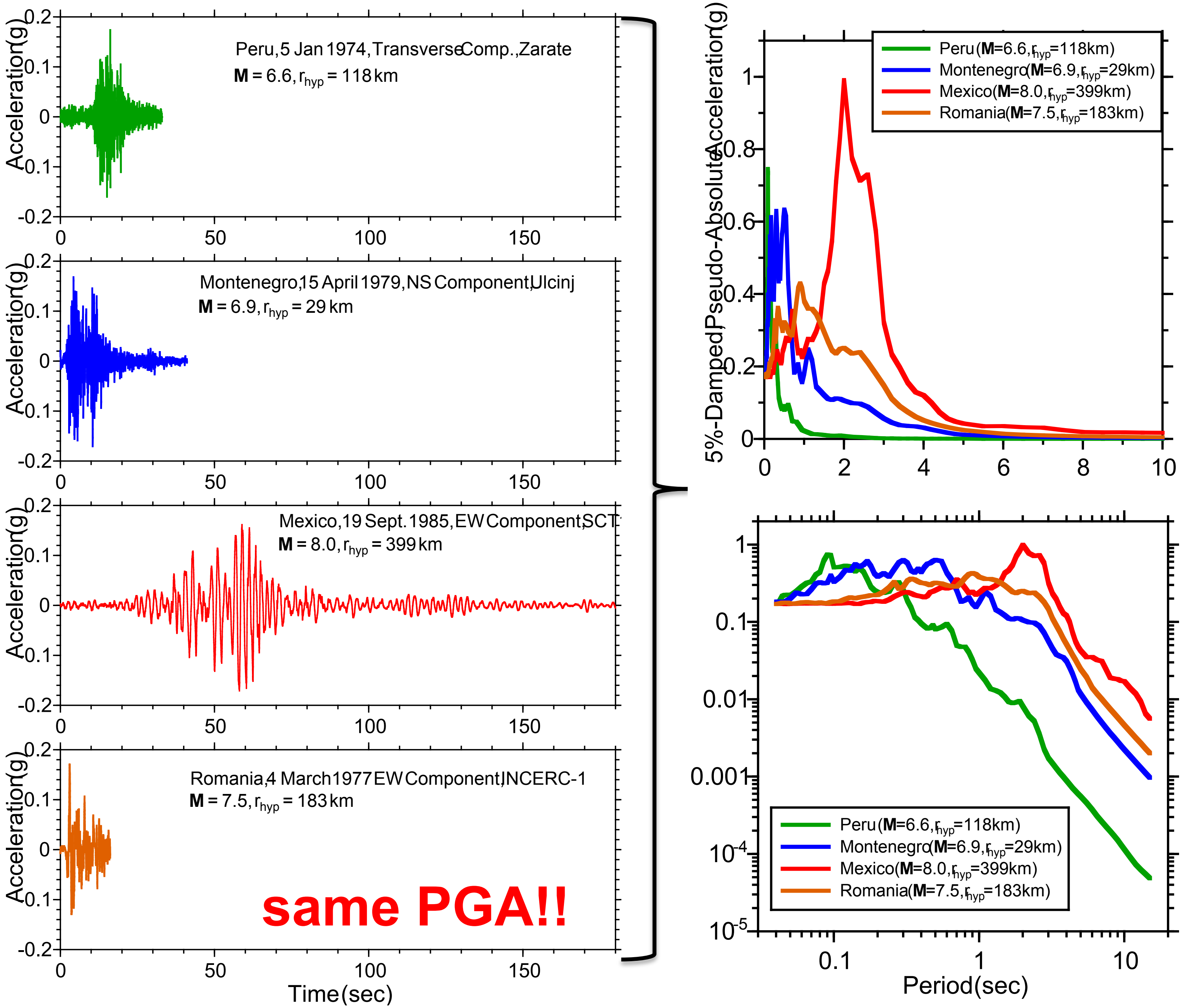
Equivalent linear and high frequencies



Equivalent linear and high frequencies



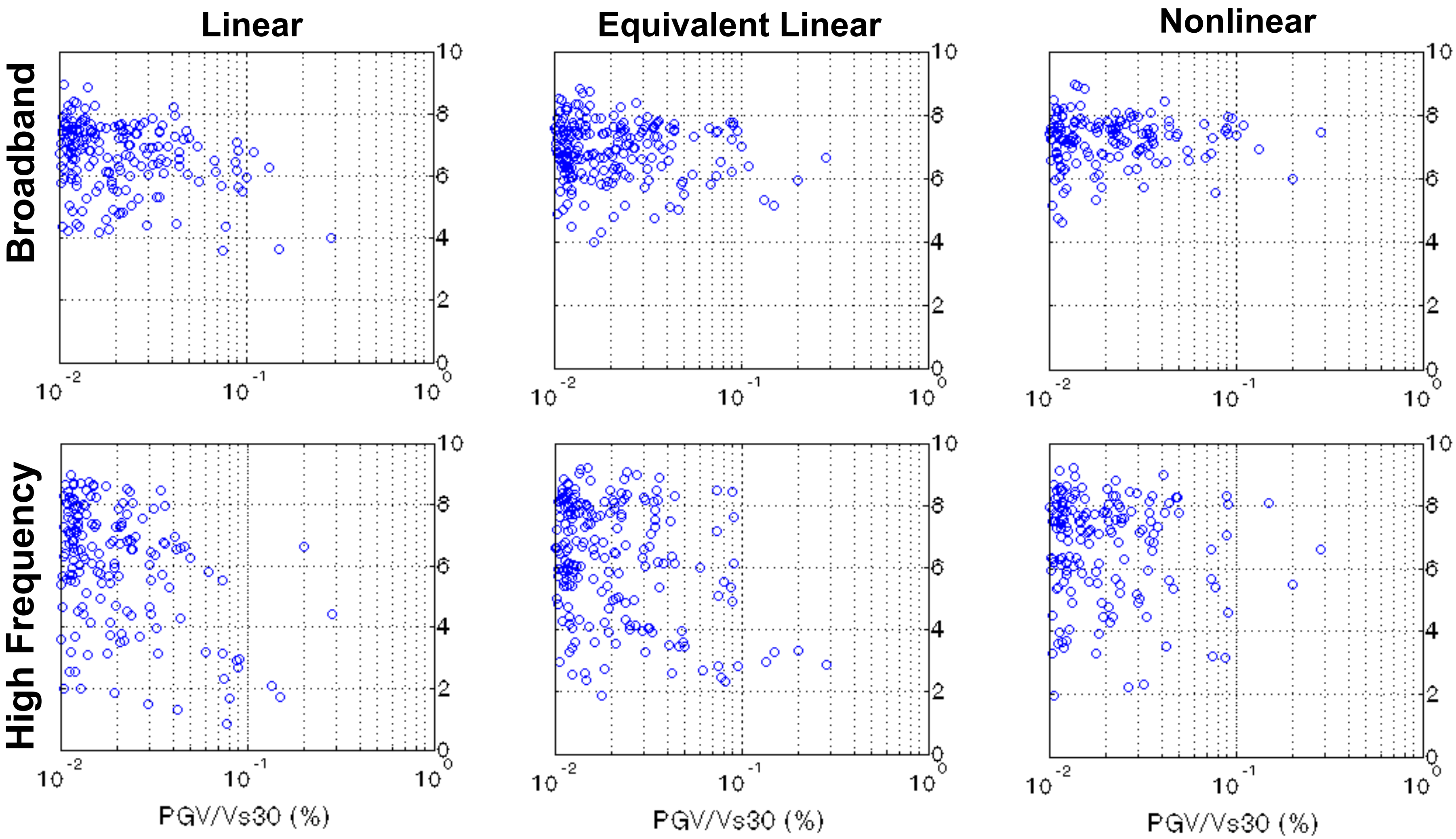
PGA as intensity measure



PGV/$V_{s,30}$ is a measure of strain

Waves in unbounded medium:

$$\frac{\partial u}{\partial t} \times \frac{1}{V_s} = \frac{\partial u}{\partial x} = \gamma$$

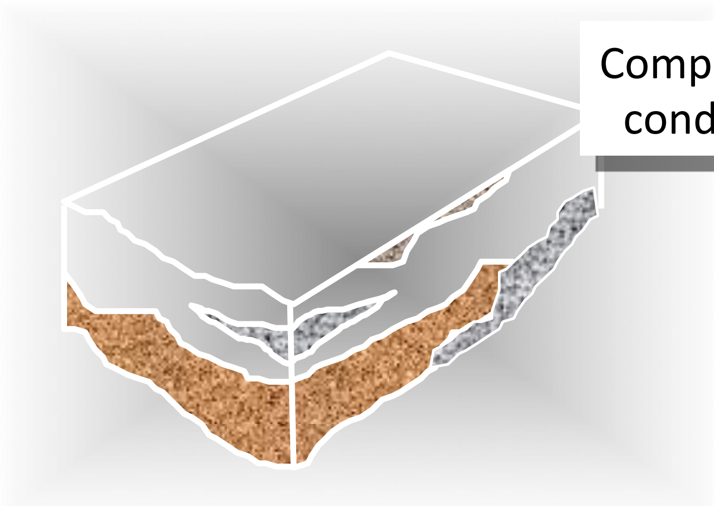


(Idriss, 2011)

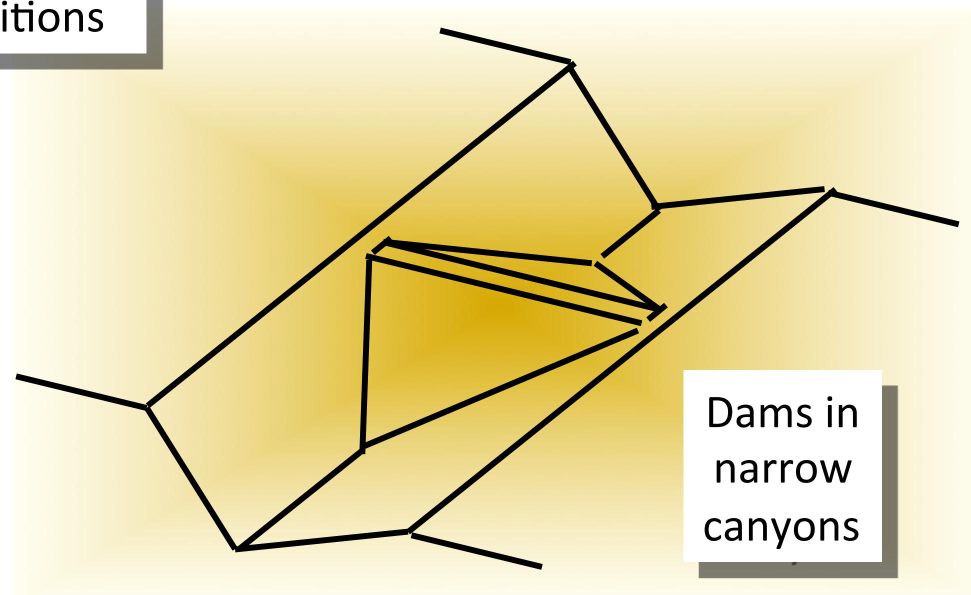
What did I learn today?

- Three approaches to compute <u>site-specific</u> response: **viscoelastic, eq. linear and nonlinear**
- Three methods to integrate site response in ground motion simulations: **empirical amplification factors, GTL and site-specific**
- Which one's better depends on what information we have in hand…

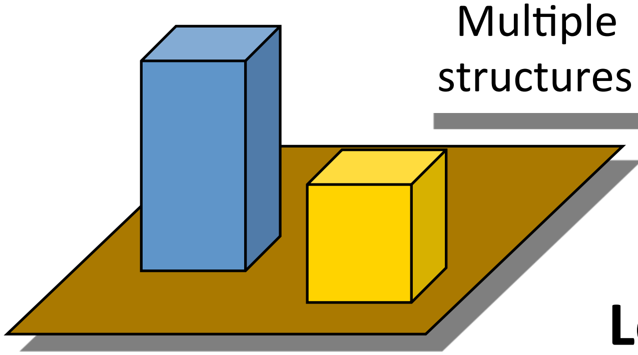
When are these approaches very wrong?



Complex soil conditions



Dams in narrow canyons



Multiple structures

Localized structures and liquefiable sites may require use of 3-D response analyses

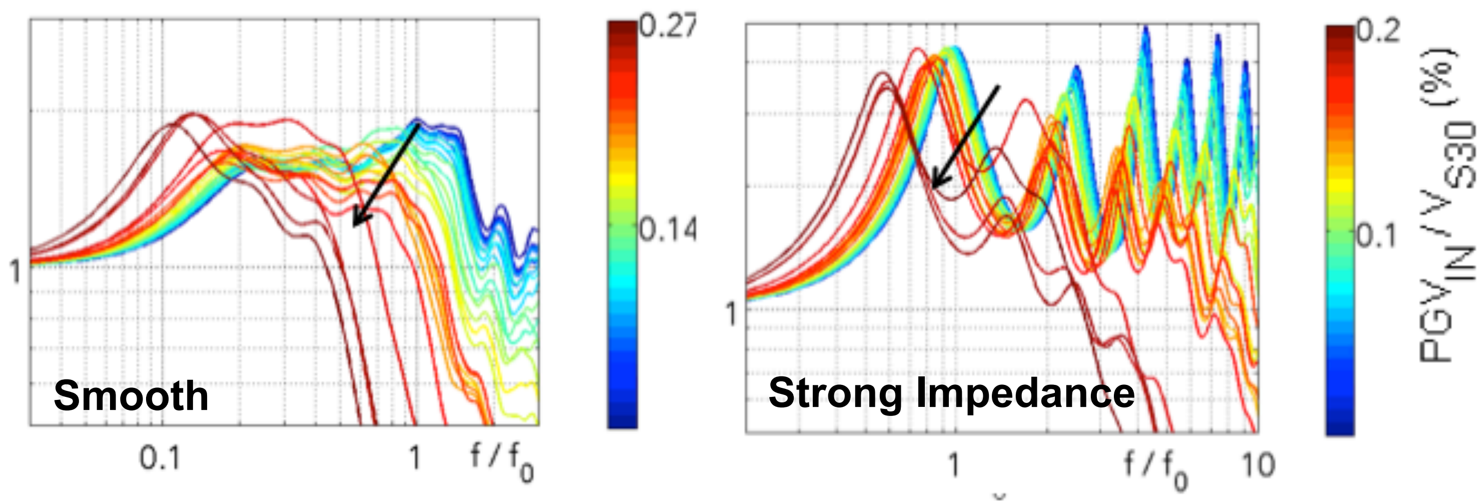
slide by Steve Kramer (UW)

What should we improve?

Empirical:

Amplification factors based on Fourier spectral ratios

Intensity Measures <u>relevant</u> to site response



Regional: Need improved geotechnical layer

Site-specific: Need realistic 3D soil constitutive models

Questions?