THE CHALLENGE OF NONLINEAR SITE RESPONSE: FIELD DATA OBSERVATIONS AND NUMERICAL SIMULATIONS

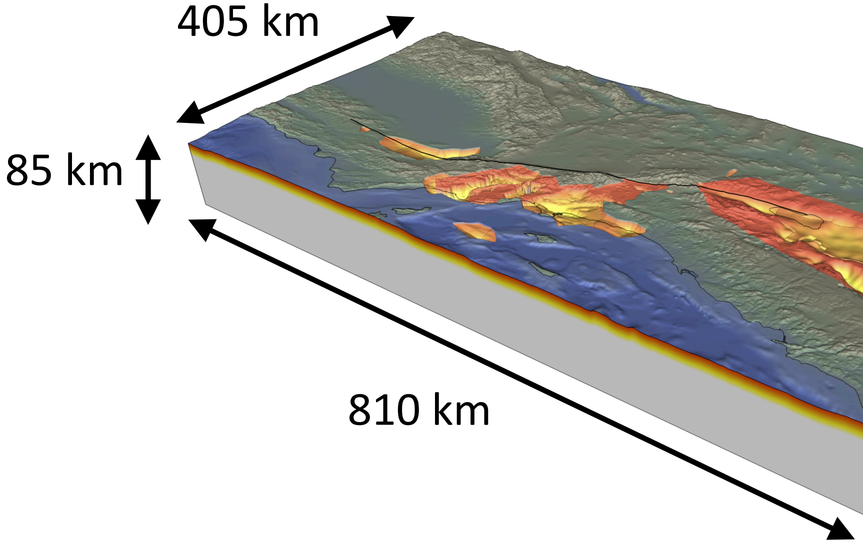
Luis Fabian Bonilla(1), Celine Gelis(2), Julie Regnier(3)

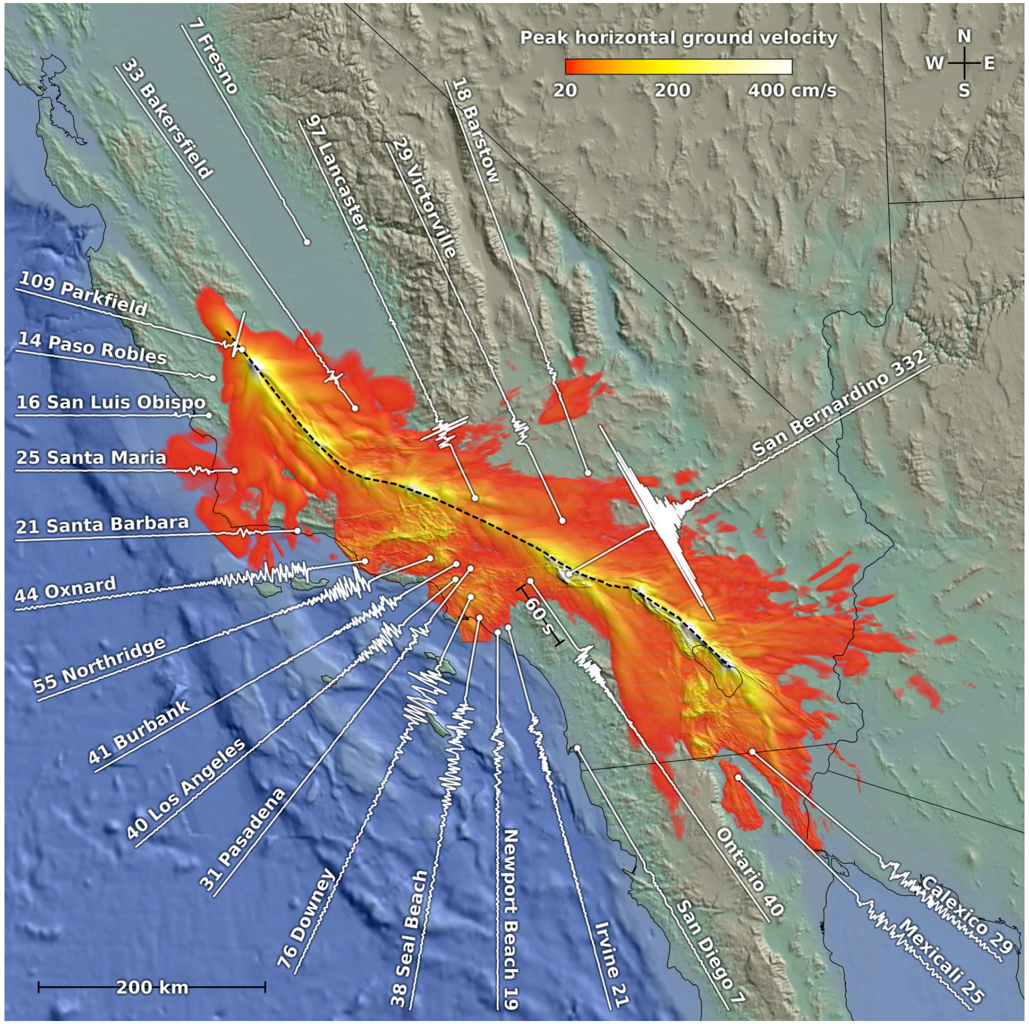
(1) Universite Paris-Est, IFSTTAR, France
(2) Institut de Radioprotection et de Surete Nucleaire, France
(3) CETE-Mediterrannee, France

Outline

- Motivation
- Site-specific cases: the 1987 Superstition Hills earthquake
- Widespread nonlinear site response: the 1994 Northridge and the 2011 Tohoku earthquakes
- Lessons learnt from these earthquakes
- Conclusions

Motivation - Seismology



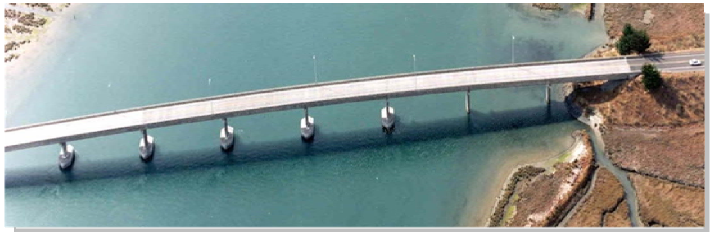


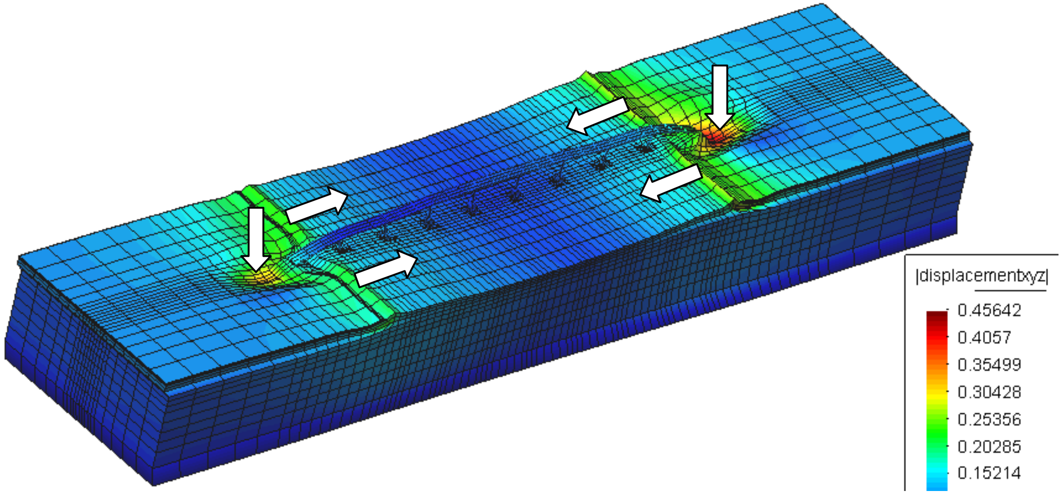
after Cui et al. (2010)

- M8
- 360 s of ground motion
- 436 billion cubic elements
- spontaneous rupture
- minimum Vs = 400 m/s
- frequency: 0 - 2 Hz

- Basin effects (PGV =1 - 4 m/s)
- Directivity and supershear effects
- How might this picture change if soil nonlinearity is taken into account?

Motivation - Earthquake Engineering



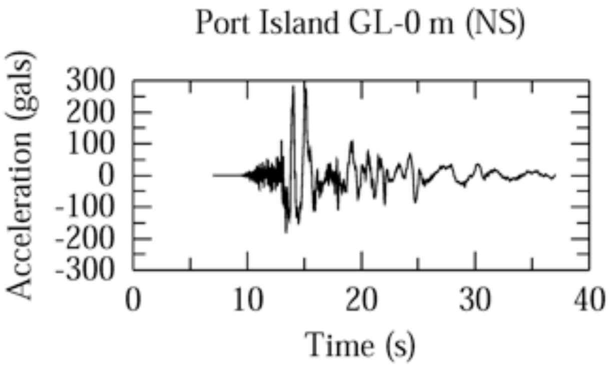


after Elgamal et al. (2008)

- Humboldt Bay Middle Channel Bridge
- 650 x 151 x 74.5 m
- Input: 1978 Tabas earthquake
- soil-structure interaction

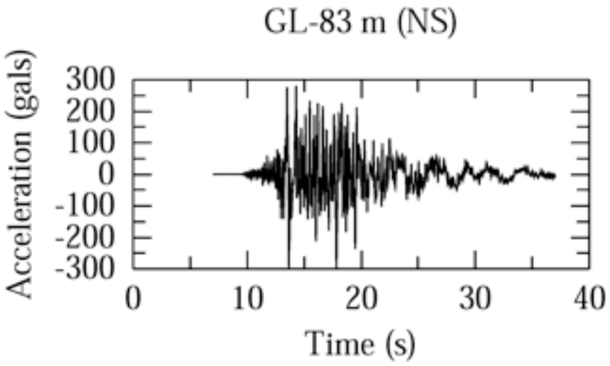
- Distribution of residual settlements of the abutment fill
- Lateral spreading along the river bank
- Bridge deformation
- How might this picture change if local or regional sources were used?

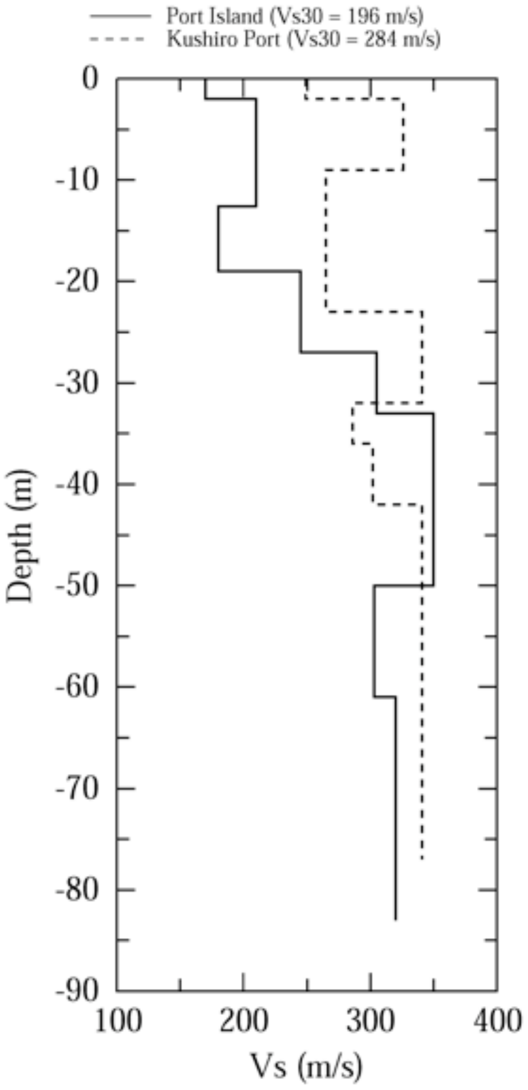
Where is the difference?

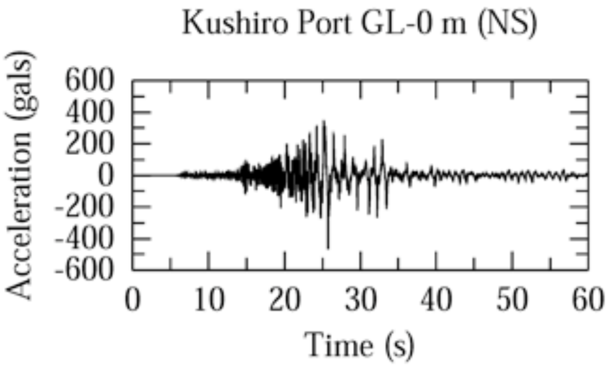

Port Island GL-0 m (NS)

Loose sand
(liquefaction)

- lowpass filtering
- deamplification

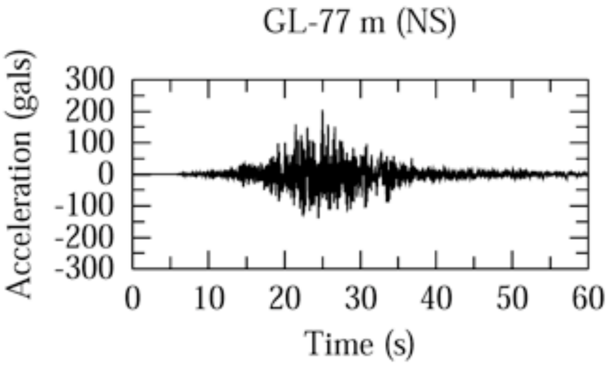

GL-83 m (NS)




Kushiro Port GL-0 m (NS)

Dense sand
(cyclic mobility)

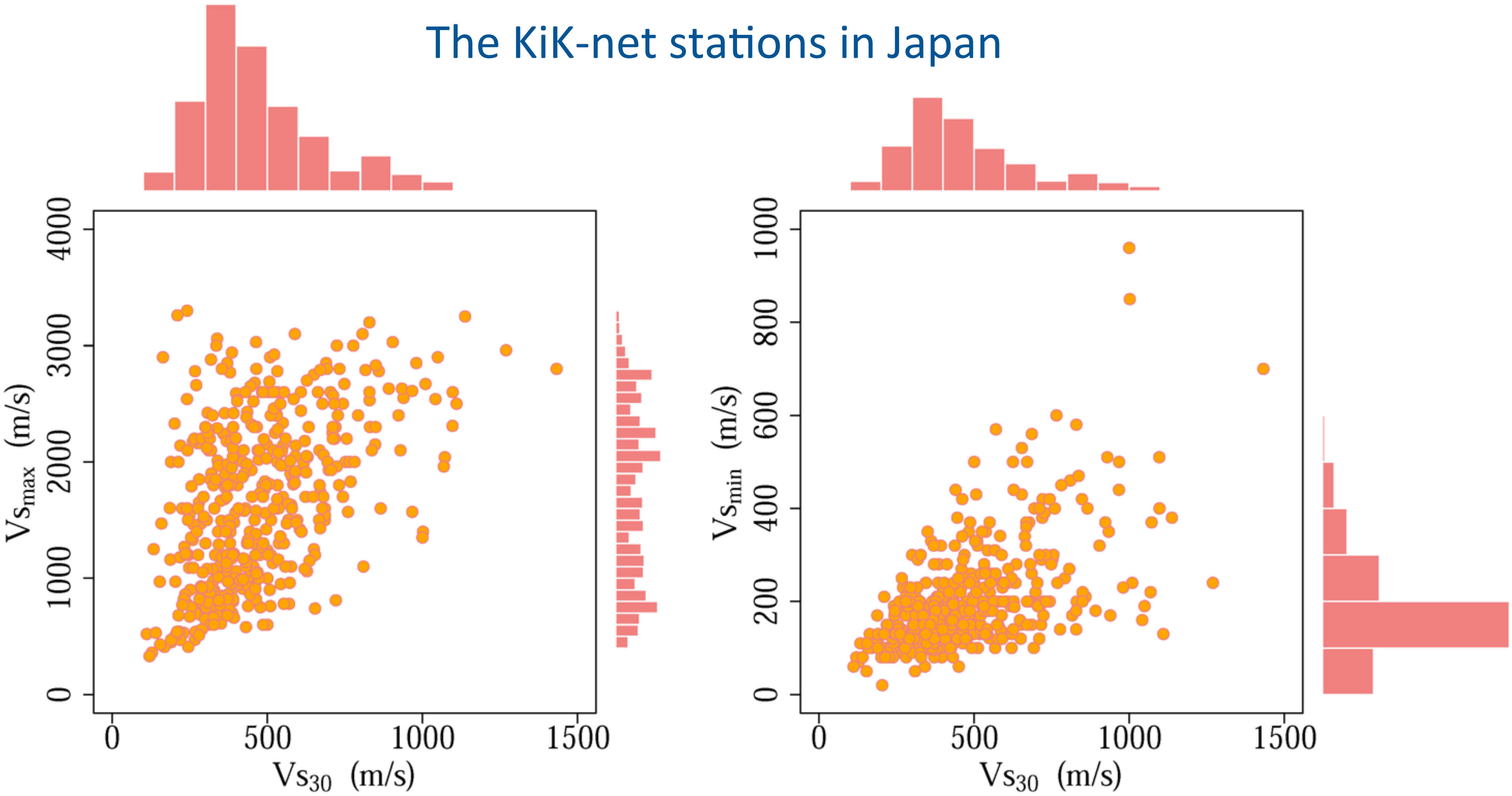
- high frequency content
- amplification


GL-77 m (NS)

Velocity profile is not enough (elastic parameters)
Seismology .NE. Earthquake Engineering

What can be done with velocity profiles?

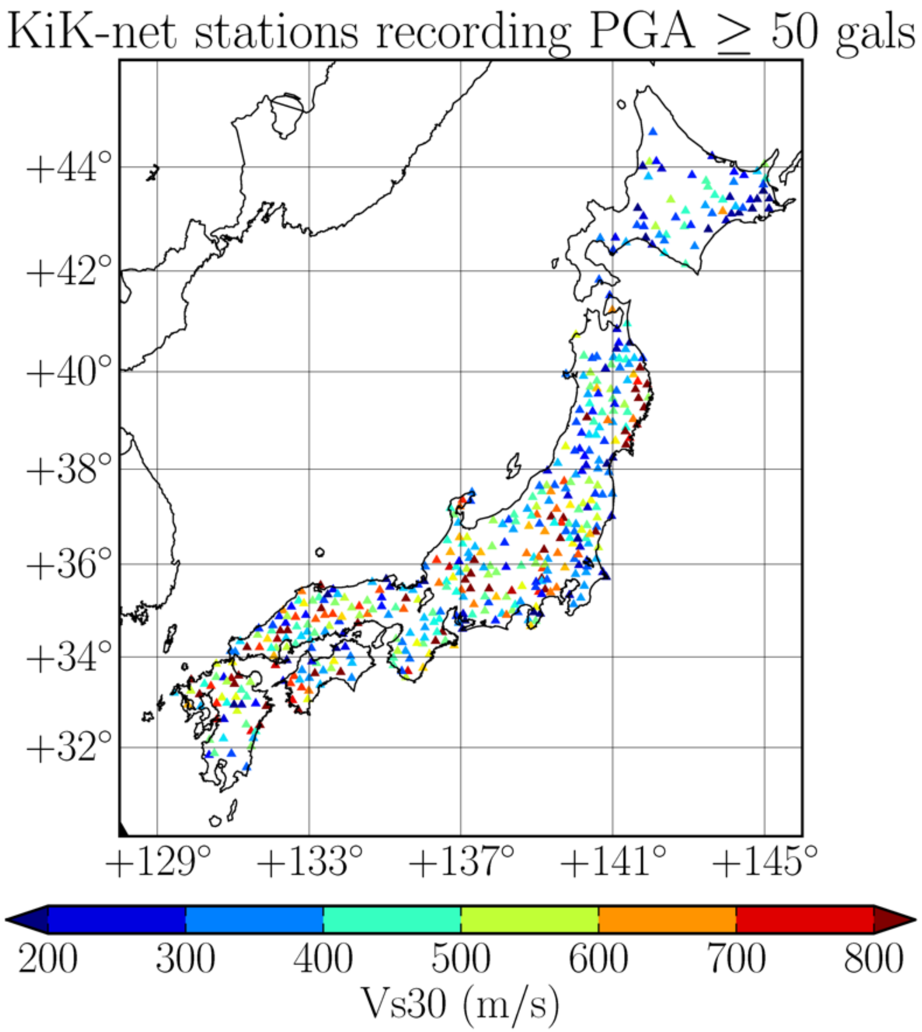
The KiK-net stations in Japan

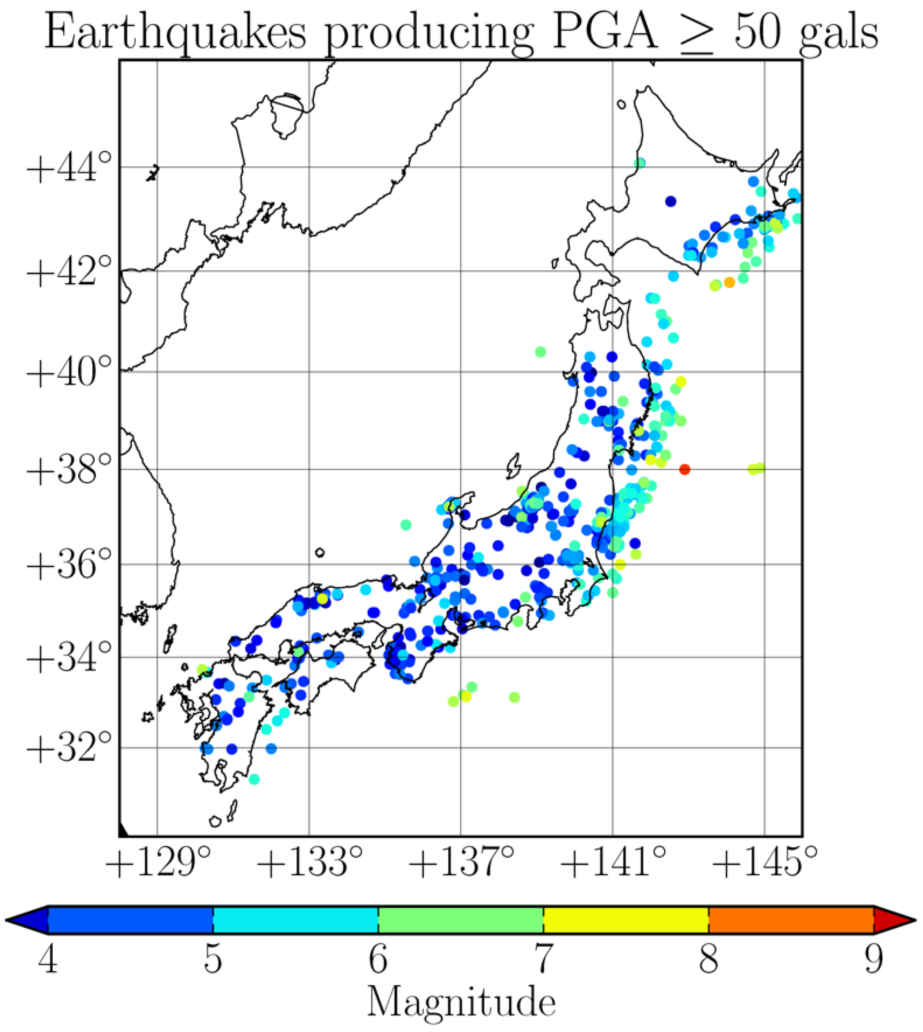


- Most of stations have a Vs30 < 500 m/s
- Maximum Vs has a uniform distribution between 500 and 3000 m/s
- Majority of stations have a minimum Vs < 200 m/s

High likelihood of strong impedance contrast

What can be done with velocity profiles?

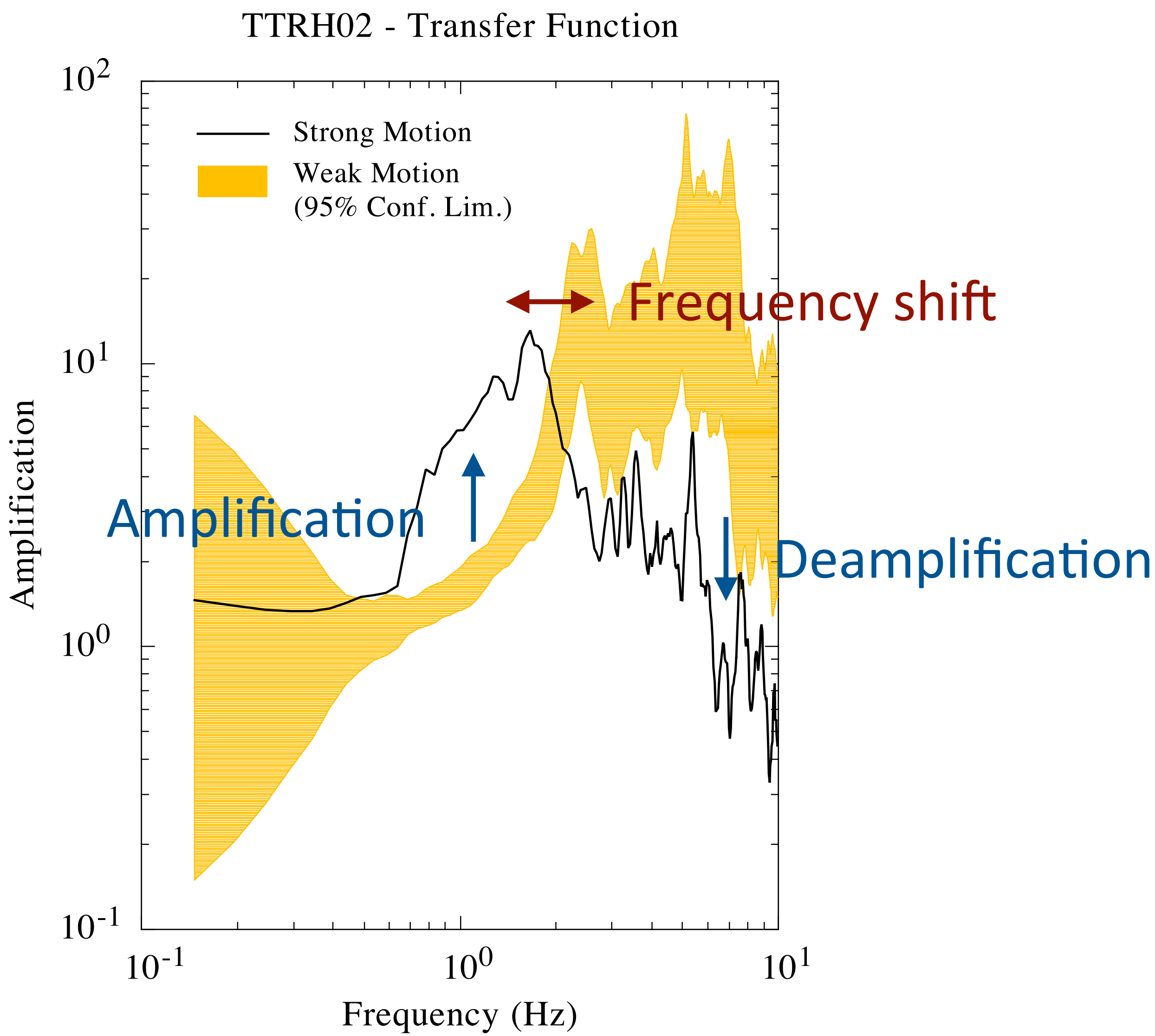

KiK-net stations recording PGA ≥ 50 gals


Earthquakes producing PGA ≥ 50 gals

- Good station coverage
- Good earthquake distribution (magnitude and epicentral location)

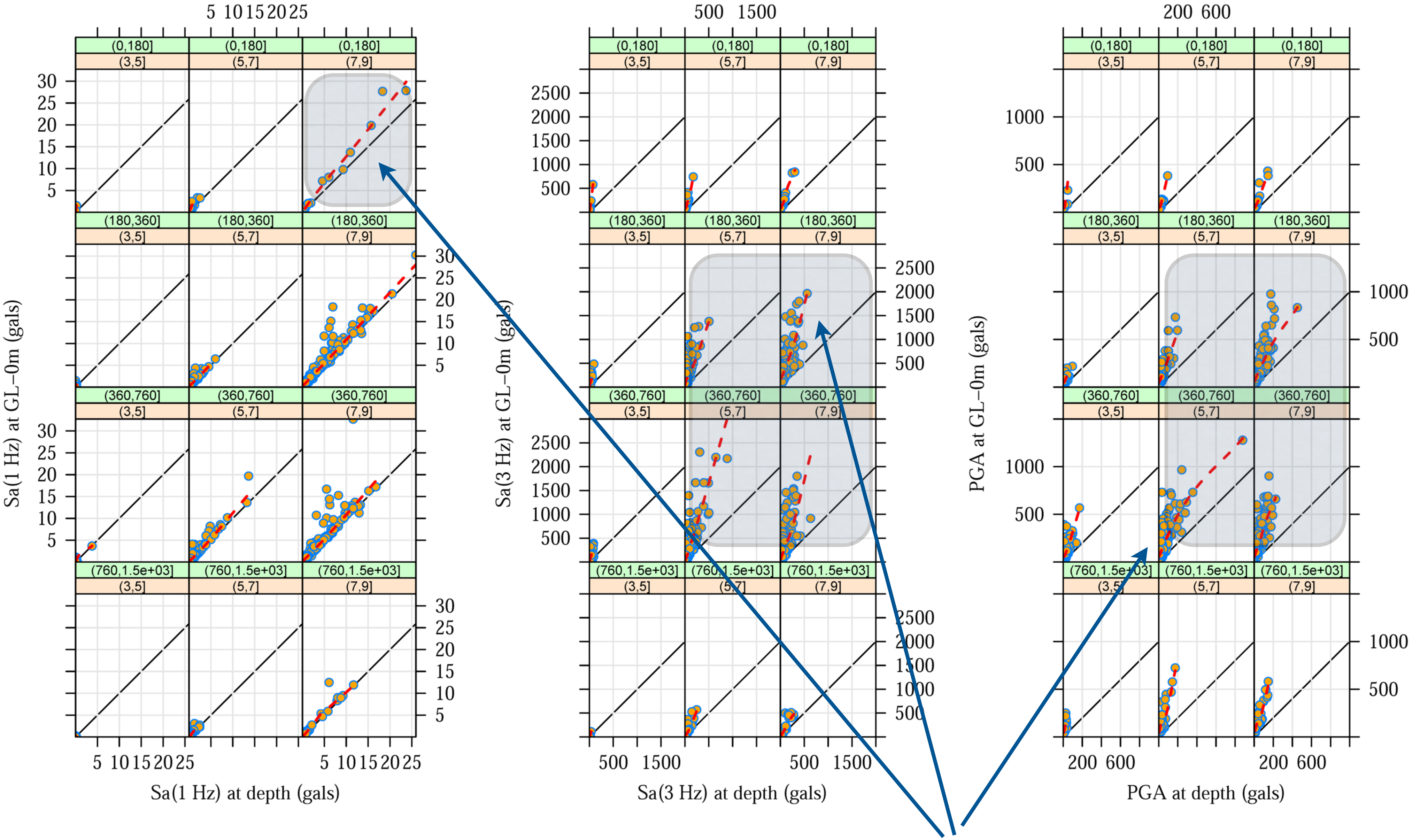
High likelihood of triggering nonlinear soil behavior

Frequency domain analysis



- Linear borehole response using data having PGA < 10 gals
- Nonlinear response using the 2000 Tottori data (M7.3)
- Broadband deamplification and shift to low frequencies

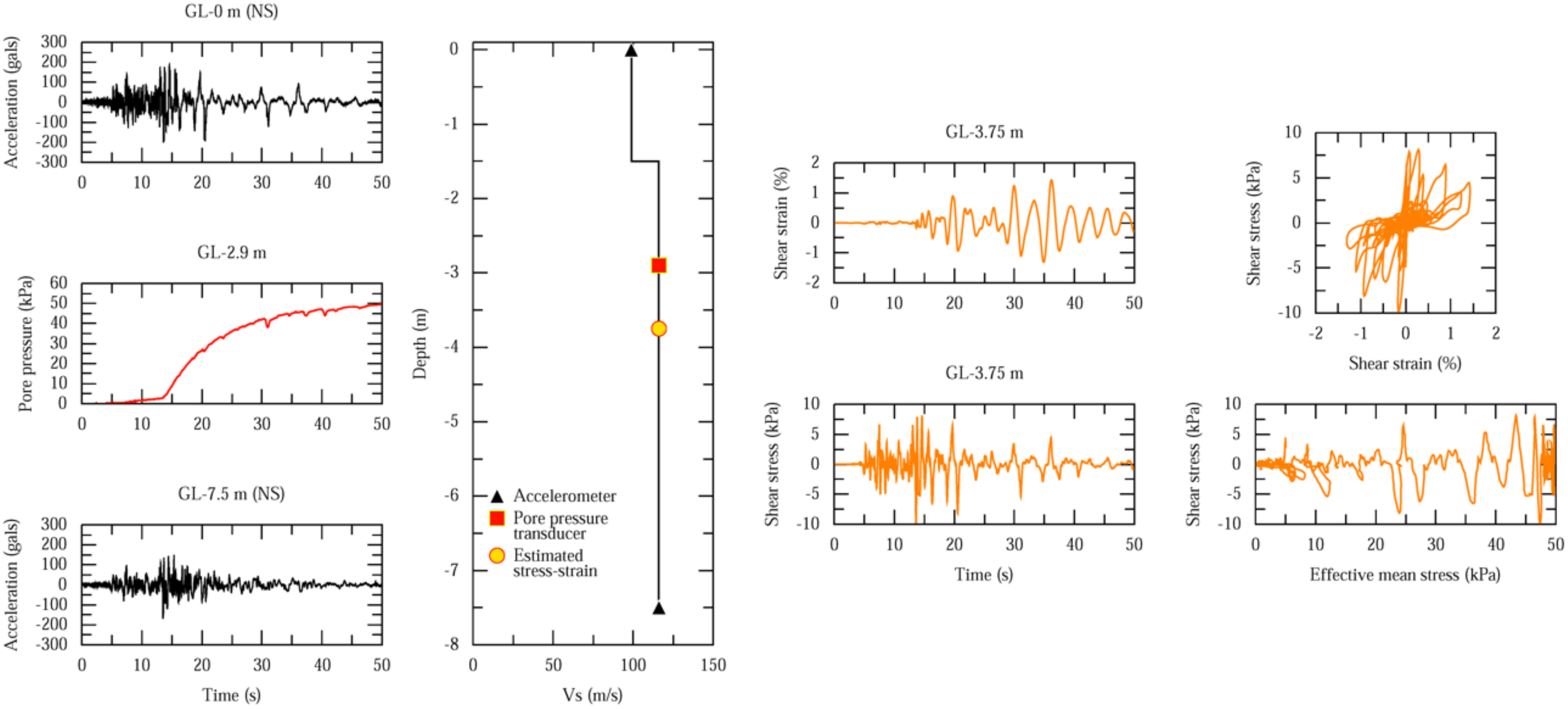
Other analyses: what index to use?



Note that ground motion at surface is always larger than at depth

Nonlinear trend?

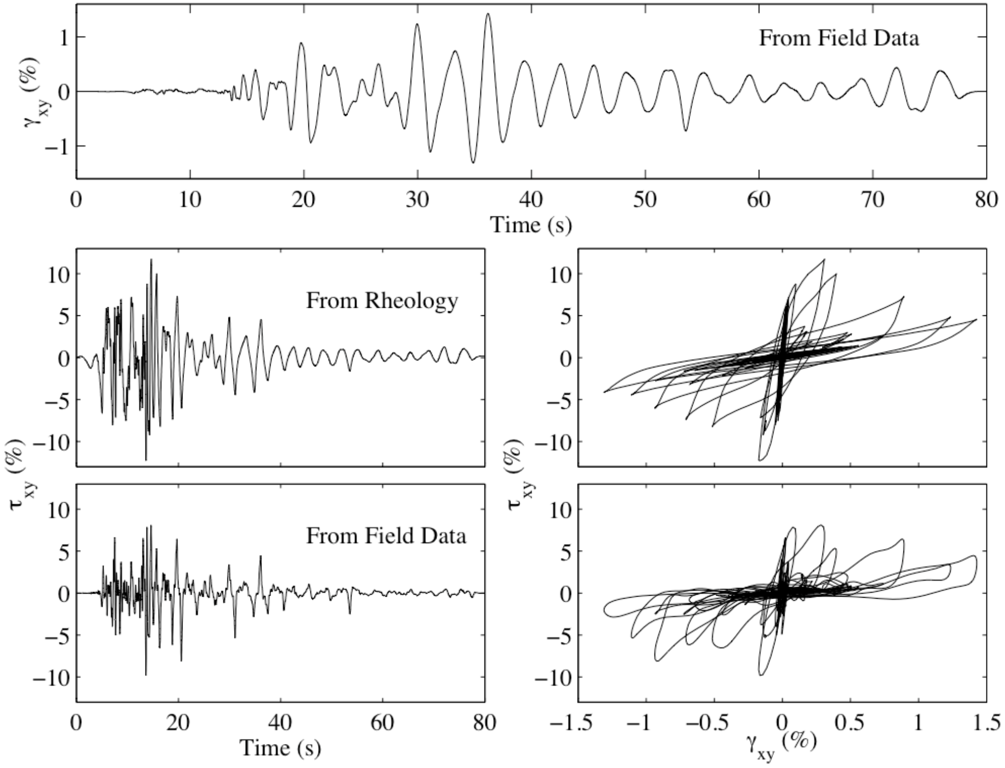
Time domain analyses: site-specific studies



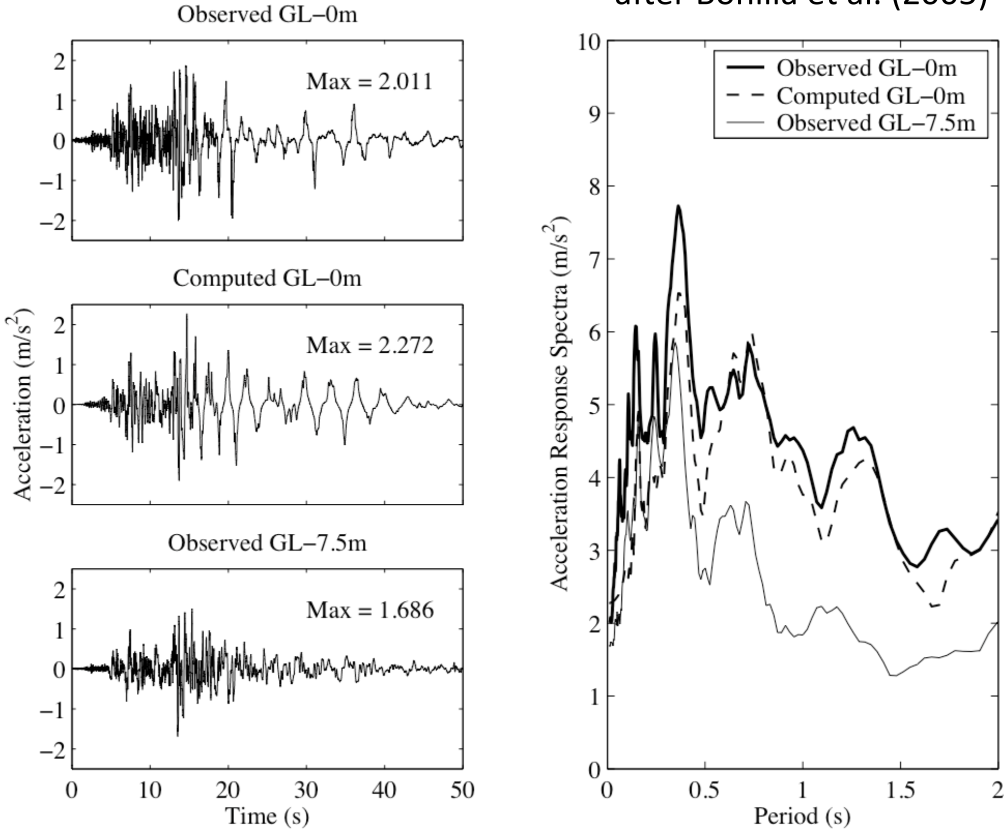
- 1987 Superstition Hills earthquake, M_L 6.6
- Wildlife Refuge site
- Co-located accelerometers and pore pressure transducers (Holzer et al., 1989)
- *In situ* computation of stress-strain time histories and stress path (Zeghal and Elgamal, 1994)

Use of *in-situ* data to calibrate nonlinear rheology

after Bonilla et al. (2005)



Stress computation from deformation data



Waveform modeling

- Model calibration by fitting stress-strain data (and pore pressure)
- Good fit in terms of acceleration and response spectra
- Hint: laboratory data can also be used; always fitting stress-strain data

Empirical evidence of nonlinear site response at a scale of a sedimentary basin

Empirical amplification at sedimentary sites after the Northridge M6.7 earthquake (Field et al., 1997)

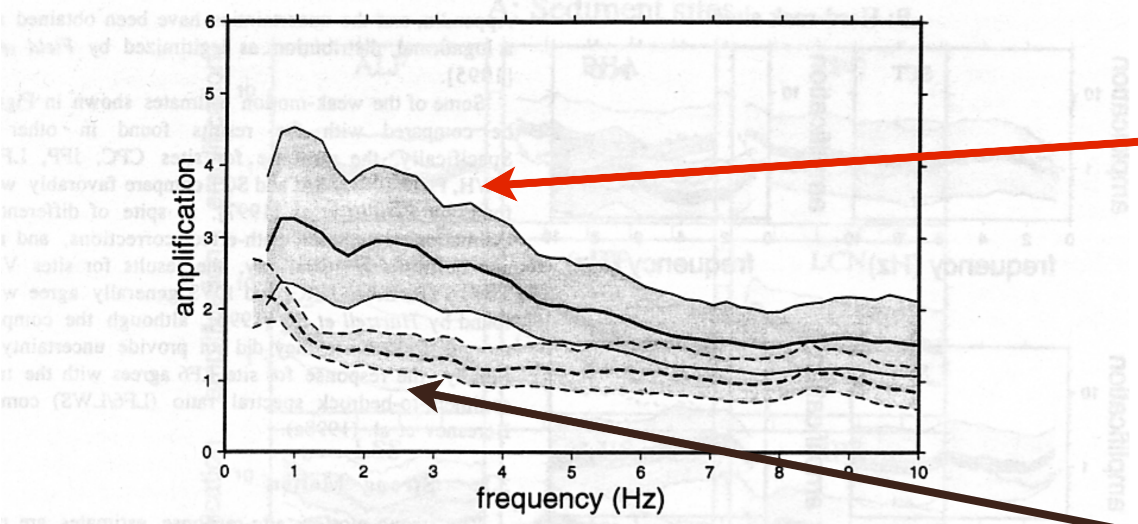
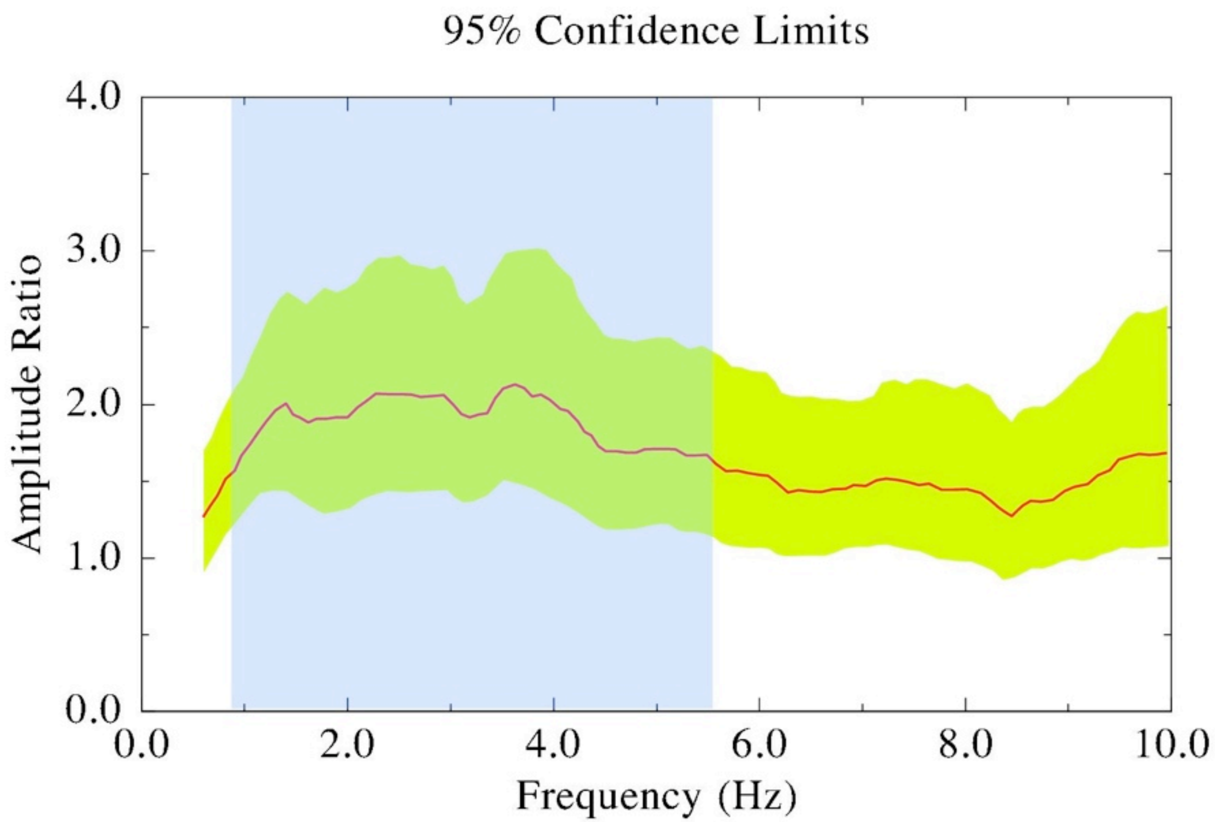


Figure 3. The mean and ±2 standard deviation of the mean confidence limits for the 15 alluvium site-amplification estimates. The solid lines represent the weak-motion results for the aftershocks, and the dashed lines represent the strong-motion results for the main shock. Reprinted by permission from *Nature* [Field et al., 1997, Copyright 1997, Macmillan Magazines Ltd.].

Aftershocks
(weak-motion)

Mainshock
(strong-motion)

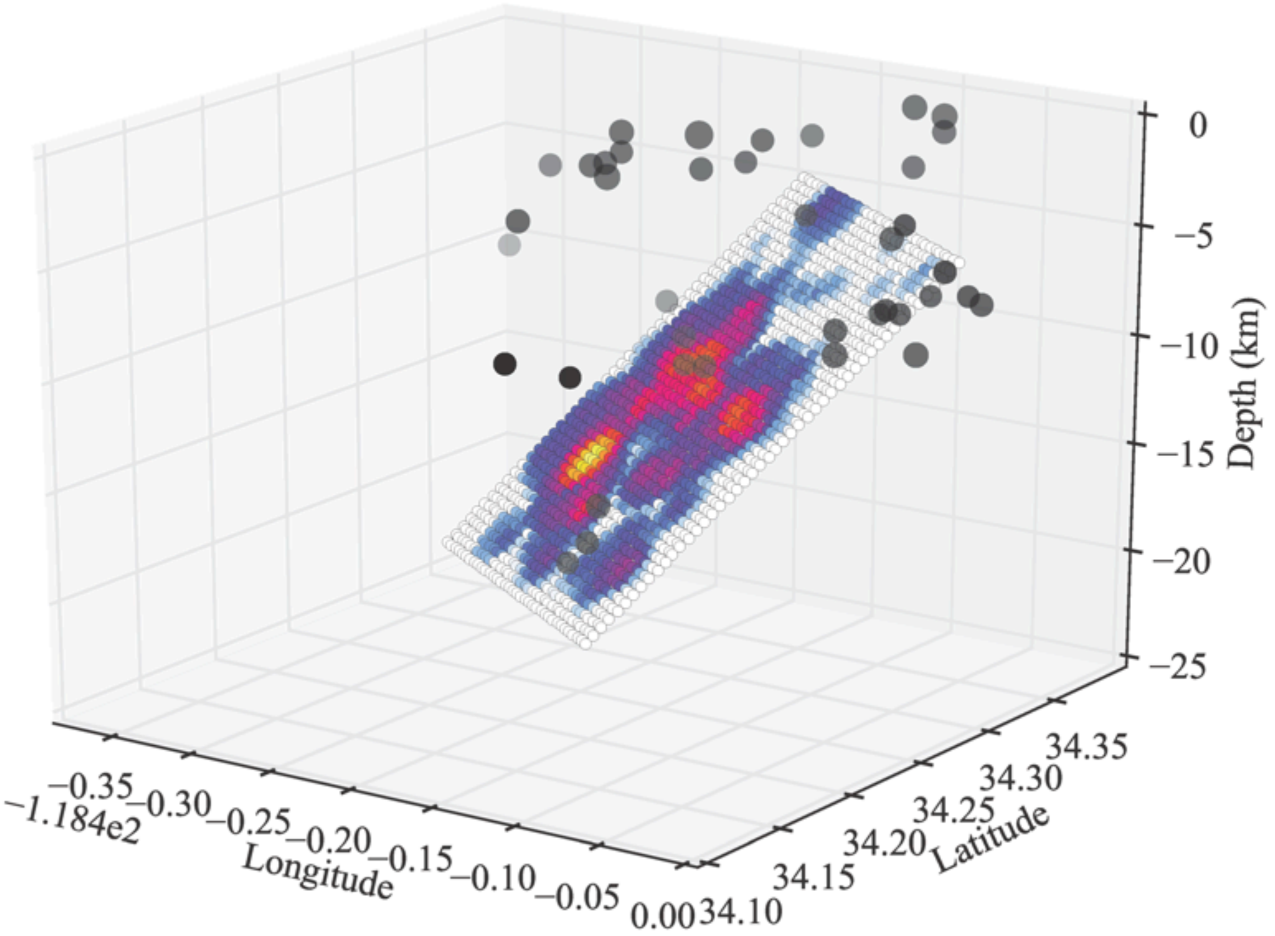
Statistical analysis (Field et al., 1997)



- Weak/Strong motion ratio (if ratio > 1, nonlinear effects occurred)
- 95% confidence limits defining the acceptance criterion
- Strong motion is “significantly” deamplified between 0.8 and 5.5 Hz

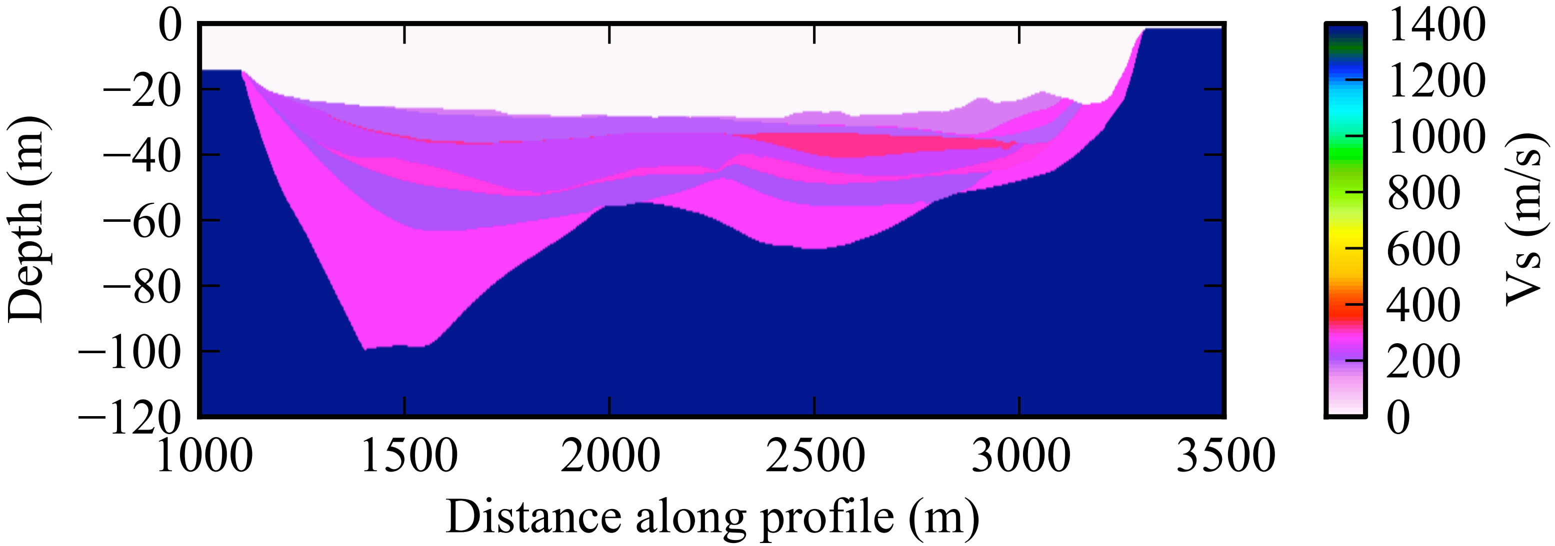
Why is the observed deamplification located at intermediate frequencies?

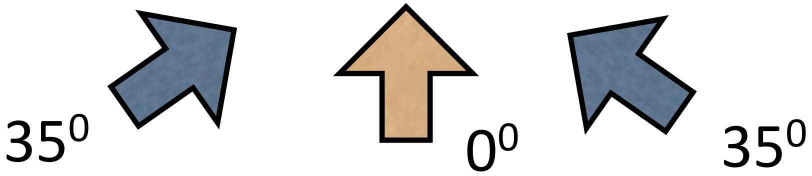
1994 Northridge aftershocks



Use of aftershock data implies different angles of incidence of the incoming wavefield

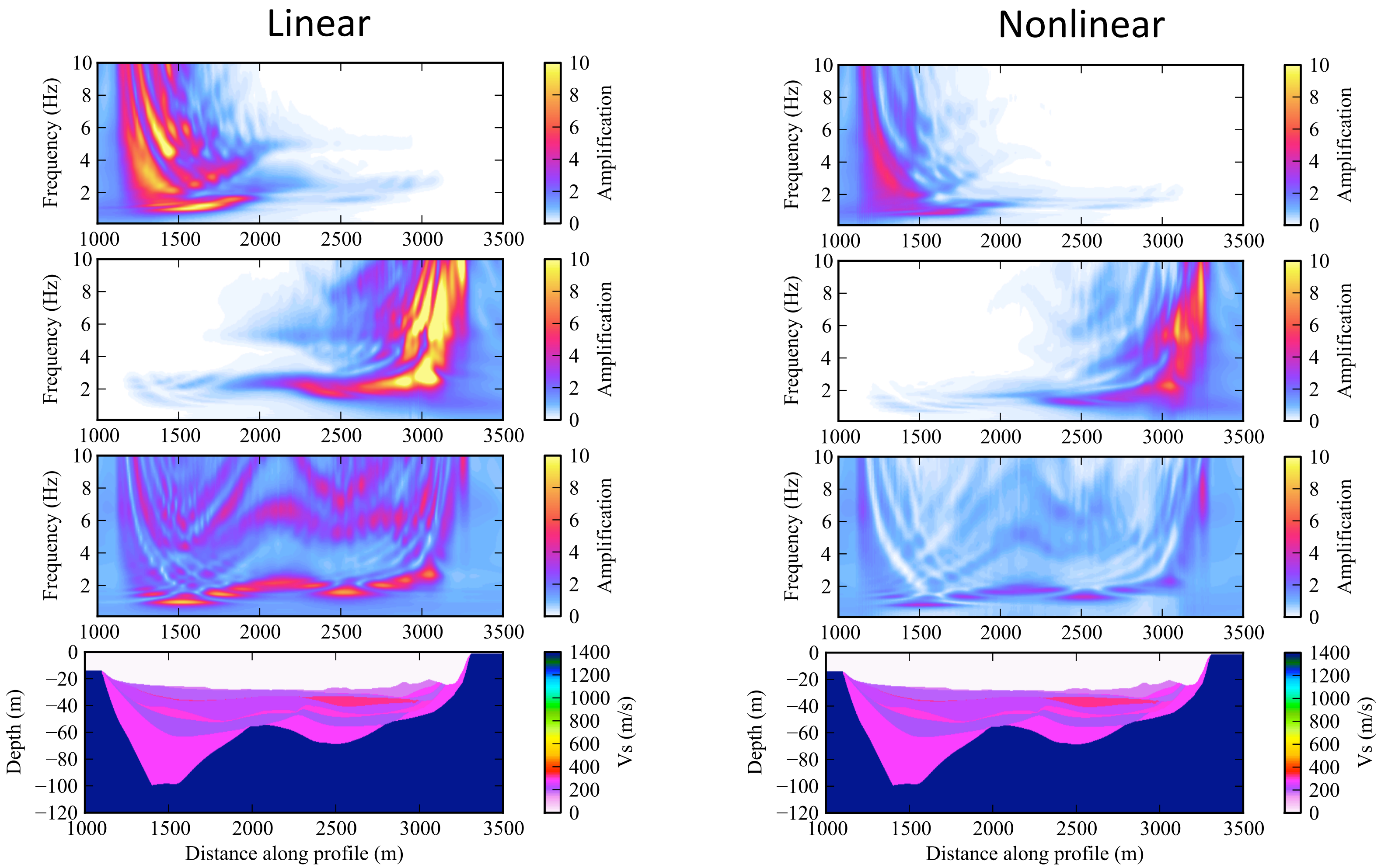
2D response of a smaller basin





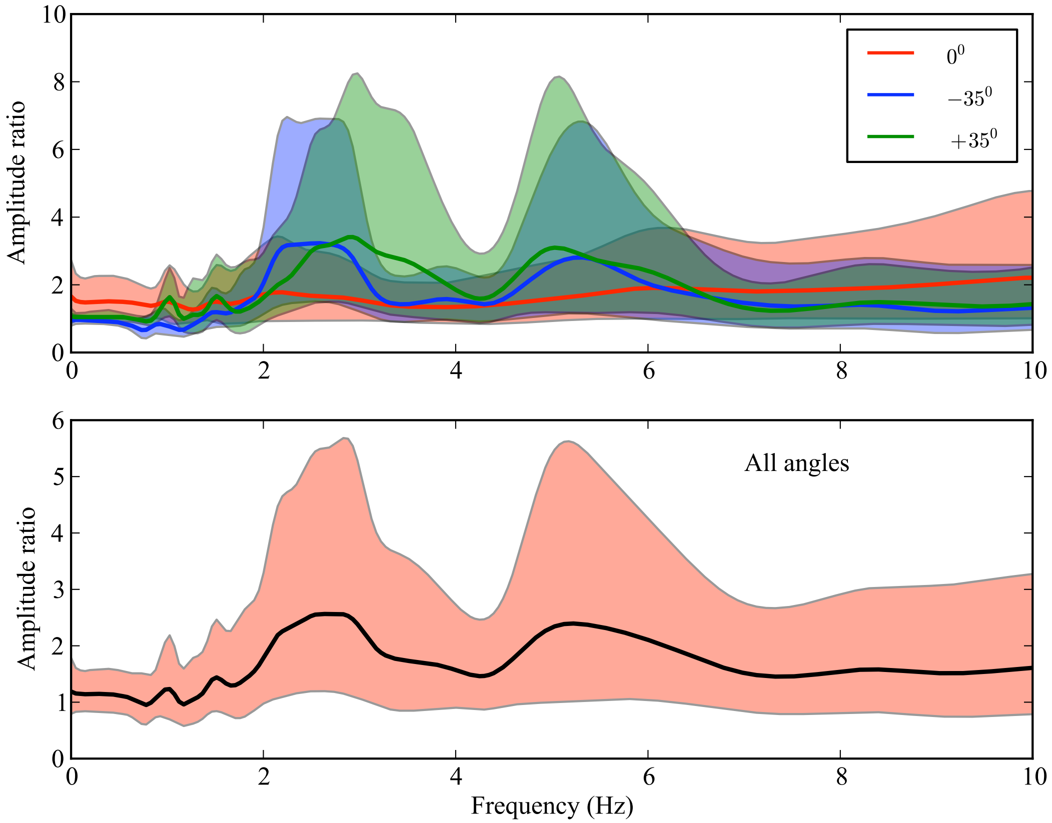
- Available 3D model for the area of Nice, France (CETE Mediterranean)
- Study of the effect of angle of incidence
- Linear and nonlinear basin response up to 10 Hz

Basin response (transfer function) - PGA=0.1g



- “Traditional” nonlinear response mainly observed for vertical incidence
- Vertical incidence underestimates the amplification at the basin edges (linear and nonlinear results)
- Yet, broadband amplification is observed at basin edges for inclined wavefield (linear and nonlinear results)

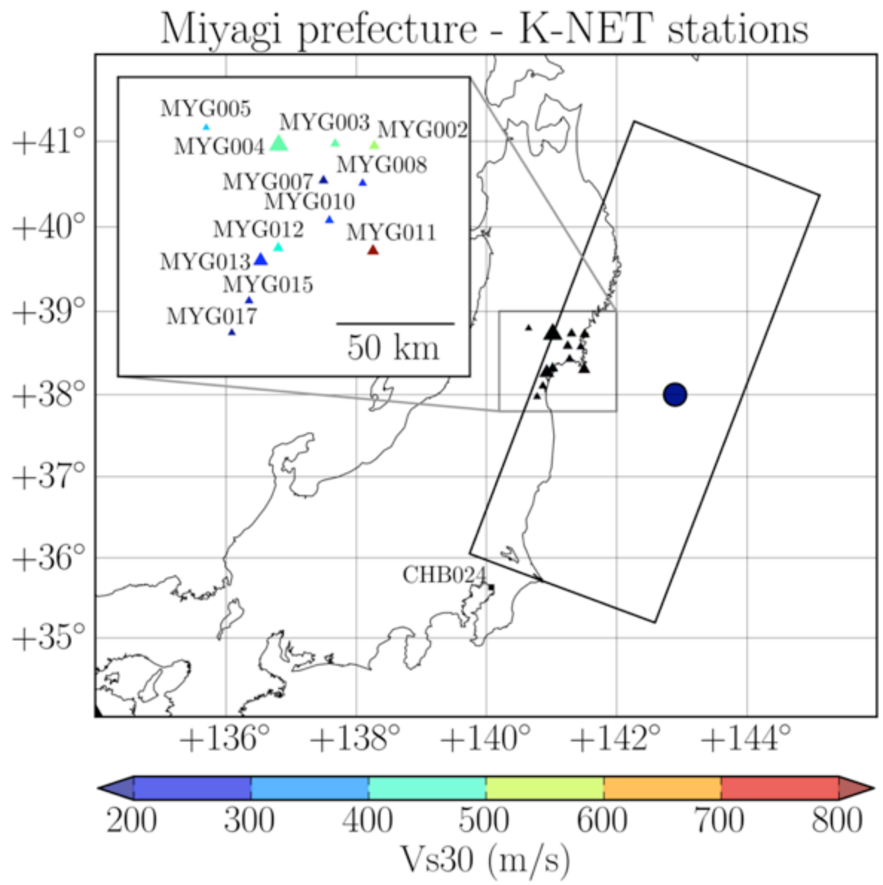
Statistical analysis as Field et al. (1997)

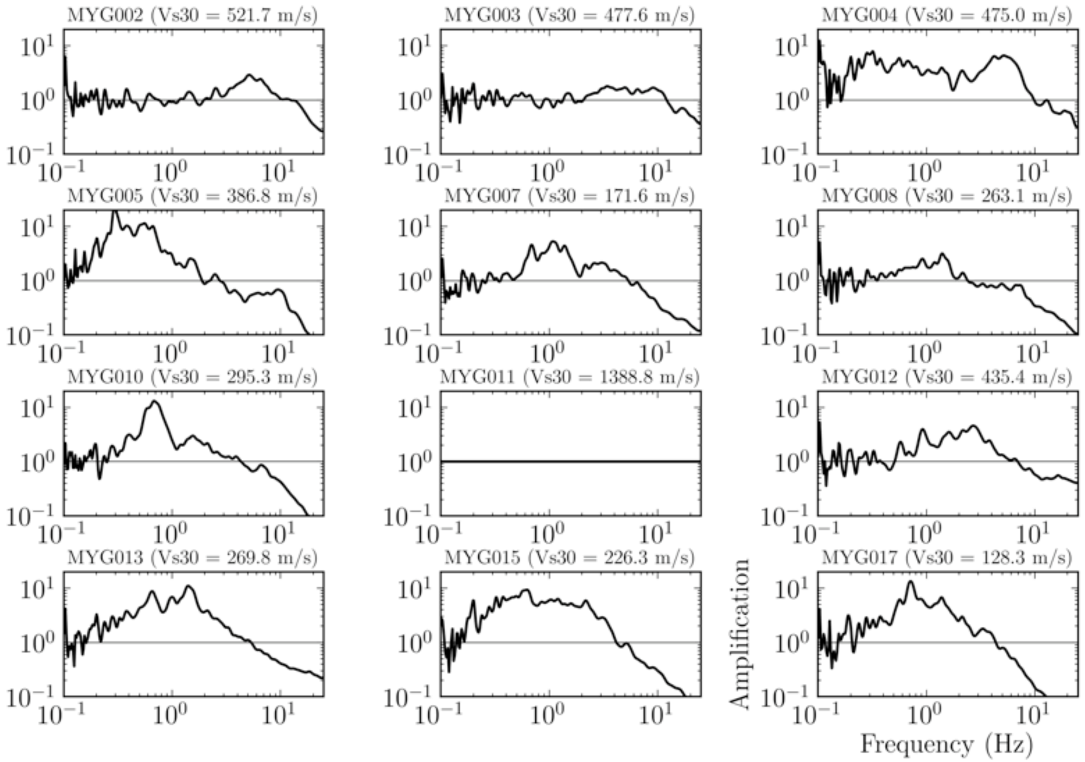


- Computation of mean linear/nonlinear response ratio along the basin profile
- Vertical incidence shows an almost constant linear/nonlinear ratio
- Inclined incidences show stronger nonlinear effects (ratio ~ 3) at 2.5 and 5.5 Hz
- Average linear/nonlinear ratio (including all angles) shows stronger nonlinear effects at these intermediate frequencies than at high frequencies

Northridge nonlinear signature maybe related to angle of incidence
(use of aftershock data only)

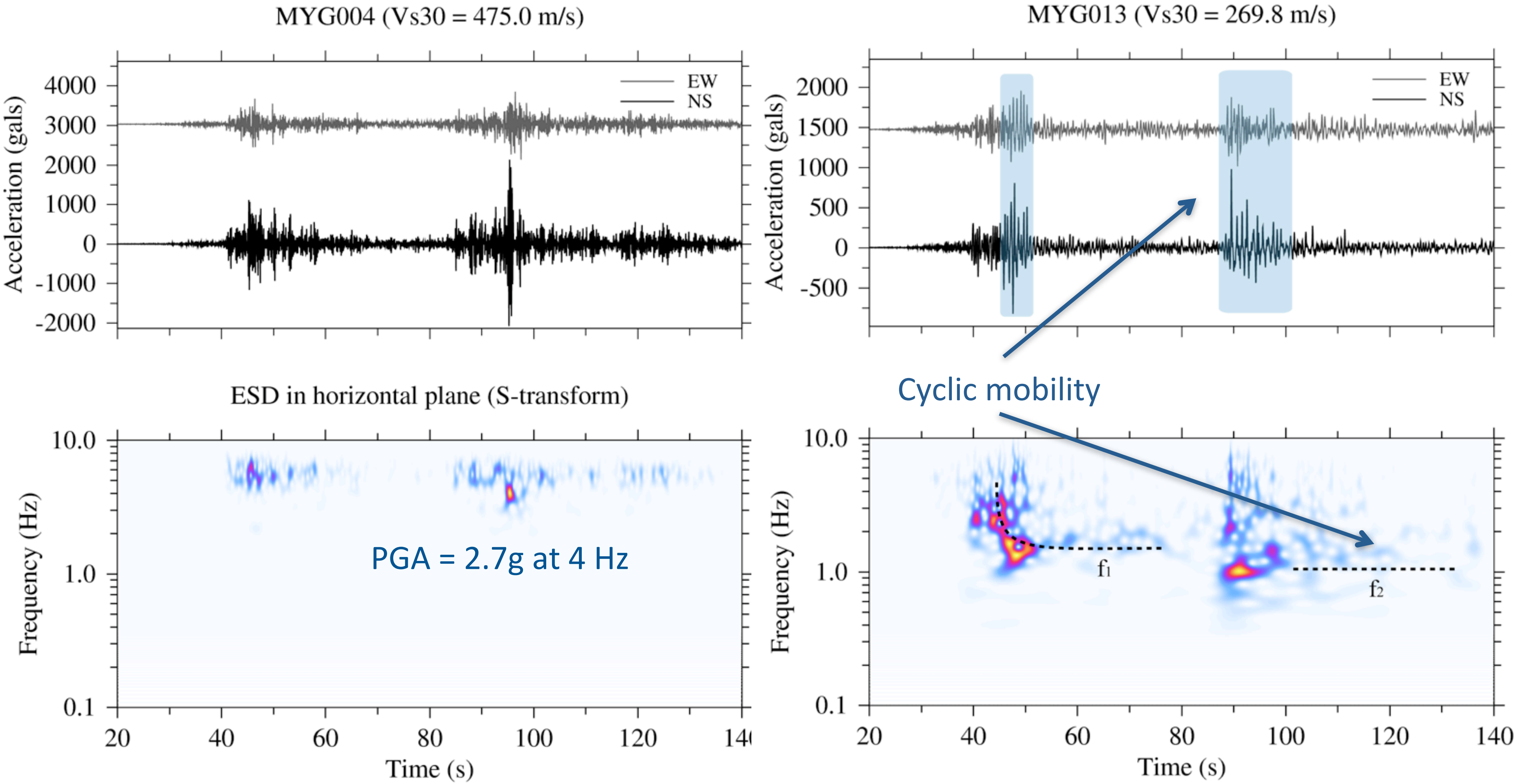
The M_W 9, 2011 Tohoku earthquake





- Traditional spectral ratios w.r.t. MYG011 (Vs30 ~ 1400 m/s)
- Deamplification at frequencies > 5-8 Hz (Vs30 < 400 m/s)
- Strong amplification at low frequencies
- Difficulty to separate source, path and site effects

Time-frequency analysis



Cyclic mobility

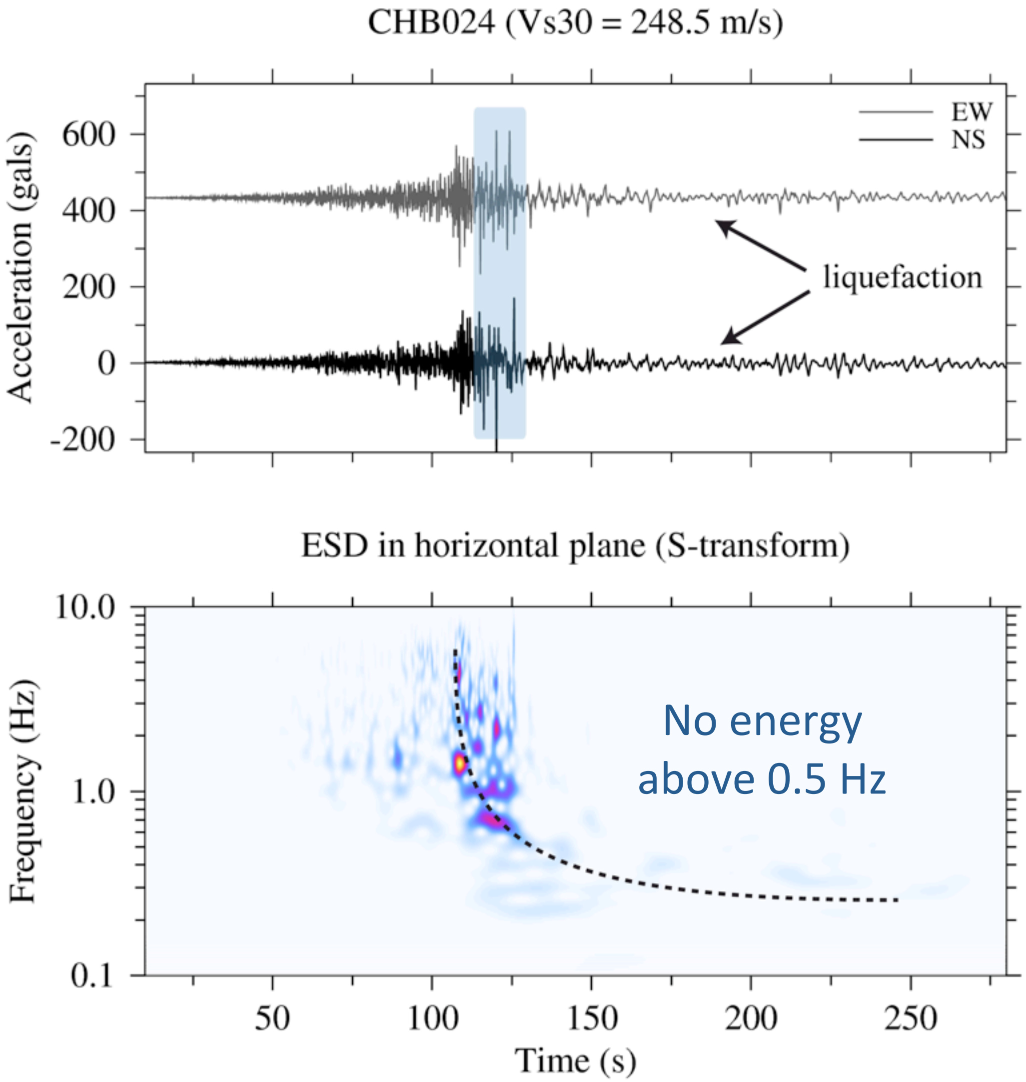
PGA = 2.7g at 4 Hz

MYG004: no energy above 8 Hz since the beginning of strong motion

MYG013: empirical evidence of cyclic mobility

strong shift of energy to lower frequencies at each event's rupture

Chiba - near Tokyo



CHB024 (Vs30 = 248.5 m/s)

ESD in horizontal plane (S-transform)

No energy above 0.5 Hz

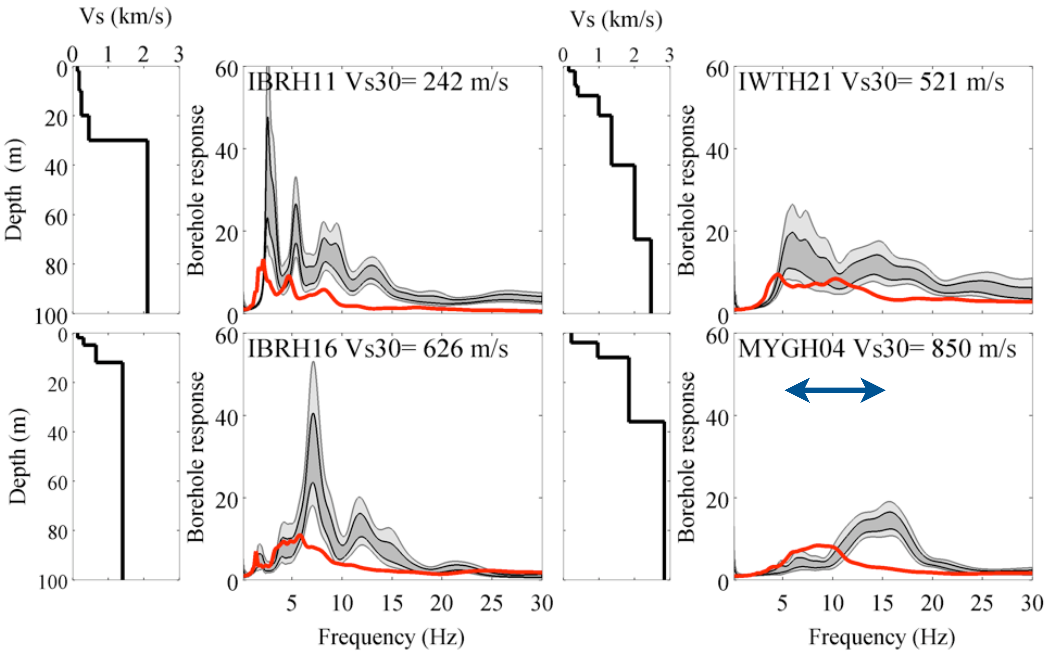
K-NET稲毛

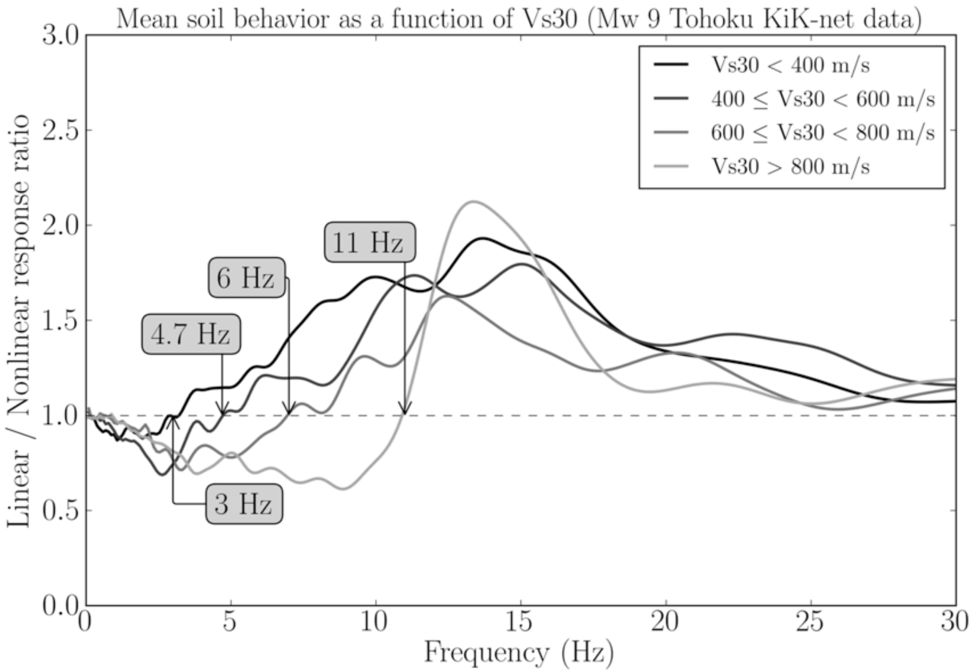
観測点周辺では多くの噴砂が見られ，電柱が傾くなどの被害もあった

Sekiguchi and Nakai, 2011

Cyclic mobility + liquefaction

Nonlinear soil response of KiK-net stations and correlation with Vs30





- Deamplification begins at higher frequencies as Vs30 increases
- Shift of “predominant” frequency toward low frequencies
- Rock sites (Vs30 > 800 m/s) also show nonlinear effects at f > 10 10 Hz due to thin shallow layers having Vs30 ~ 400 m/s

Lessons learnt from these events

- Densification of surface and borehole arrays including pore pressure transducers to study *in situ* site effects (direct computation of site response and inversion of nonlinear material properties)
- Borehole arrays are very useful to quantify linear and nonlinear effects and possible correlation with Vs30
- It seems that nonlinear effects are shallow (predominant frequency is more affected than the fundamental one)
- PGA only is not enough to discriminate nonlinear effects
- The 2011 Tohoku earthquake shows the need to take into account source, path, and nonlinear site response (large scale studies) to better assess the seismic hazard

Conclusions

- We need geological/geotechnical/geophysical characterization (statistical analysis of spatial variability of material properties)
- Seismology and earthquake engineering communities should work together (i.e. development of simple but robust nonlinear soil rheologies, soil-structure interaction studies having realistic input motions, etc.)
- Northridge and Tohoku earthquakes, among other events, provide empirical constraints to modelers
- Can we explain nonlinear effects with 1D or 2D models only? Do we need to go to 3D modeling?
- There is a need to quantify the uncertainty of numerical predictions given the soil and ground motion variability