Nonlinear site response in the shallow crust: Lessons from KiK-net data

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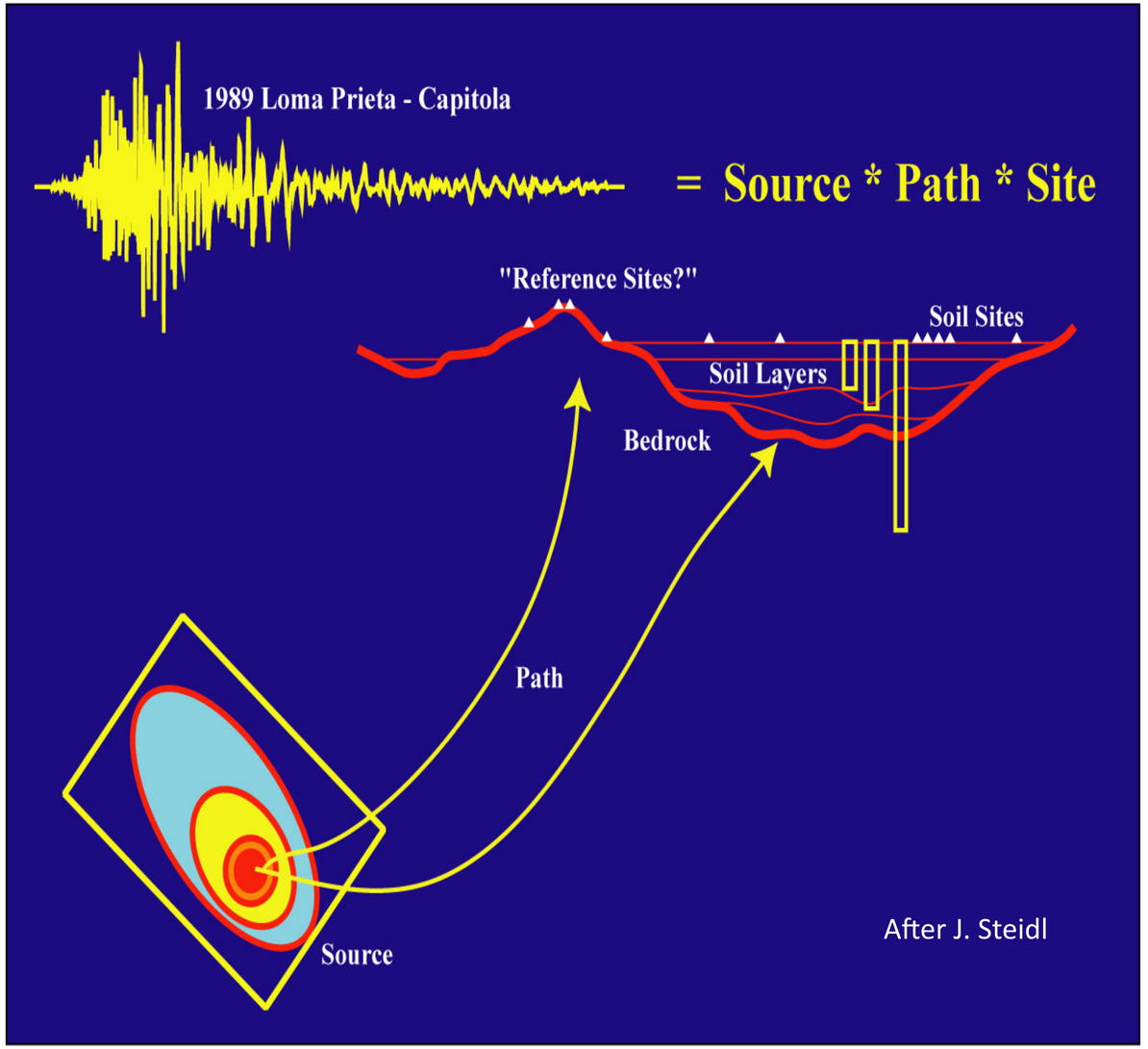
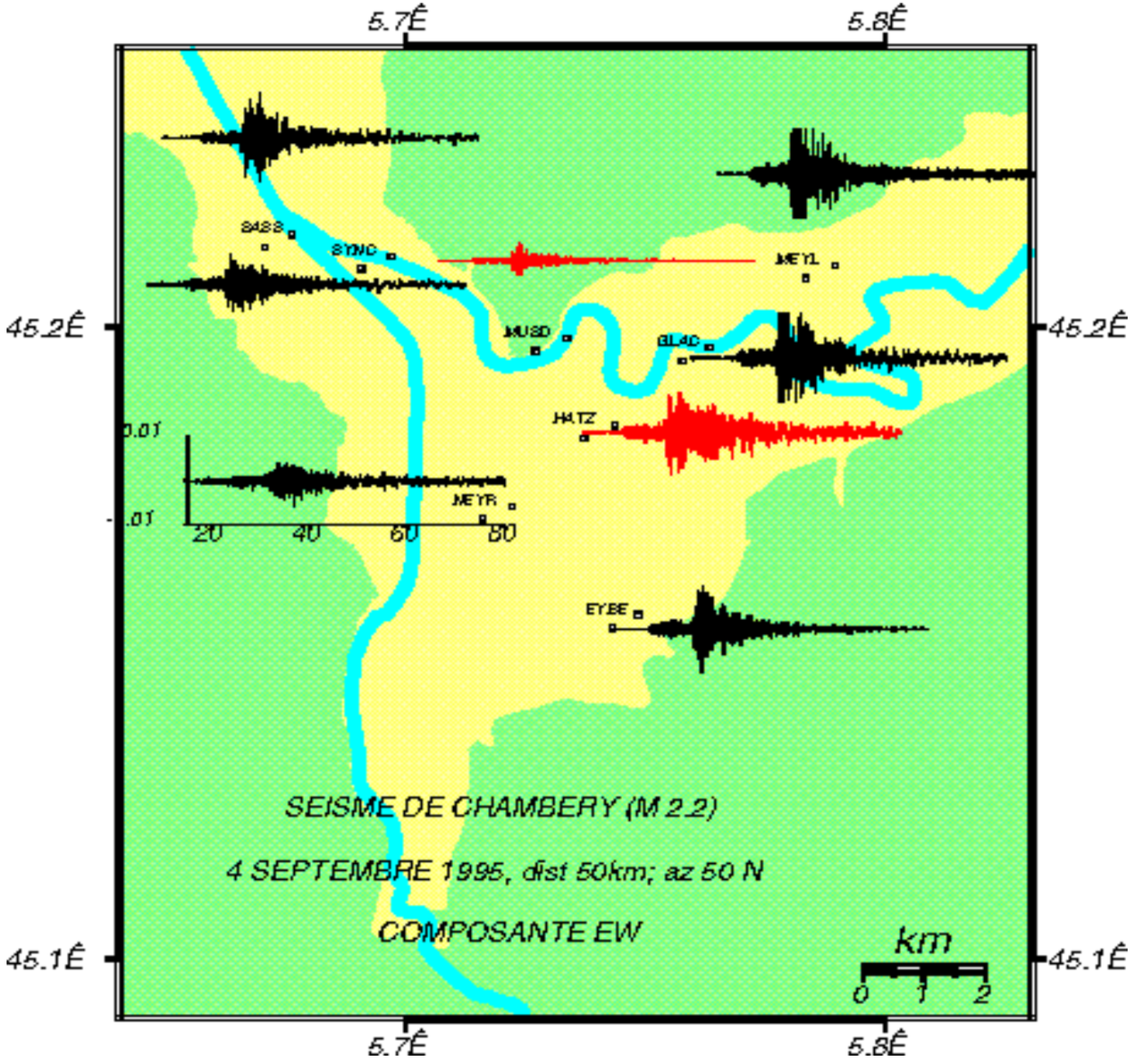
Dissecting the ground motion



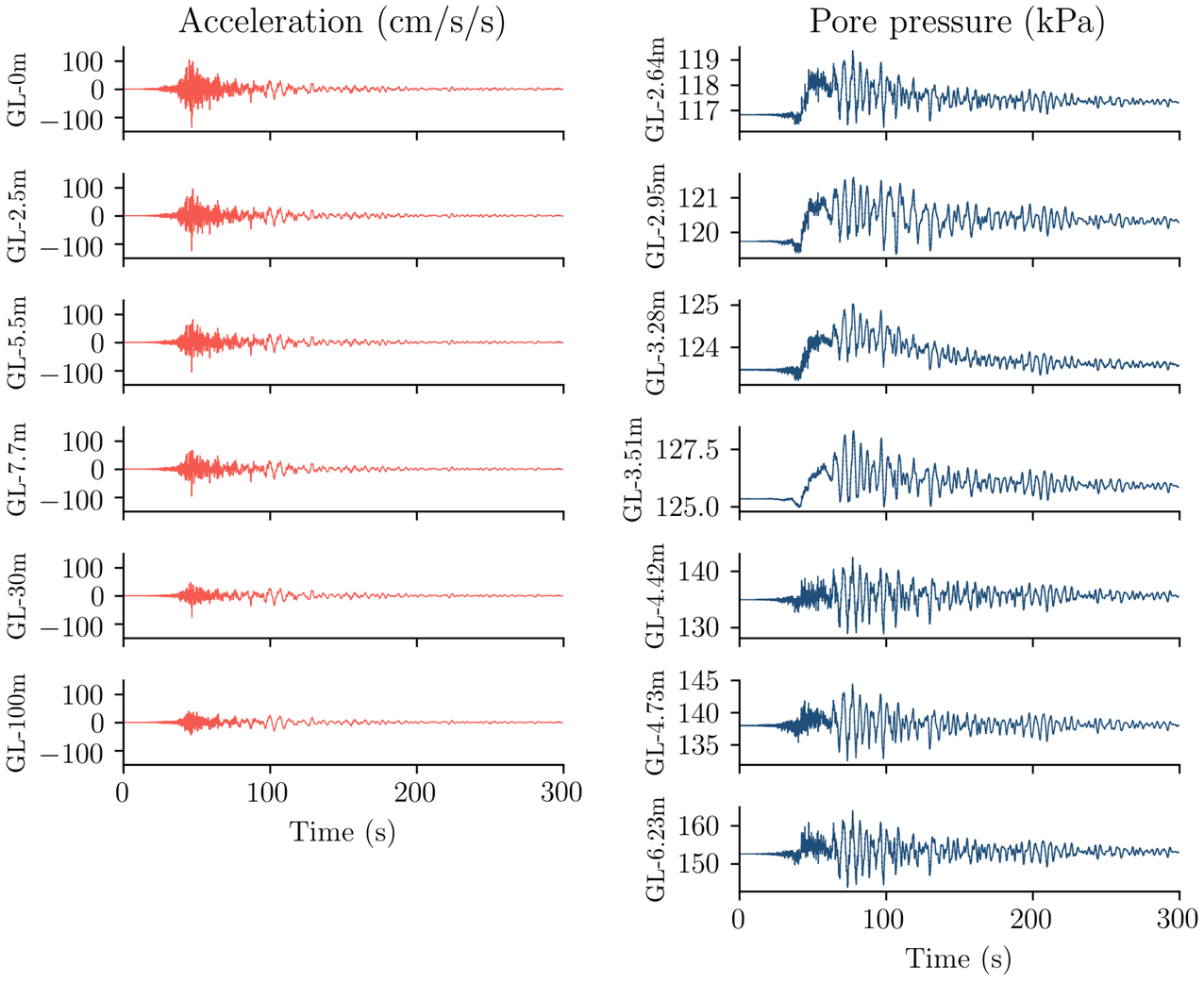
Convolution is possible only if the system is linear

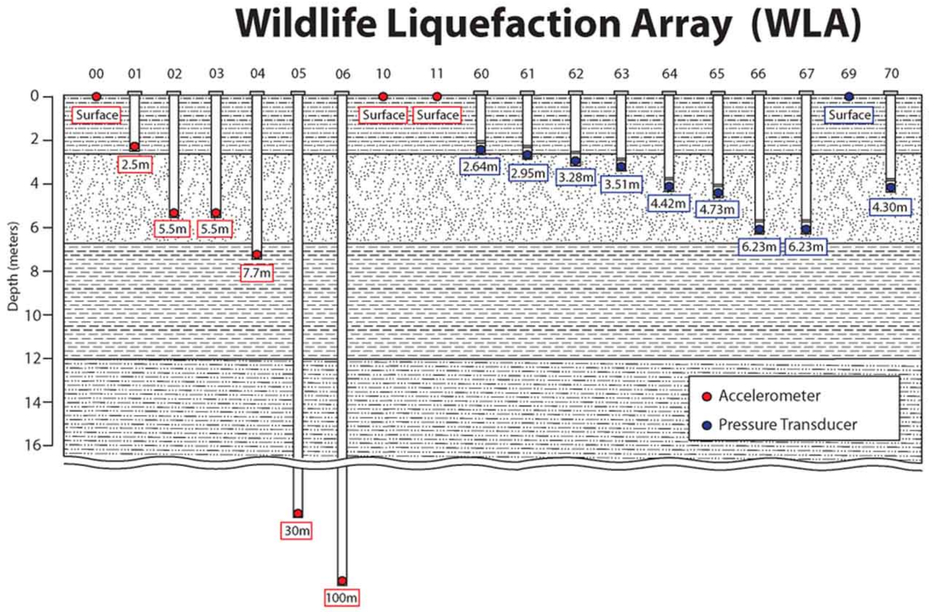
Surface observations of site effects



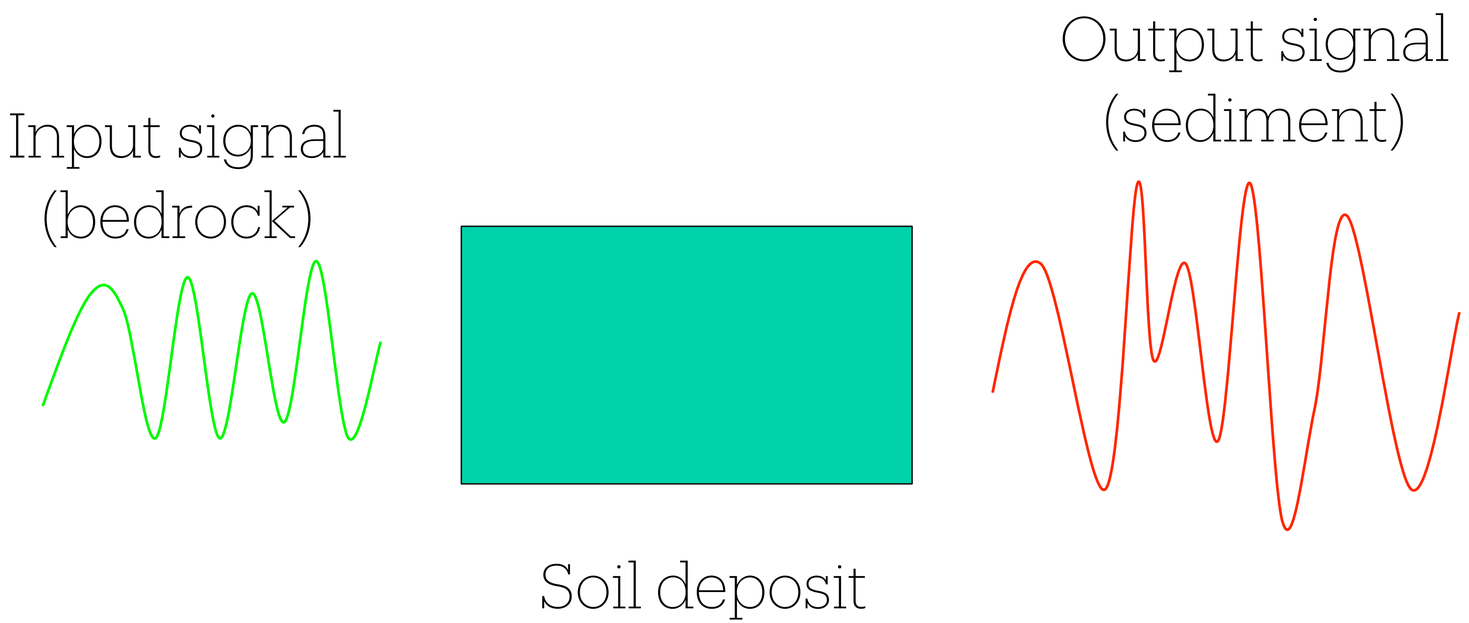
- Amplification of the ground motion
- Increment of the signal duration
- Ground motion variability

The 2010 El Mayor earthquake (Mw7.2)
100 km epicentral distance from WRLA





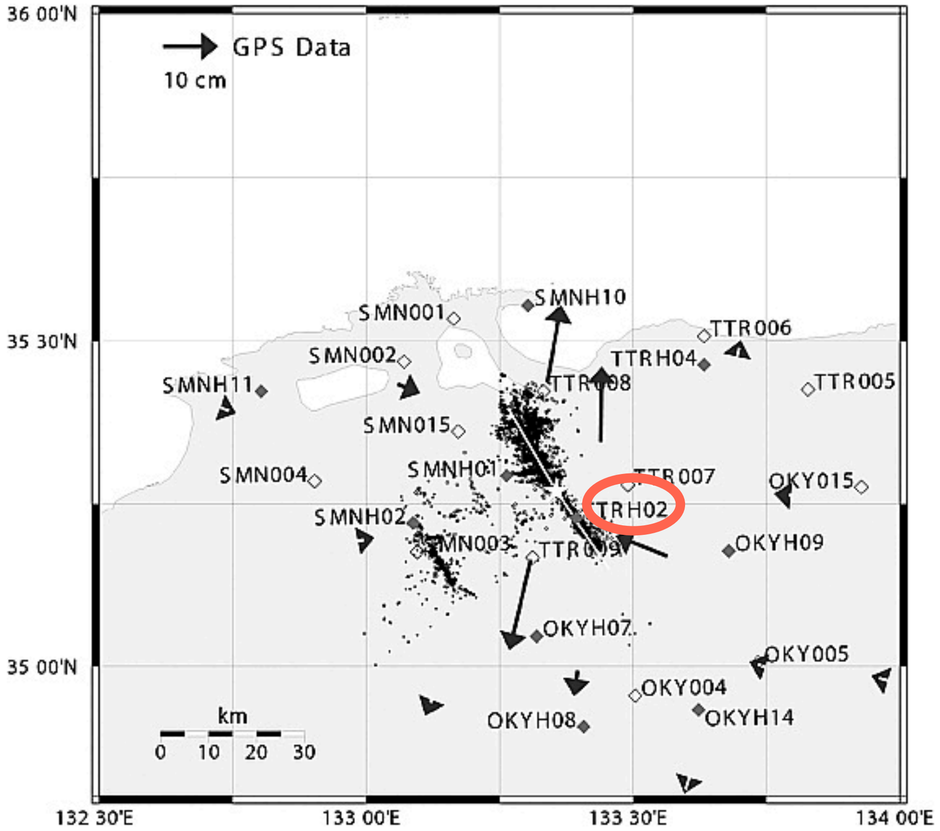
Site effect definition

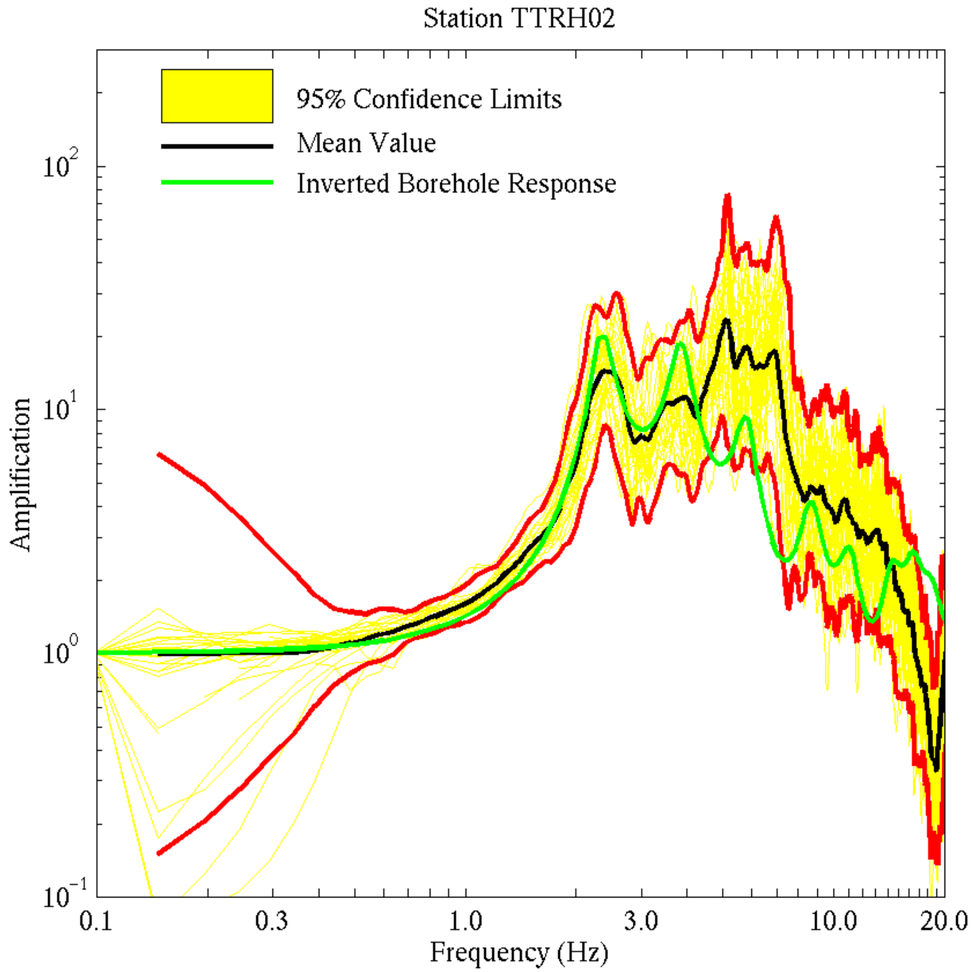


Site effect = Output / Input (deconvolution)

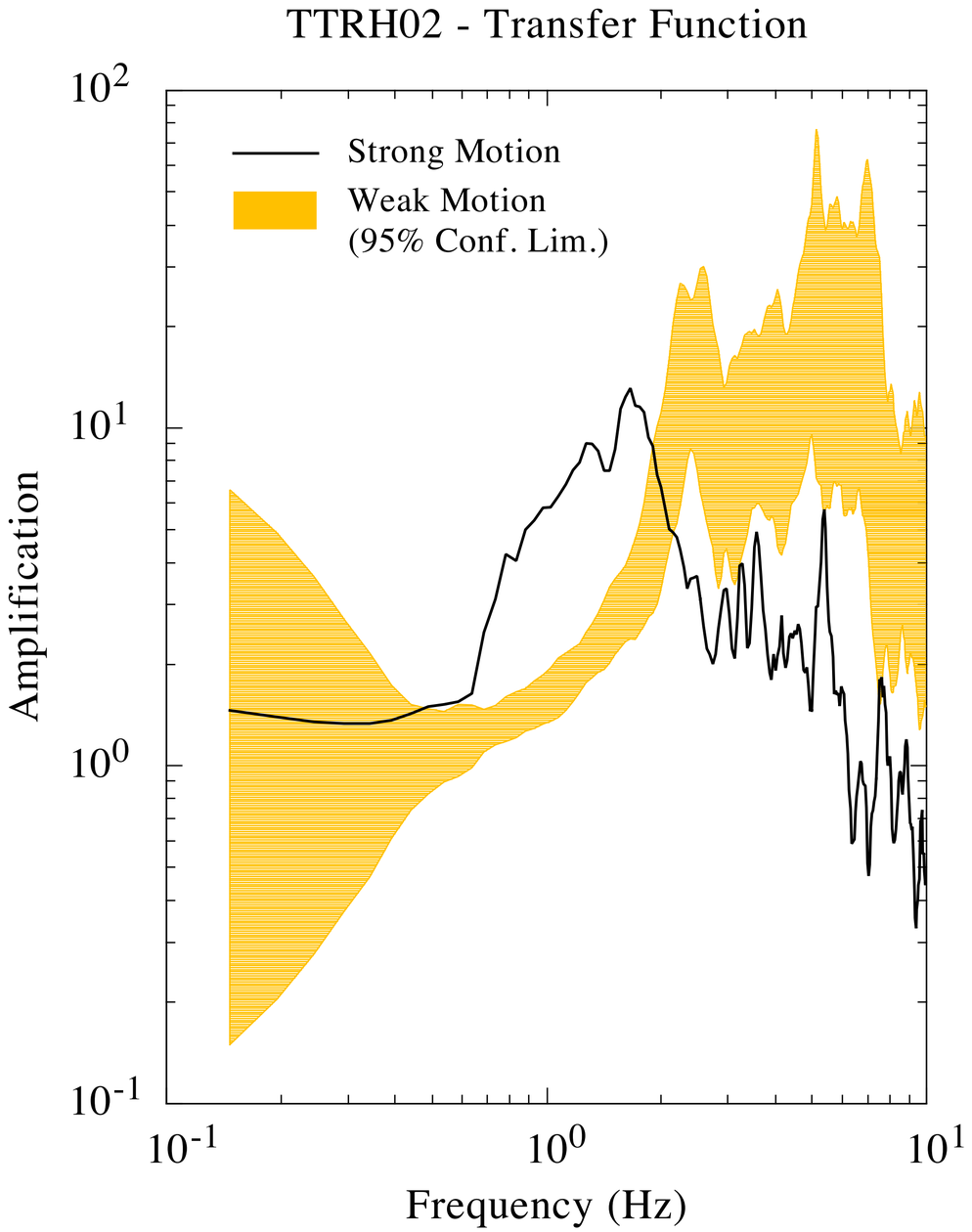
Site response representation

M7.3 Tottori, 2000





- The response is broadband
- The mean value is stable



Is the site response the same for increasing ground motion?

NOPE!!! (distance between sensors 100 m)

Site effect

- Definition: Influence of local geology on the seismic wave propagation. Site response is measured using the so-called **transfer function**
- Linear site effects: the transfer function is **independent** of the input
- Nonlinear site effects: strong **feedback** between the input and the medium

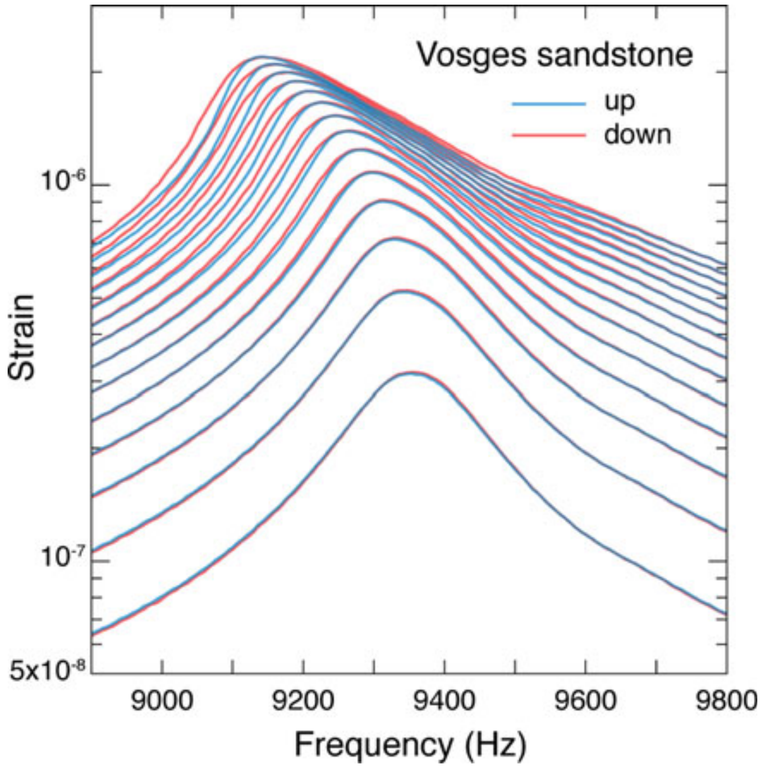
Engineers design earthquake resistant structures including site effects (if present)

Research Questions

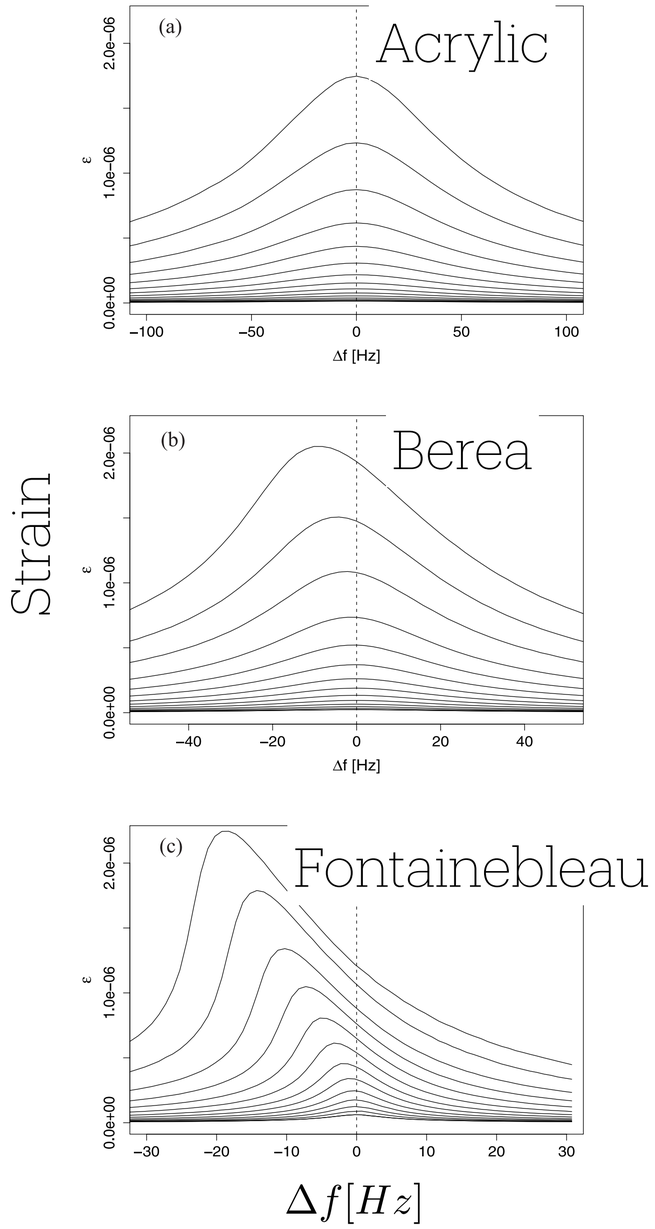
- What are the physical changes of the medium during an earthquake?
- Are these changes elastic (recoverable) or nonlinear (damage)?
- Where does nonlinear behavior take place (is it a deep or a shallow phenomenon)?
- Why is this important for monitoring sites before, during and after an earthquake crisis?

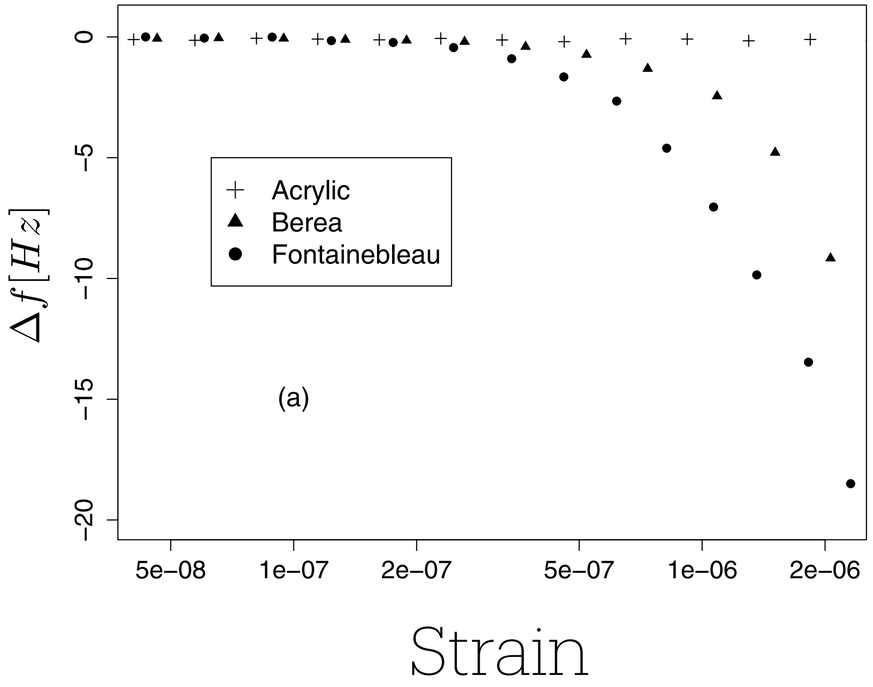
Nonlinear rock behavior (resonance experiments)

Vosges sandstone



TenCate (2011)

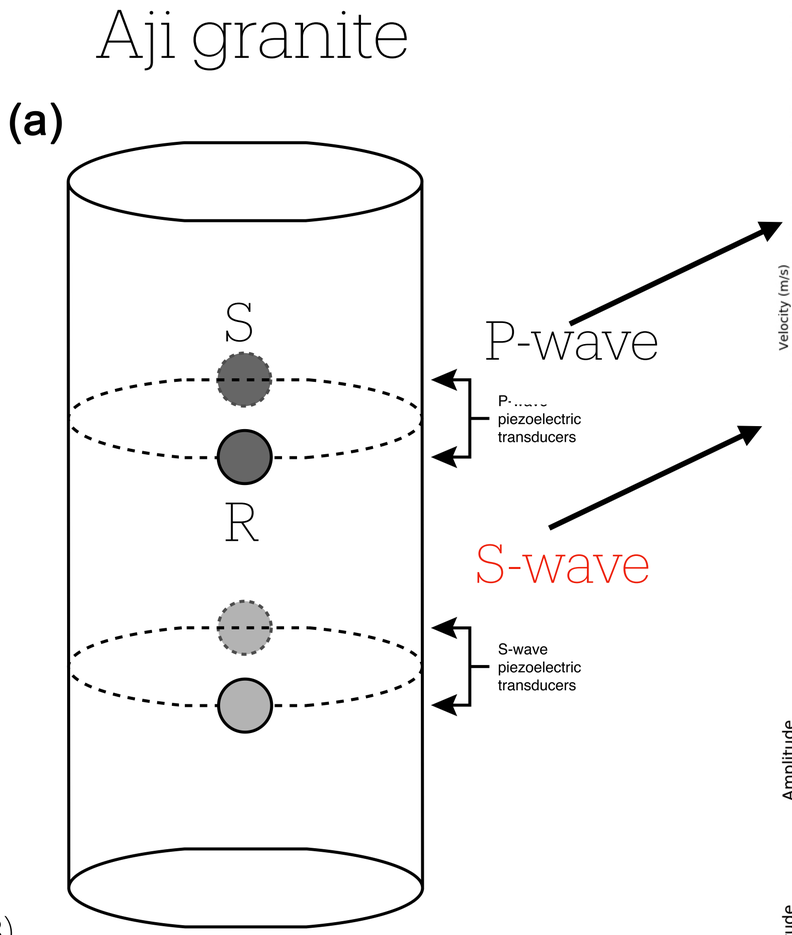




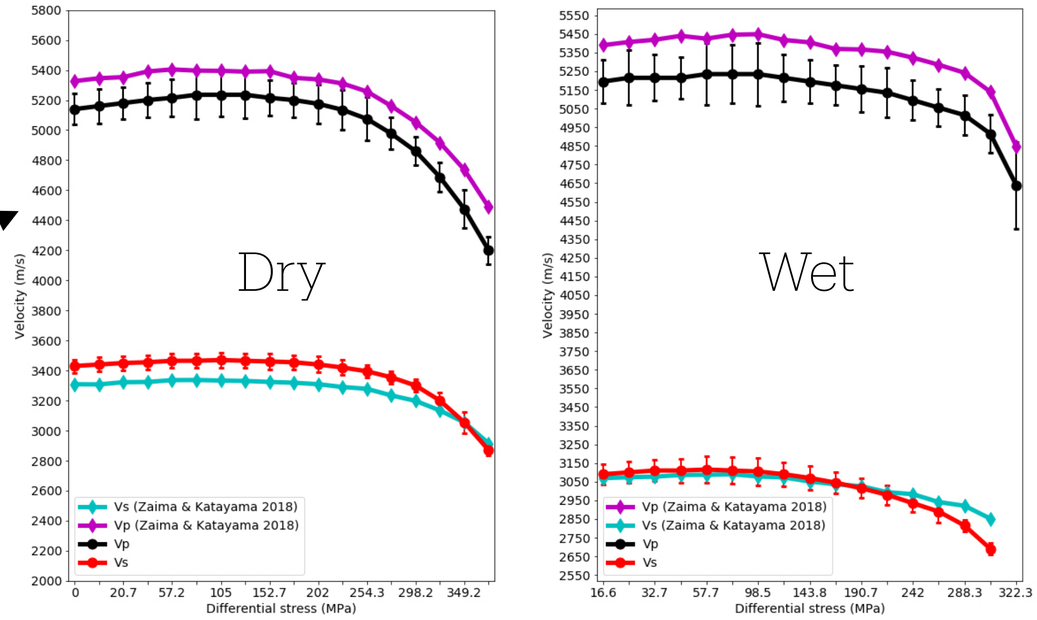
Pasqualini et al. (2007)

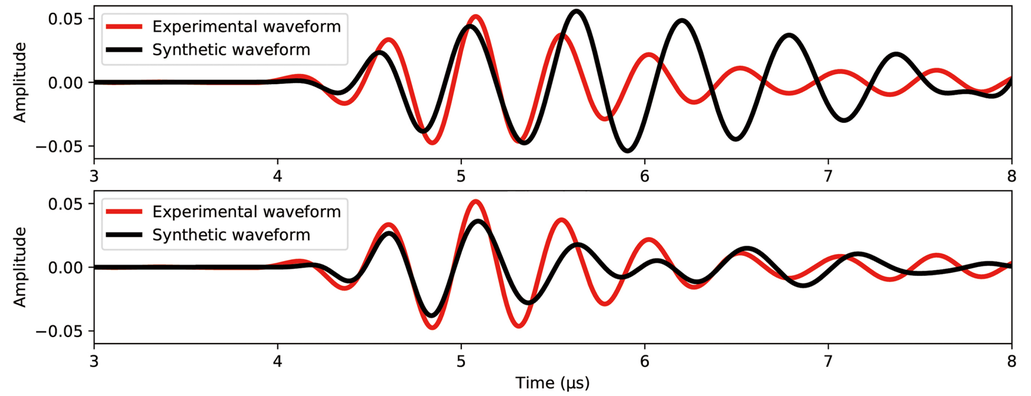
Frequency shift !!!

Nonlinear rock behavior (triaxial tests)



Zaima and Katayama (2018)

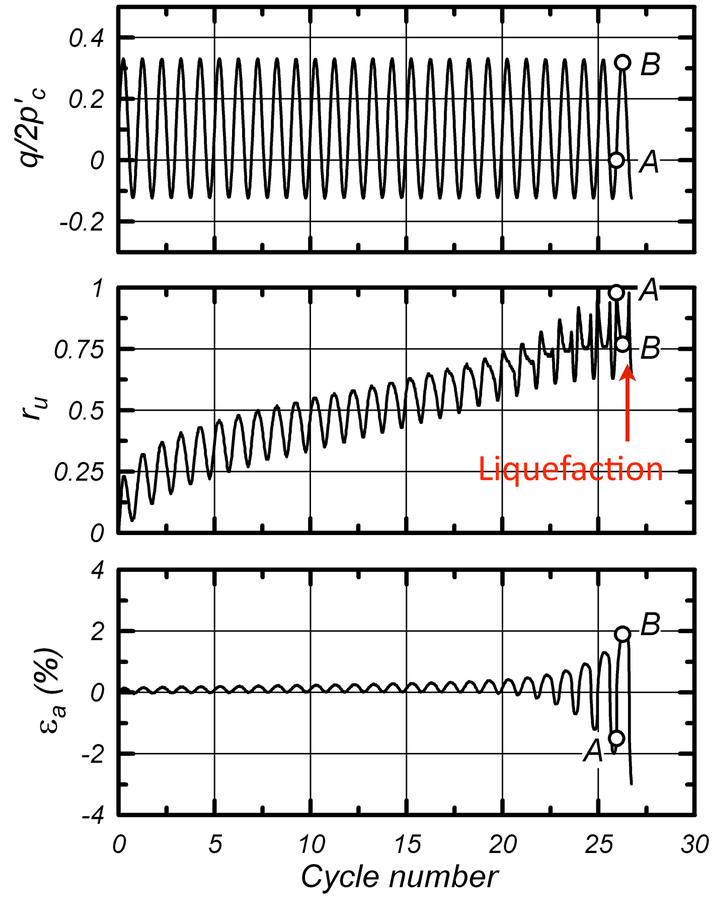




- P and S-wave records
- Increasing confining pressure
- FWI (Lai et al., 2021)

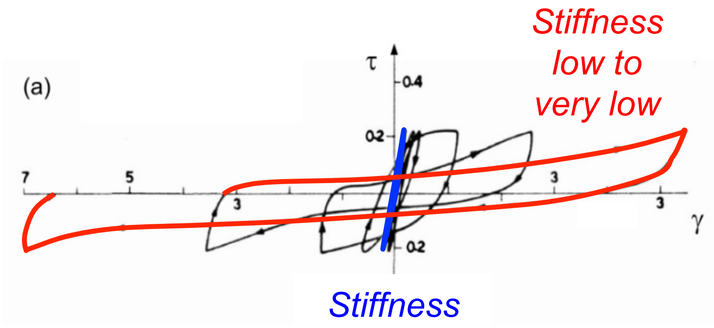
Lai et al. (2021)

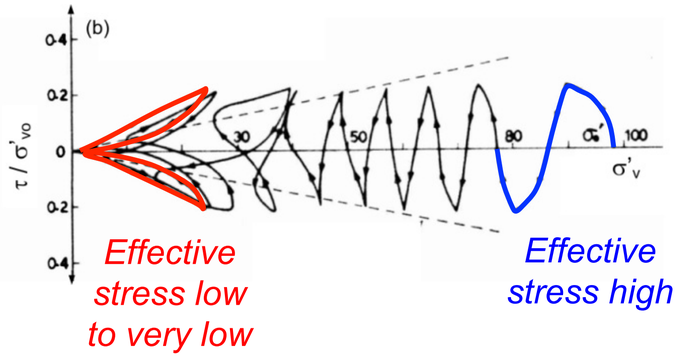
Soil nonlinear behavior (lab data)



Idriss and Boulanger (2006)

Ishihara (1985) – Cyclic simple shear test

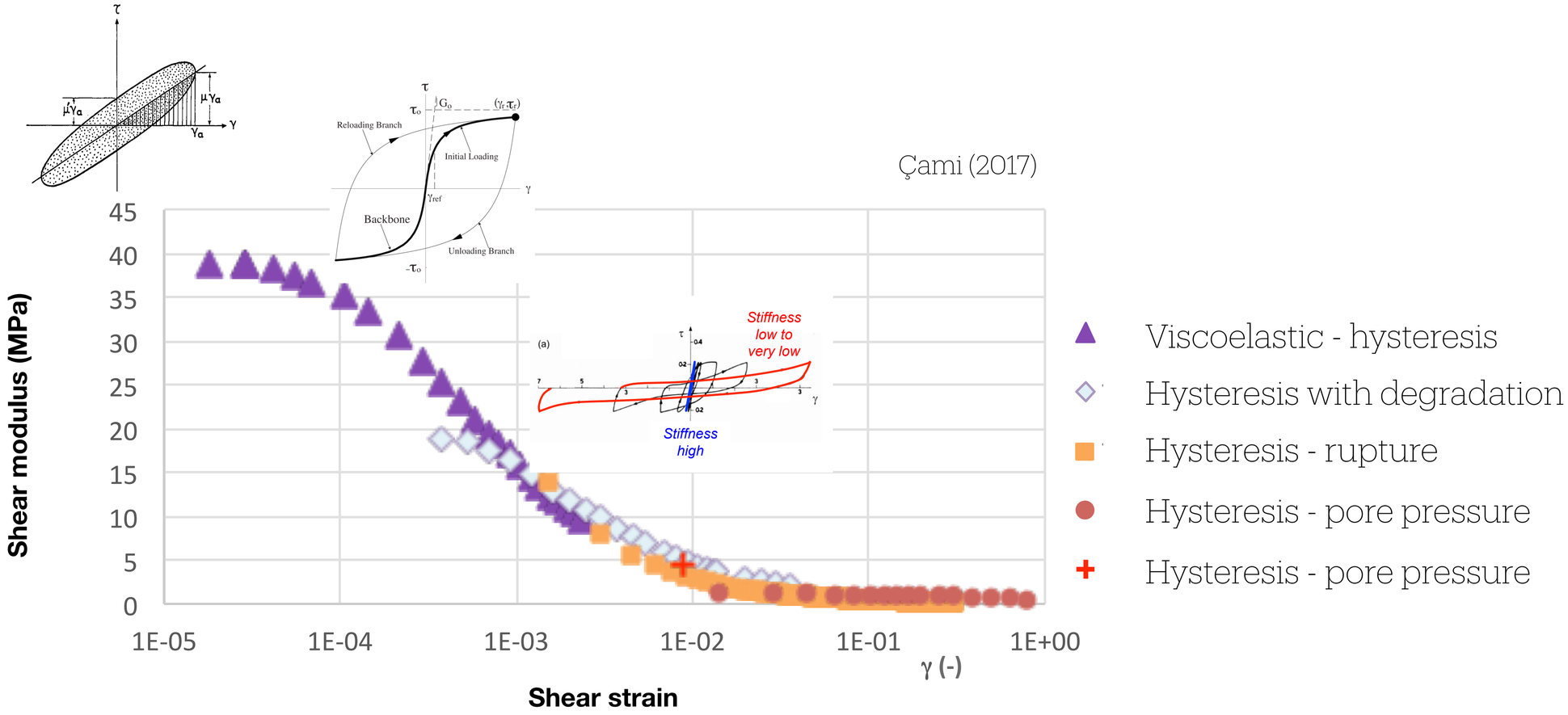




Kramer (2011)

- Pore pressure effects
- Stiffness decrease
- Material dilatancy
- Development of large deformations

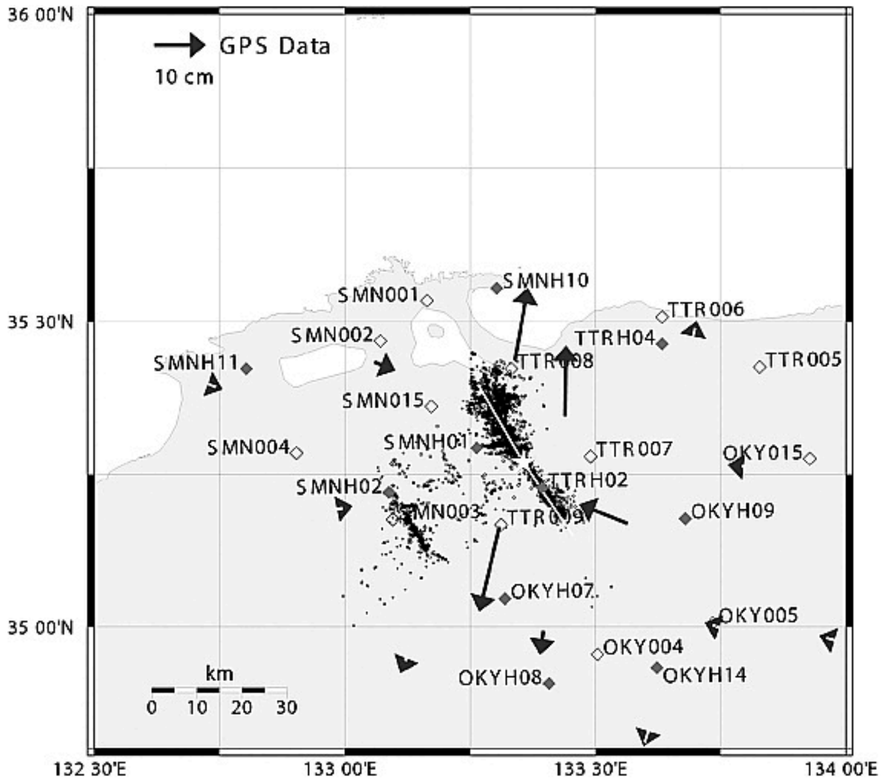
Characterizing nonlinear soil behaviour

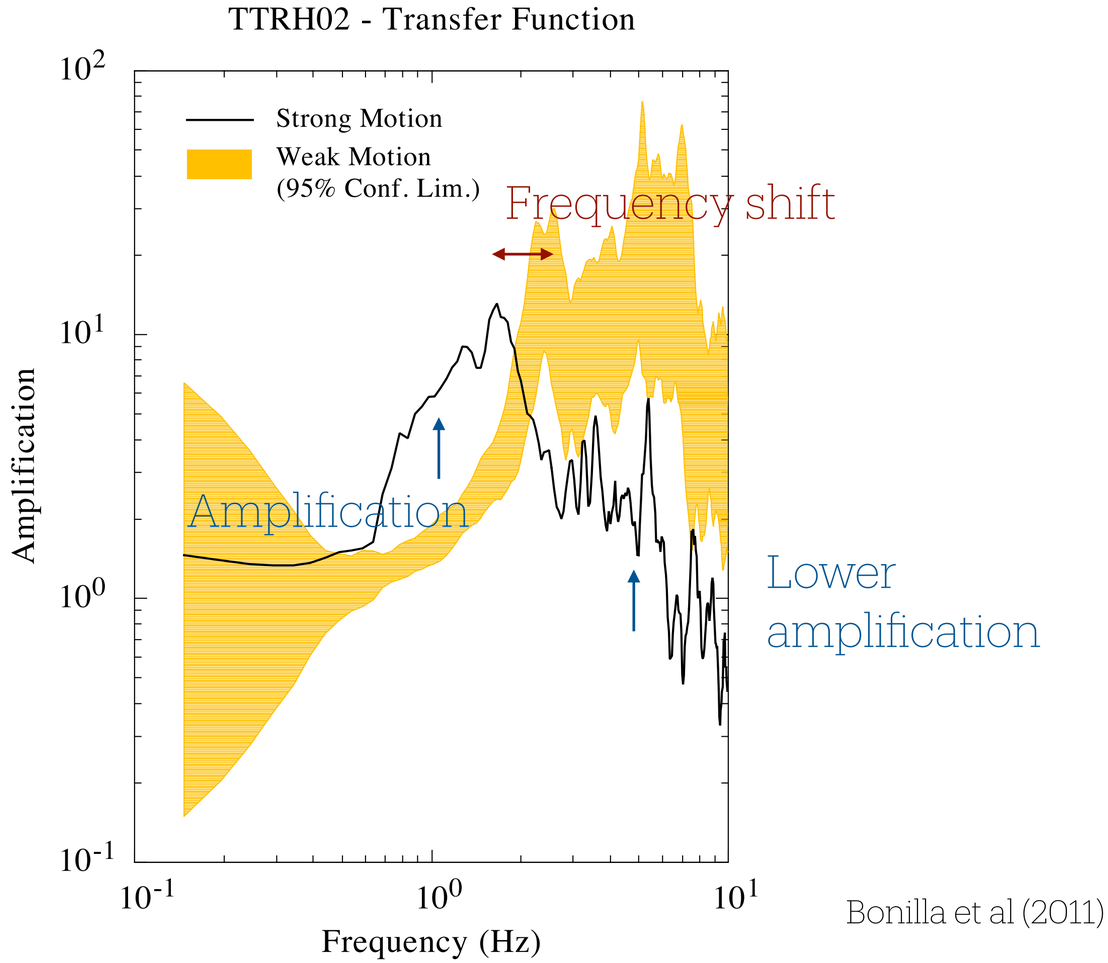


- Shear modulus decrease measurements
- Different processes depending on stress-strain state
- The challenge is to understand the physical processes when only the behaviour envelope is known

How is material nonlinearity traditionally identified?

M7.3 Tottori, 2000

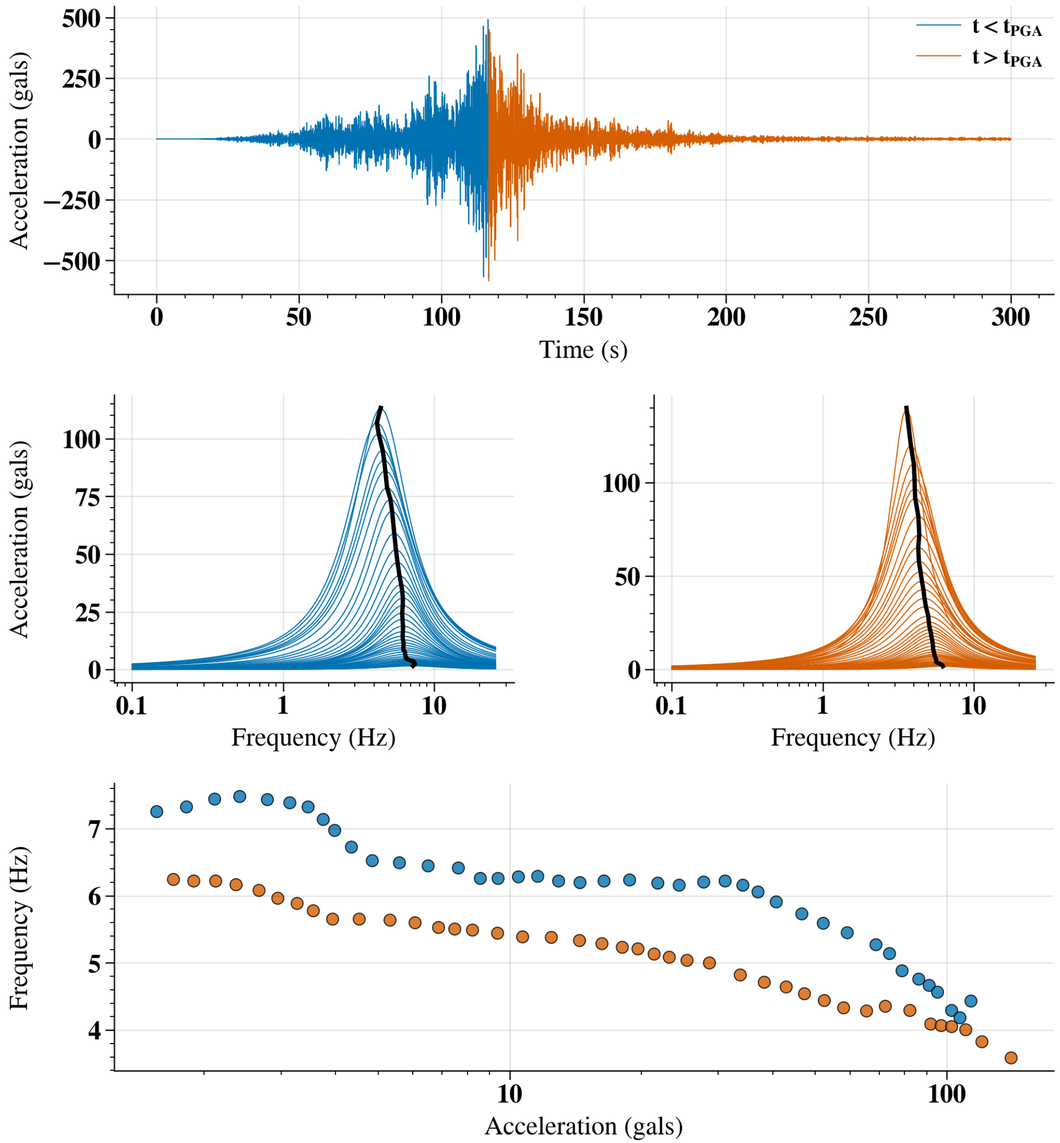


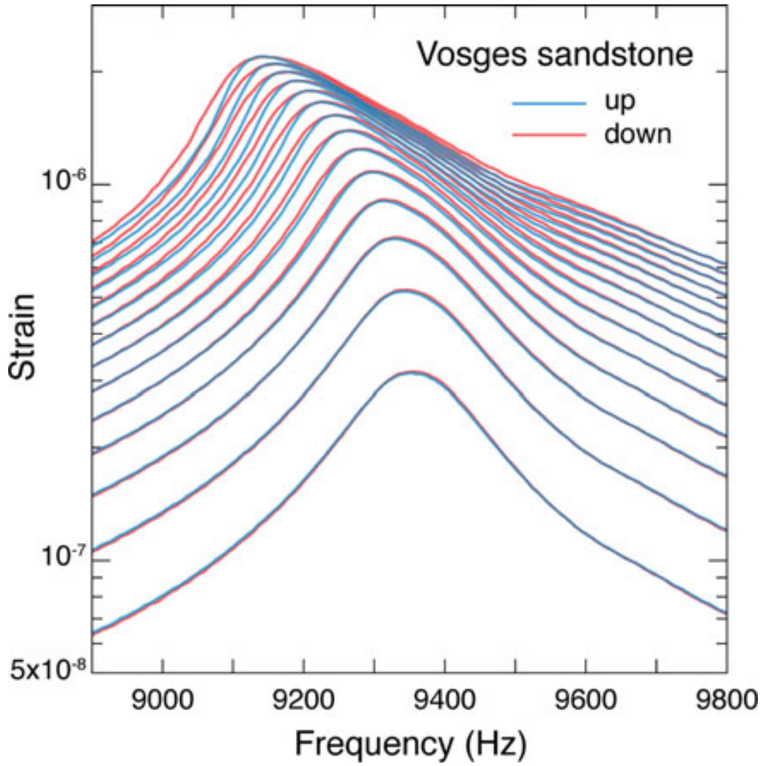


Bonilla et al (2011)

- Linear response using spectral ratios with data having PGA < 10 gals (KiK-net)
- Nonlinear response using the 2000 Tottori data (M7.3)
- Broadband effect that changes the seismic hazard

Coming back to resonance effects

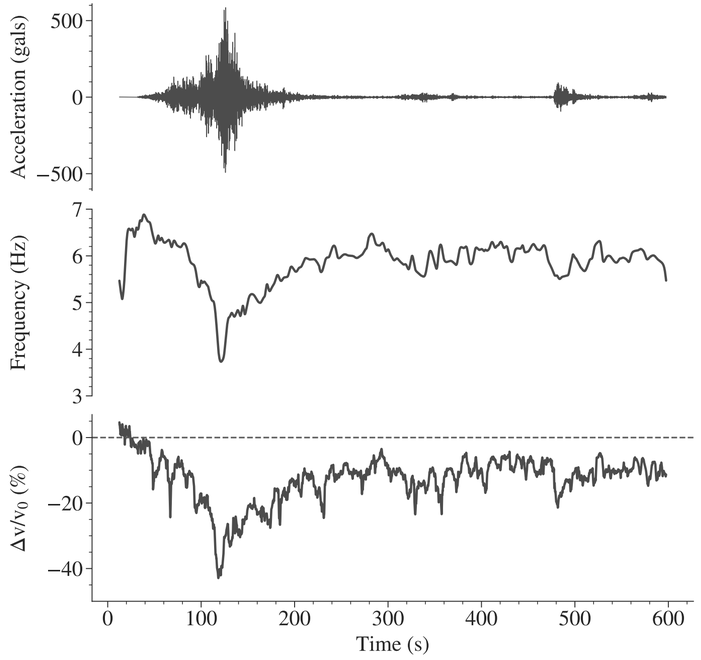




- Similar frequency shift as observed in rock samples (TenCate, 2011)
- $\Delta f/f \propto \Delta v/v$

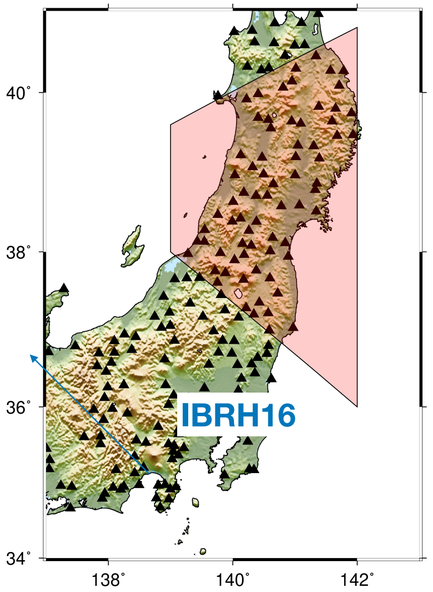
Bonilla et al (2021)

Seismic interferometry on ambient seismic noise and earthquake data

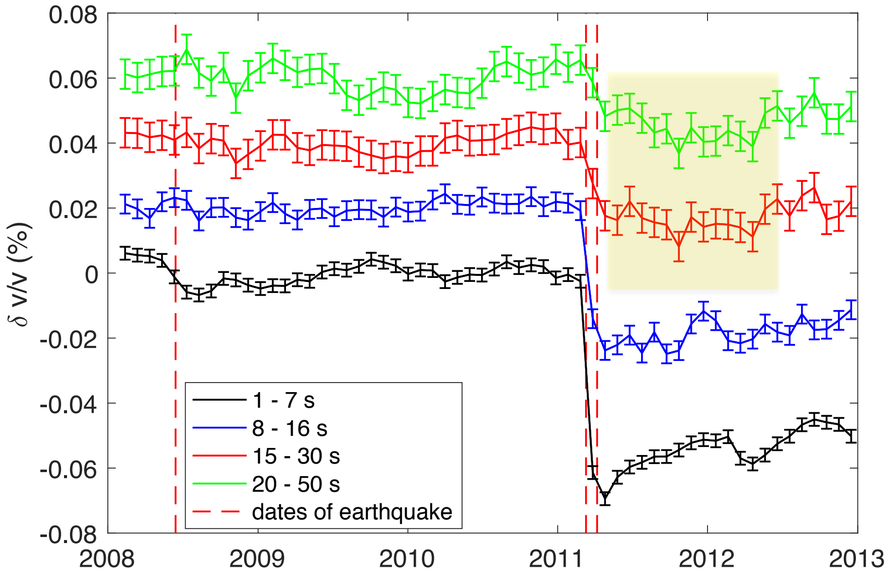


~50% (1-10 Hz)

Bonilla et al (2019)



From ambient noise data (Wang et al., 2019)

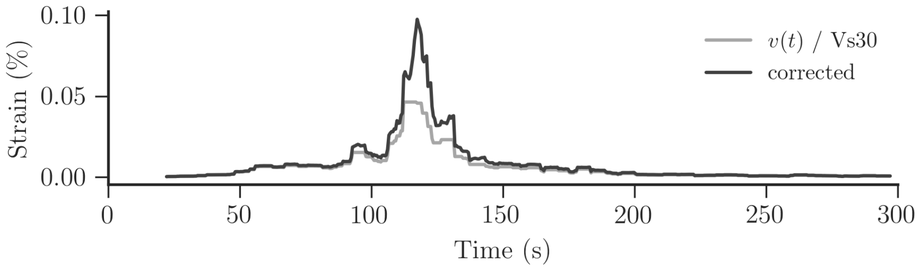


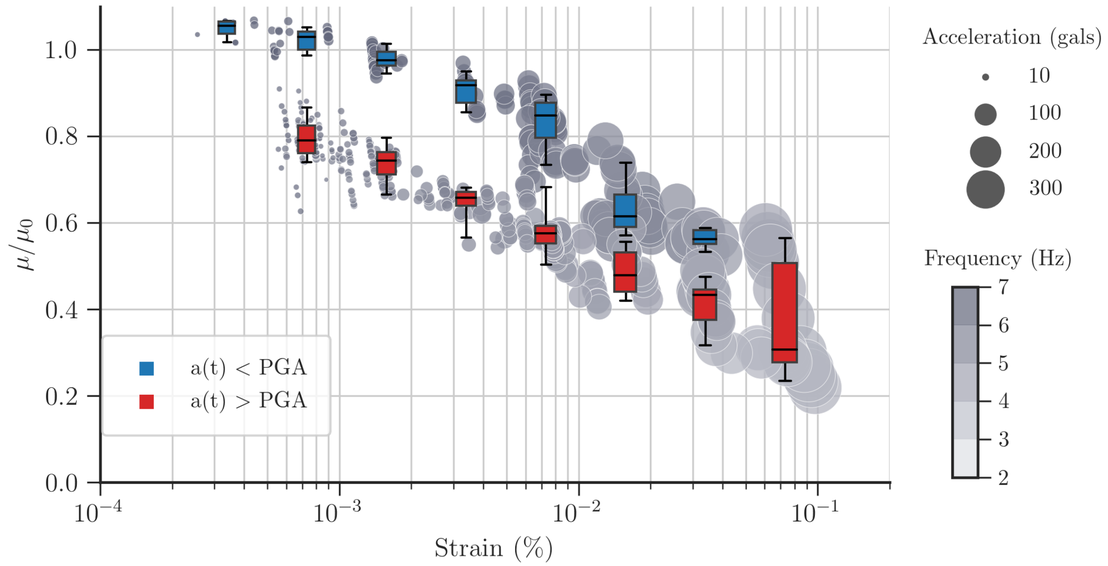
~0.05% (< 1 Hz)

- In-situ co-seismic shear modulus reduction and degradation (Bonilla et al., 2019)
- Two orders of magnitude higher (co-seismic)
- Material recovery is frequency dependent

In-situ equivalent cyclic test

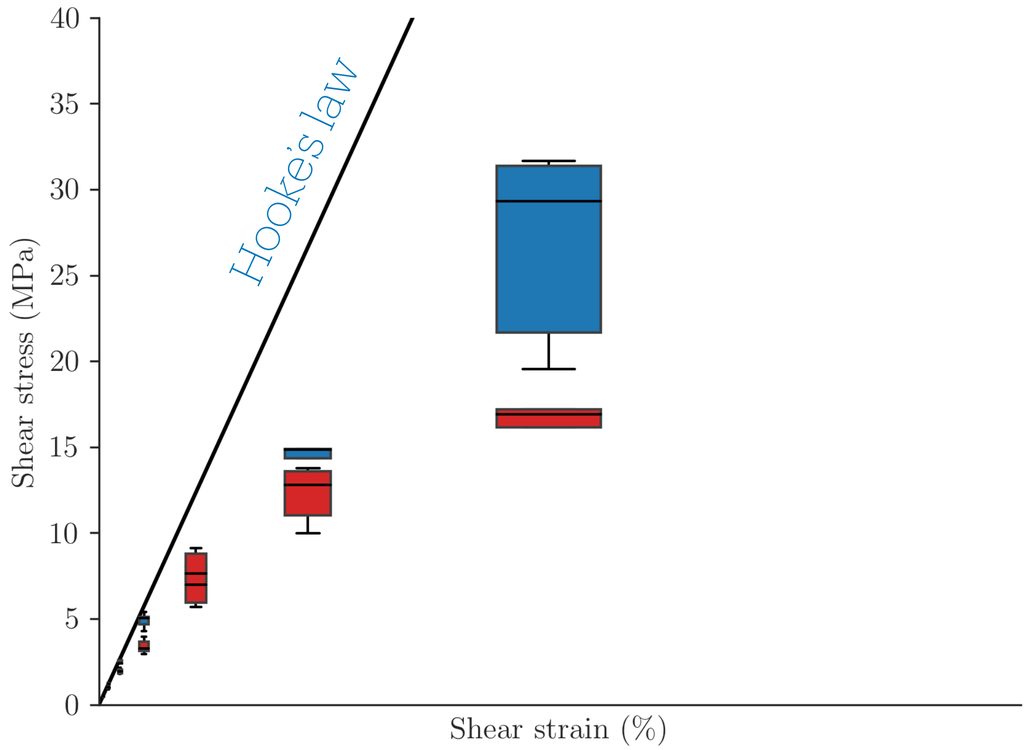
(velocity change) and strain proxy value - V(t)/Vs30(t)





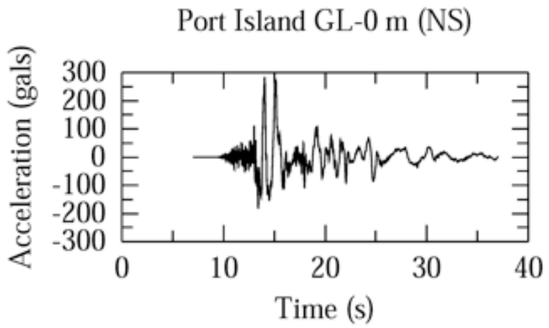
Bonilla et al. (2019)

$$(\Delta v/v_0 + 1)^2 = \mu/\mu_0$$



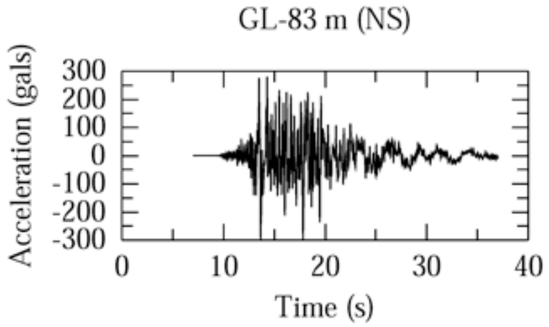
- Material behavior is different before and after PGA
- There is degradation, but what mechanism?
- Material damage and/or pore pressure effects?

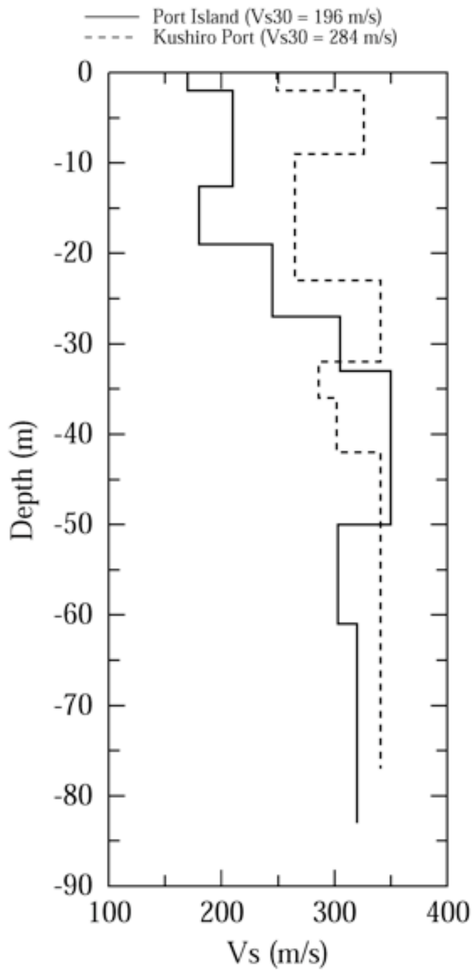
Where does the difference come from?

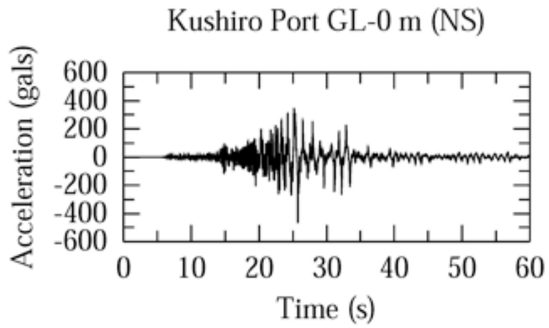


Loose sand
(liquefaction)

- lowpass filtering
- deamplification

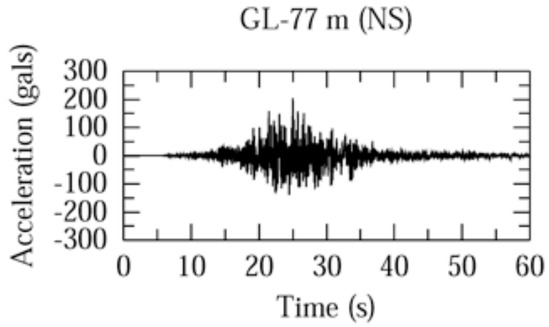






Dense sand
(cyclic mobility)

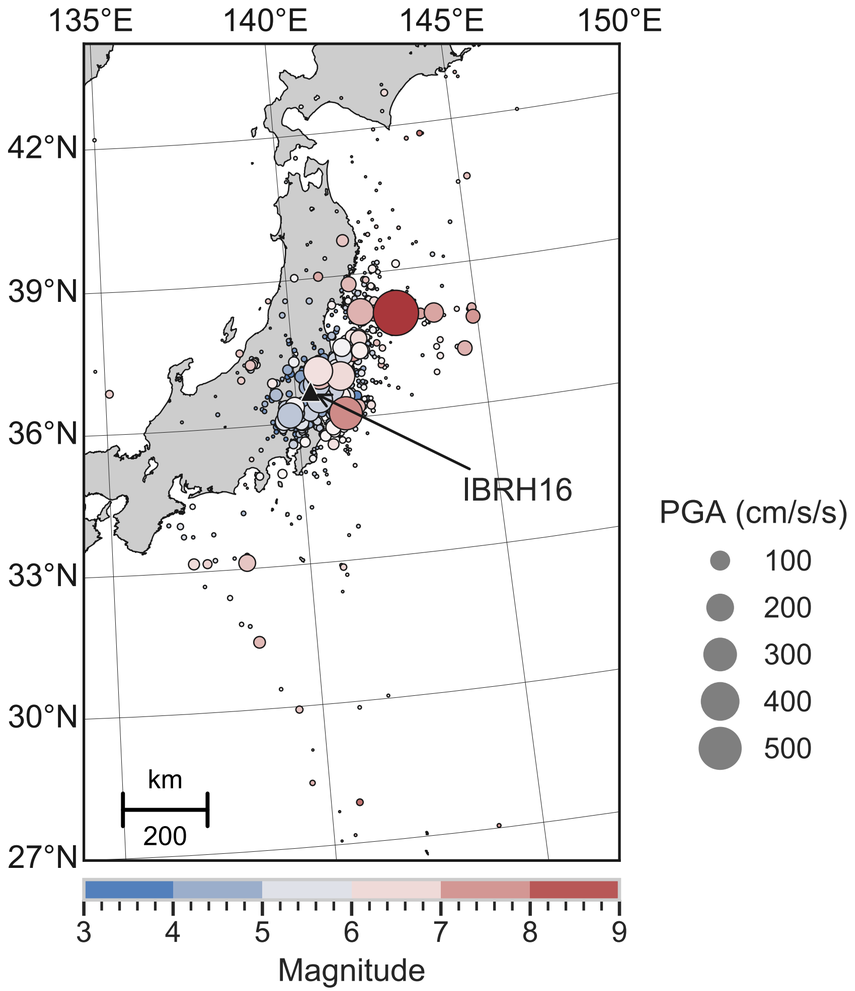
- high frequency content
- amplification

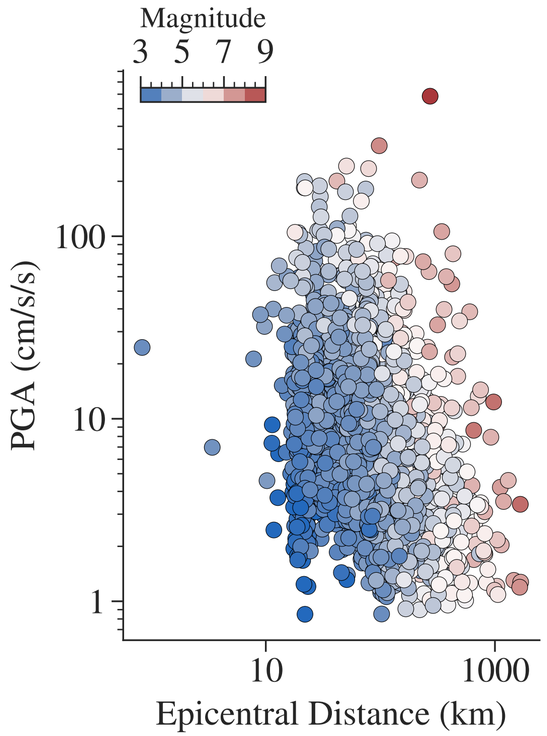


Velocity profile is not enough (elastic parameters)
Seismology != Earthquake Engineering

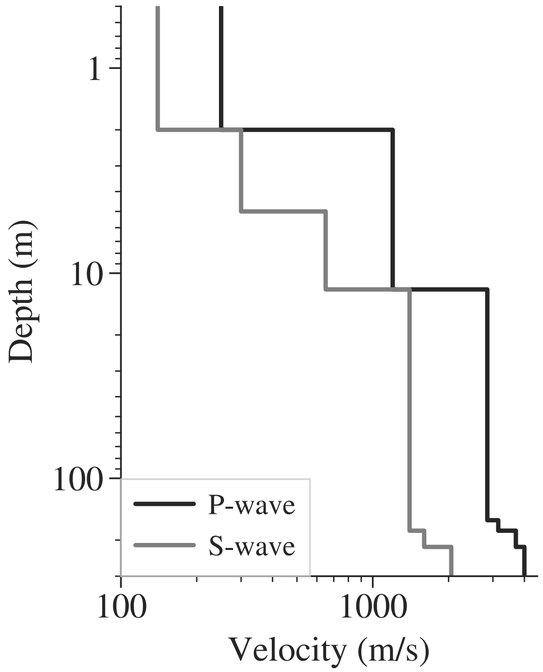
Bonilla et al (2011)

From 1 event to many:
long-term monitoring of a permanent station (IBRH16, KiK-net)





Vs30 = 626 m/s

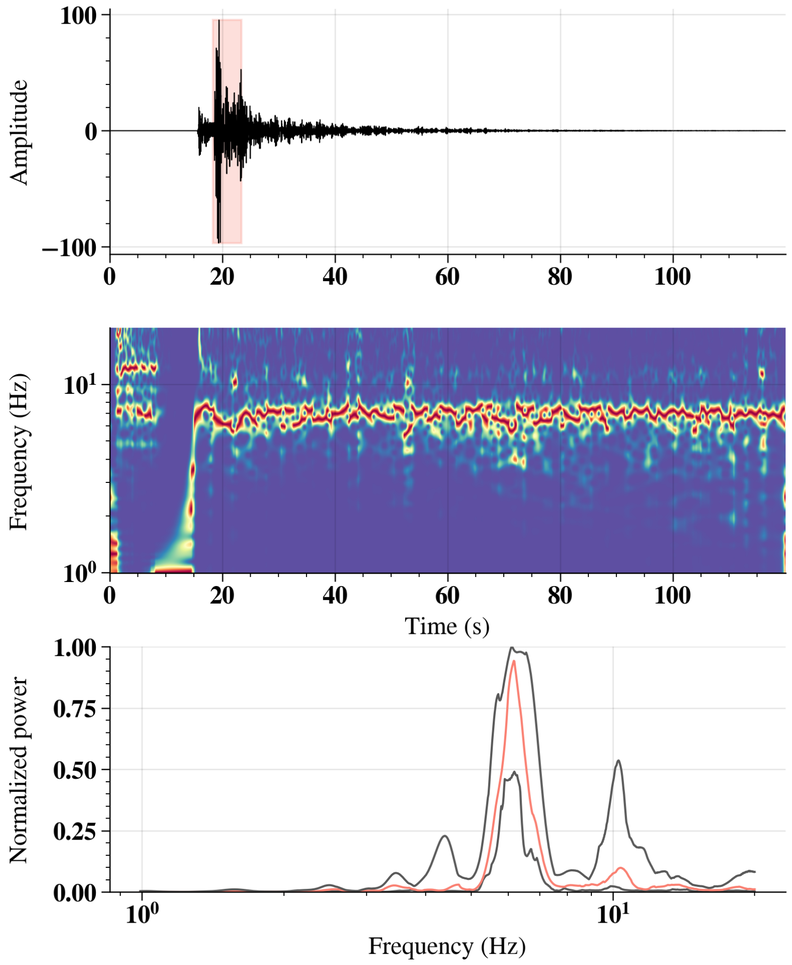


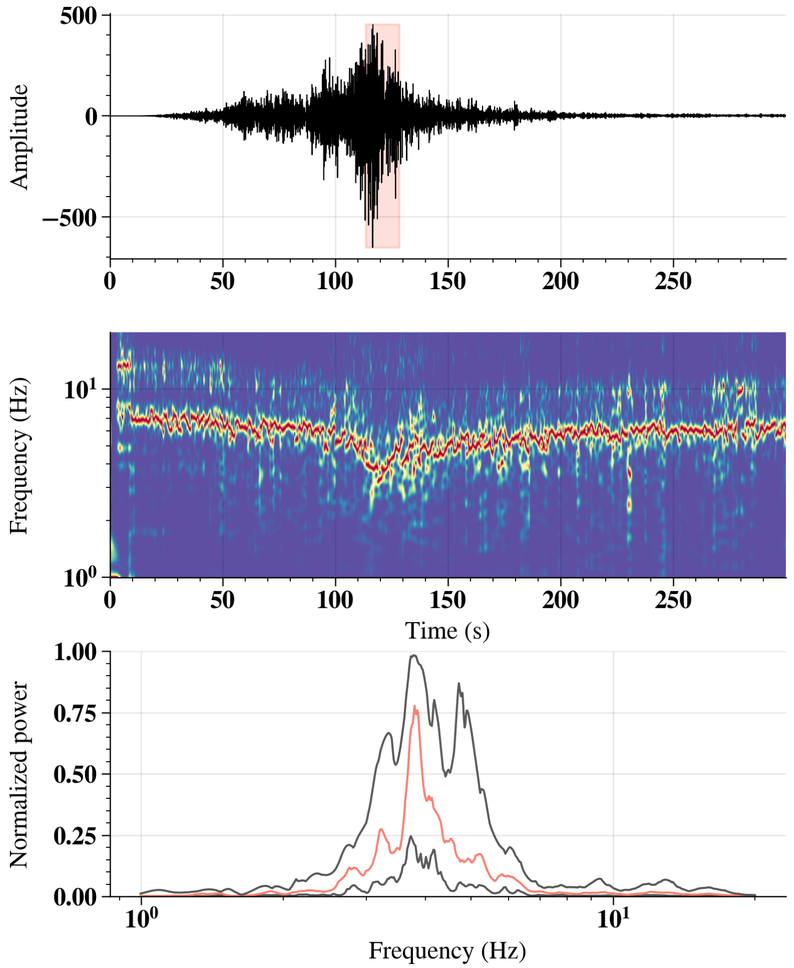
- Good magnitude-distance-azimuth distribution
- What is the station response?

Bonilla et al (2021)

Where is the maximum energy?

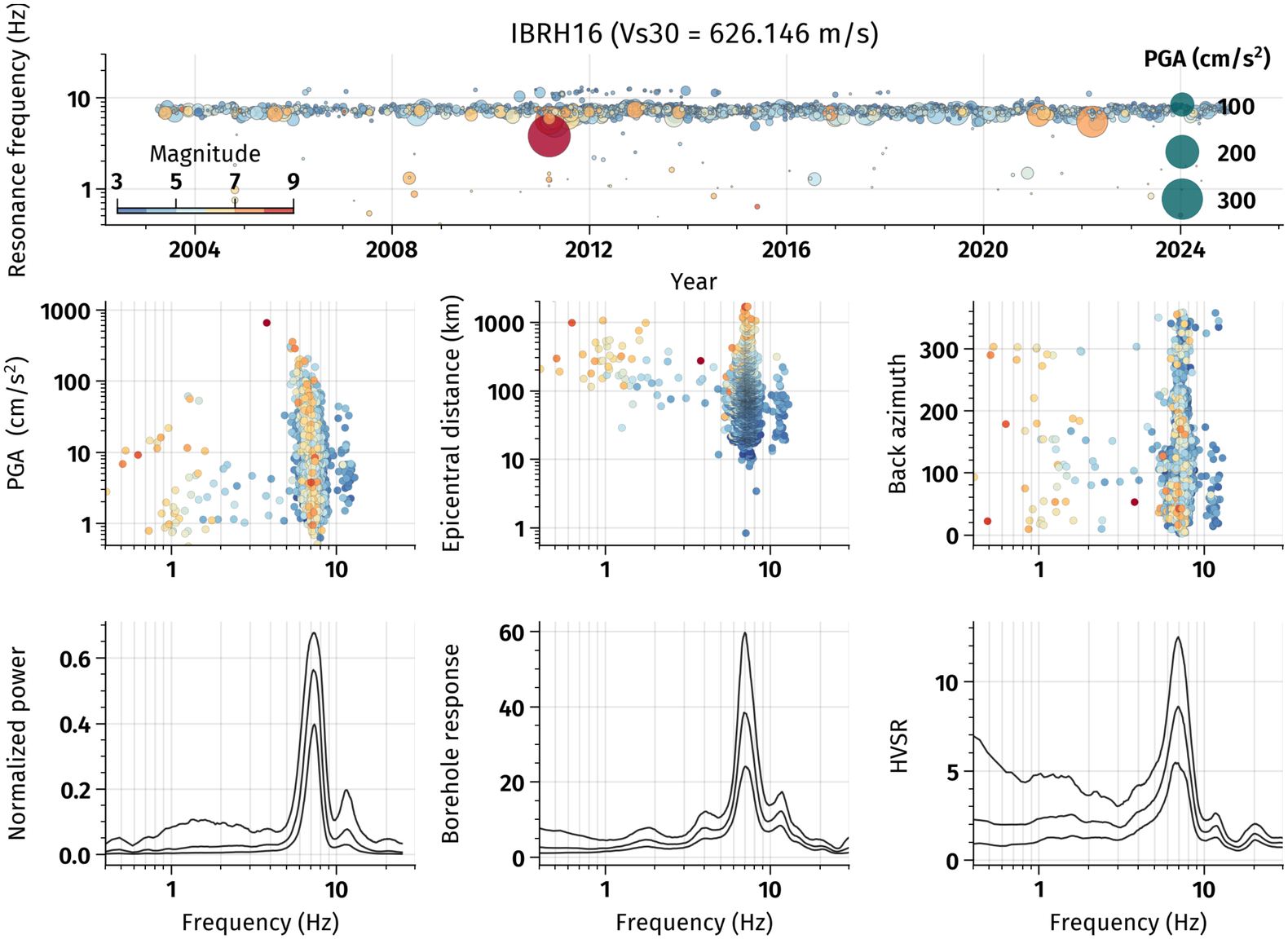
Resonance frequencies





Schibuola et al (2025)

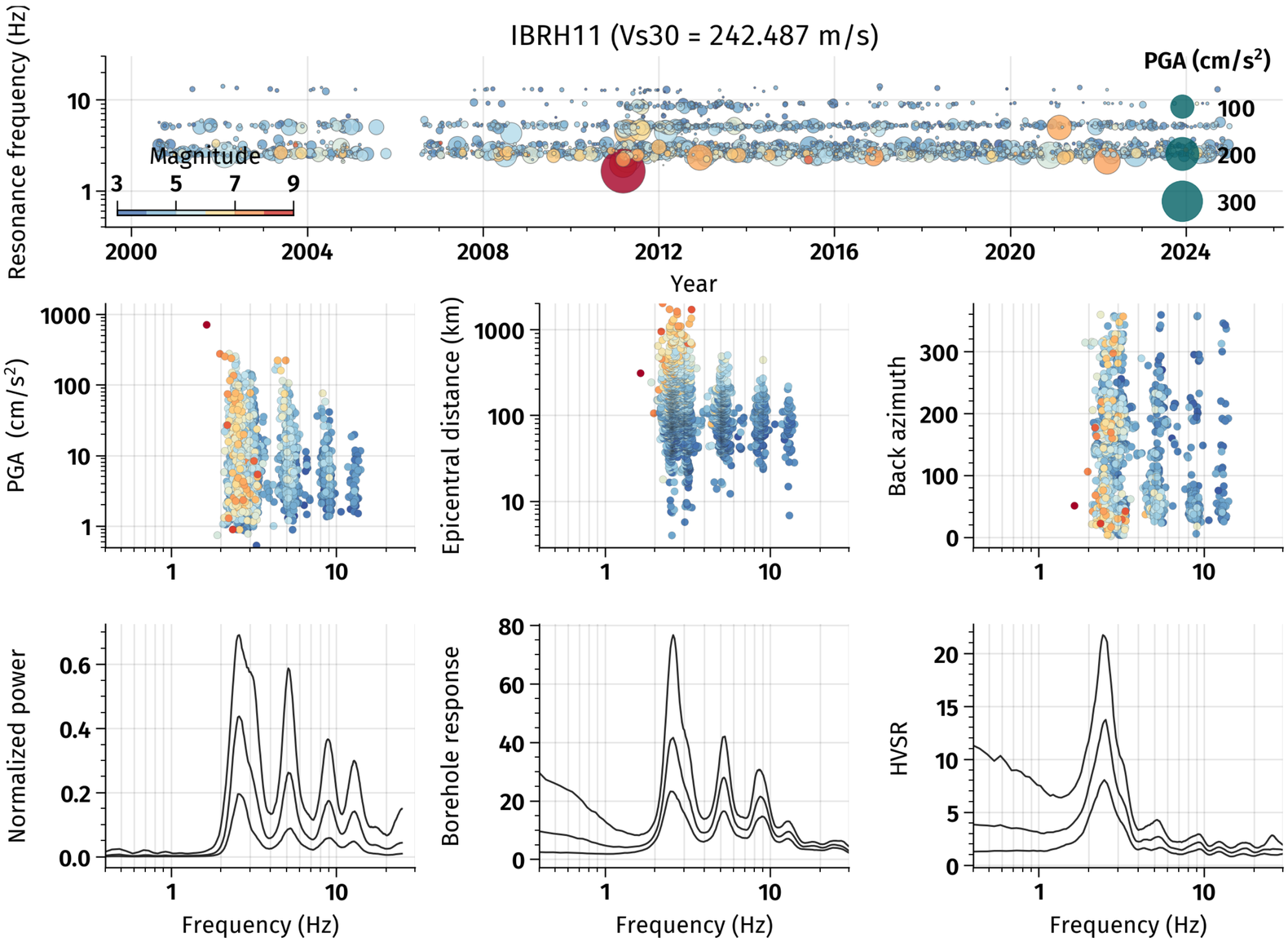
Tracking resonance frequencies of eqks



- Distant events excite low frequencies
- Local events may excite all frequencies

Schibuola et al (2025)

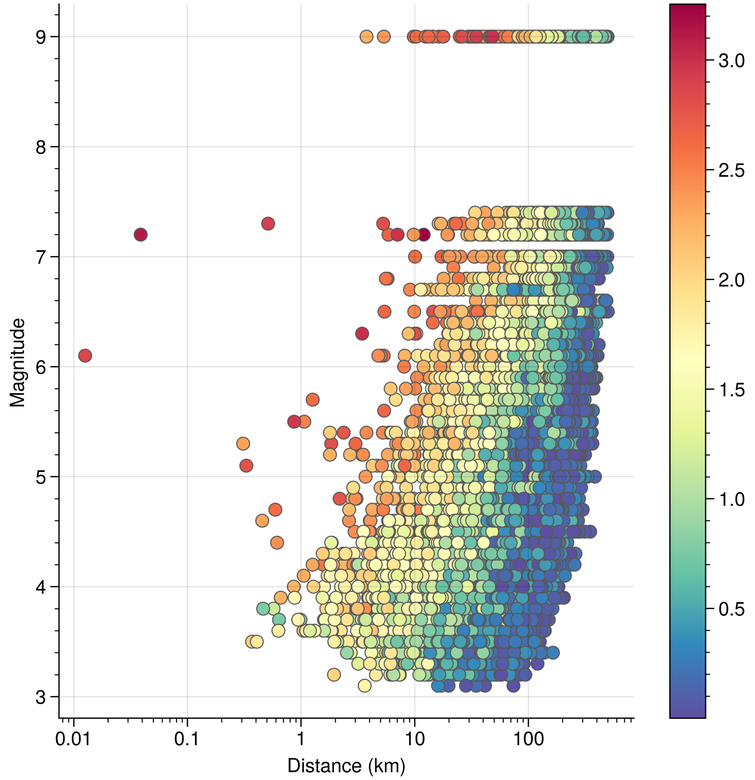
Tracking resonance frequencies of eqks

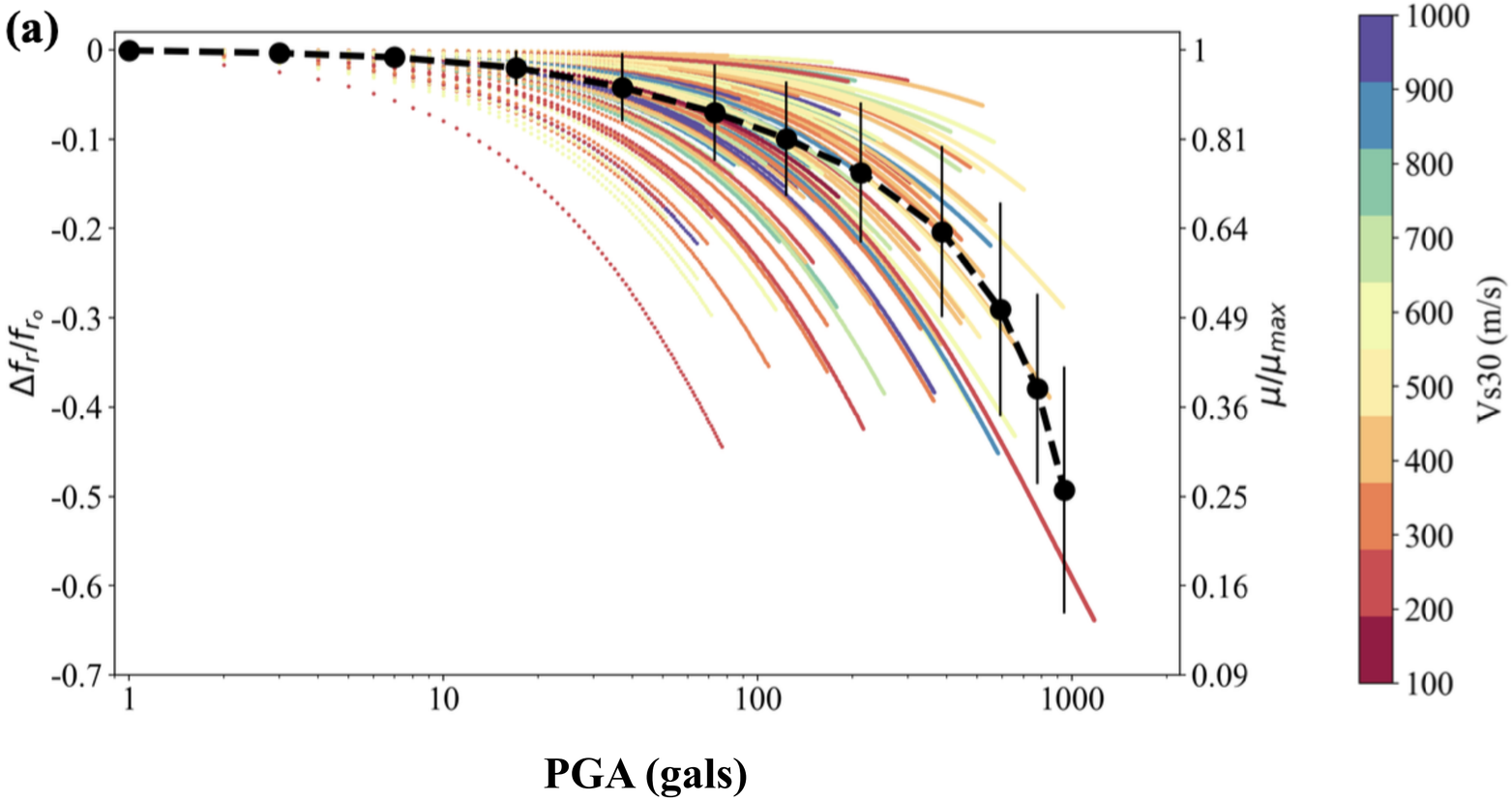


- Resonance frequencies match borehole response (**site effects control the ground motion**)
- Identification of PGA threshold

Schibuola et al (2025)

Nonlinear signature in Japan from KiK-net data



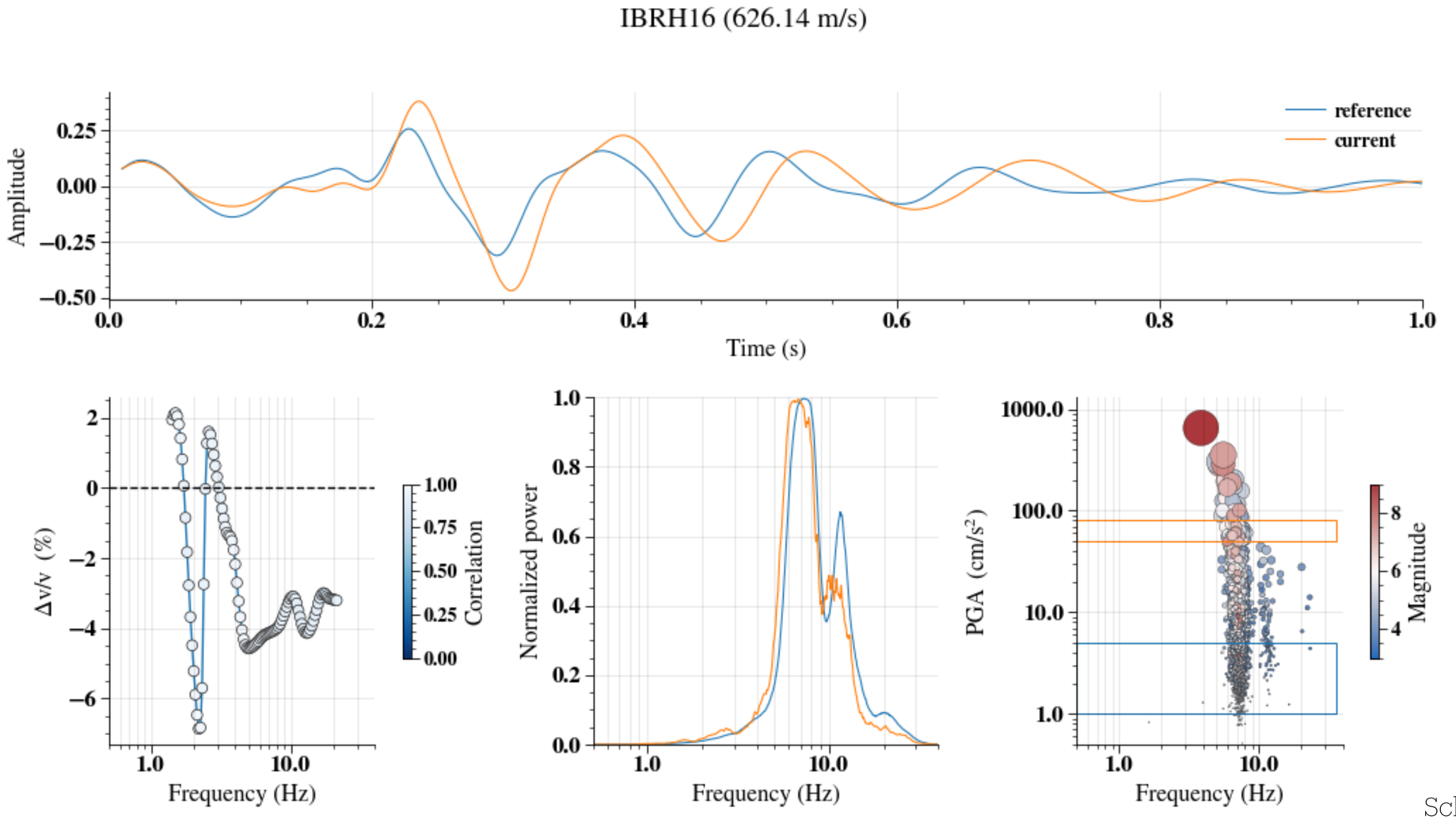


Lai et al (2025)

- Time-averaged Vs30 cannot discriminate nonlinear behavior
- 10% frequency shift (20% shear modulus decrease) is attained with 0.1g

Measuring velocity changes

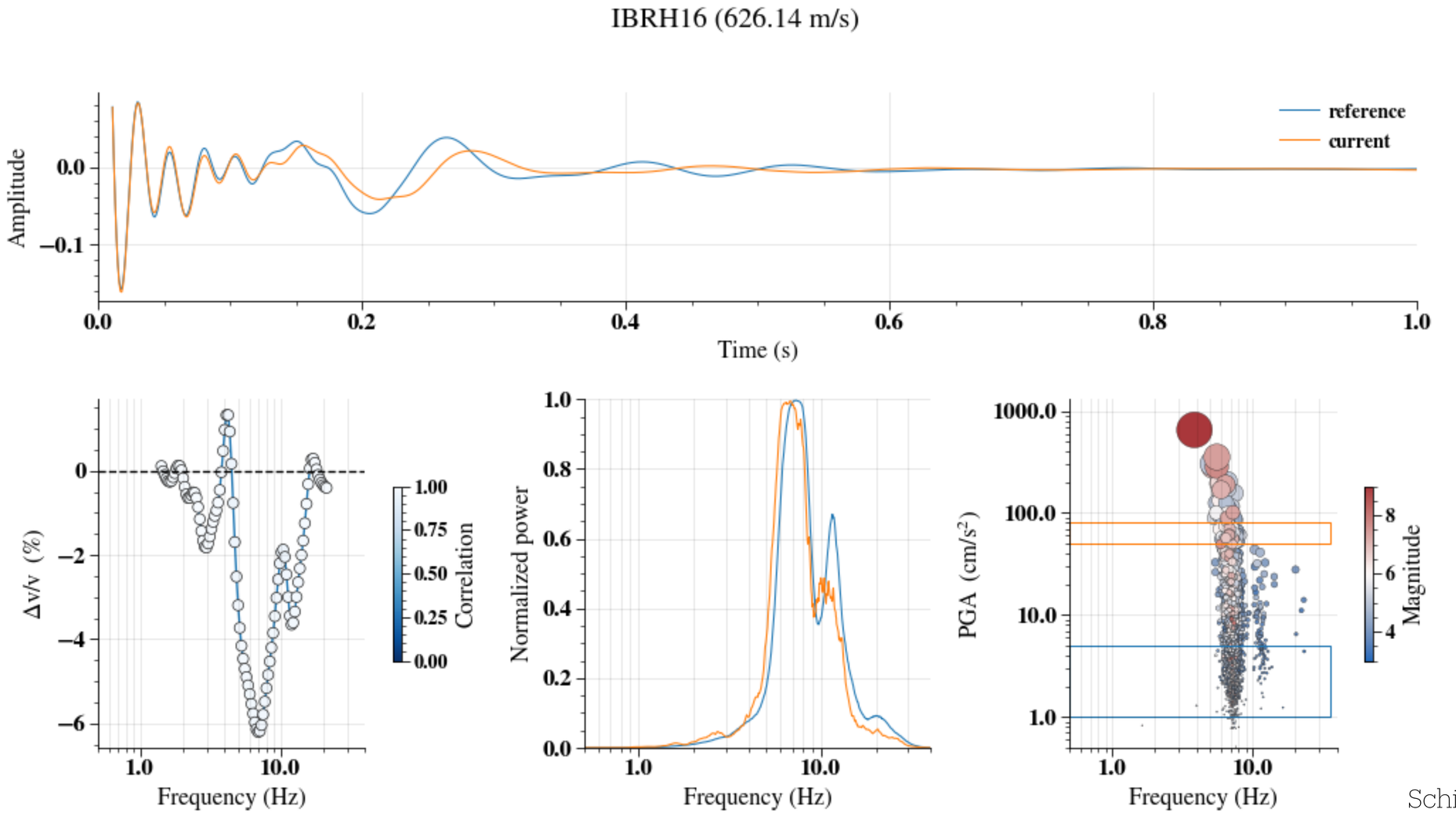
Seismic interferometry using surface/borehole data



Schibuola et al. (2025)

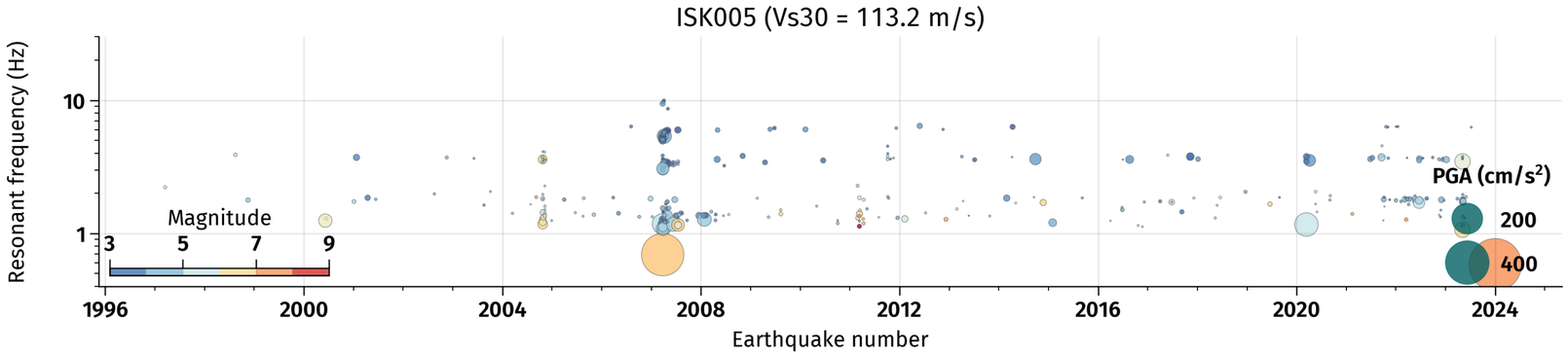
Measuring velocity changes

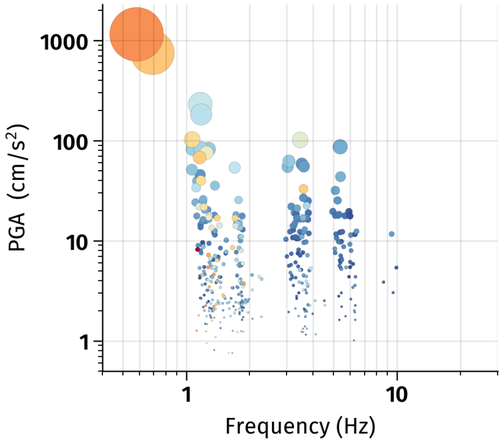
Autocorrelation functions ACF

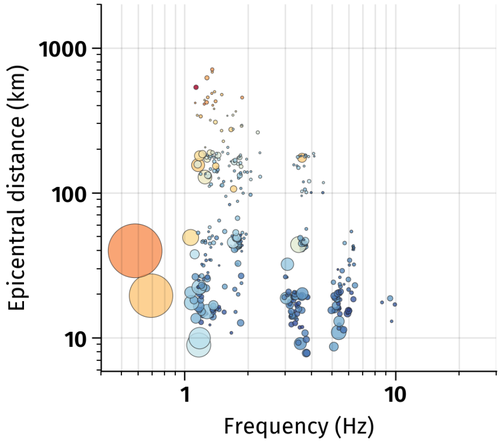


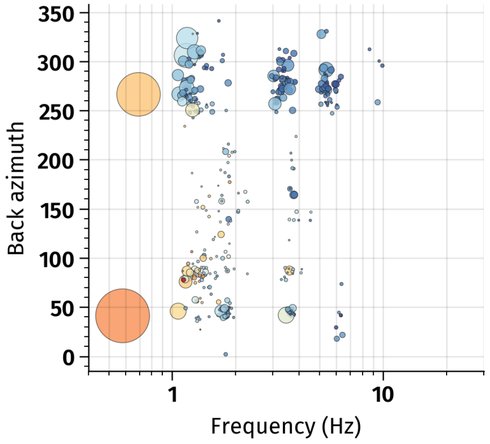
Schibuola et al. (2025)

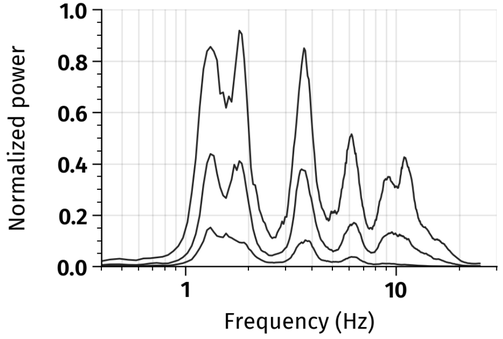
Use of KNET data (surface stations)

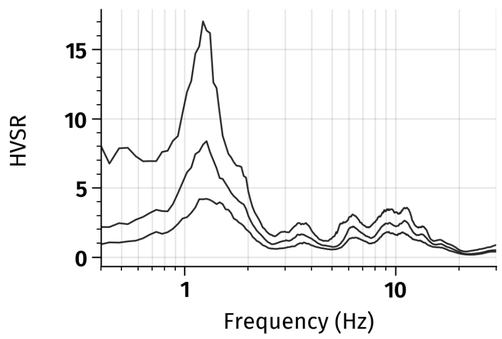












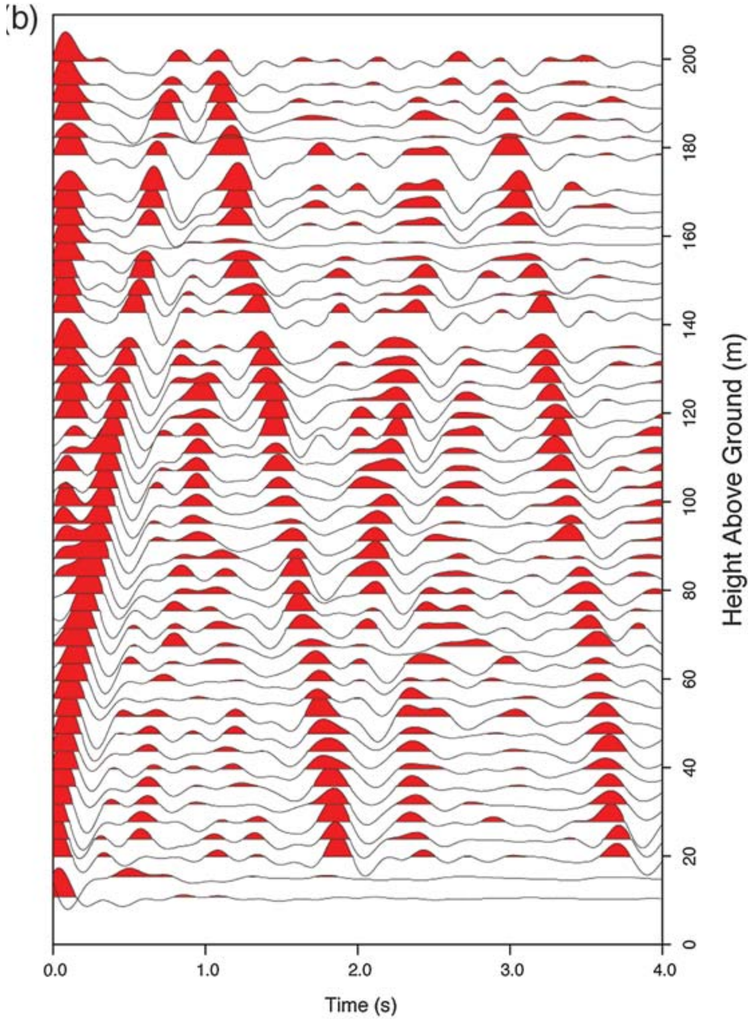
- Identification of resonance frequencies
- Proxy of site response?
- Which frequency is affected by nonlinear effects

Schibuola et al (2025)

Transfer seismological/geophysical methods to CV structures

52-stories Los Angeles building

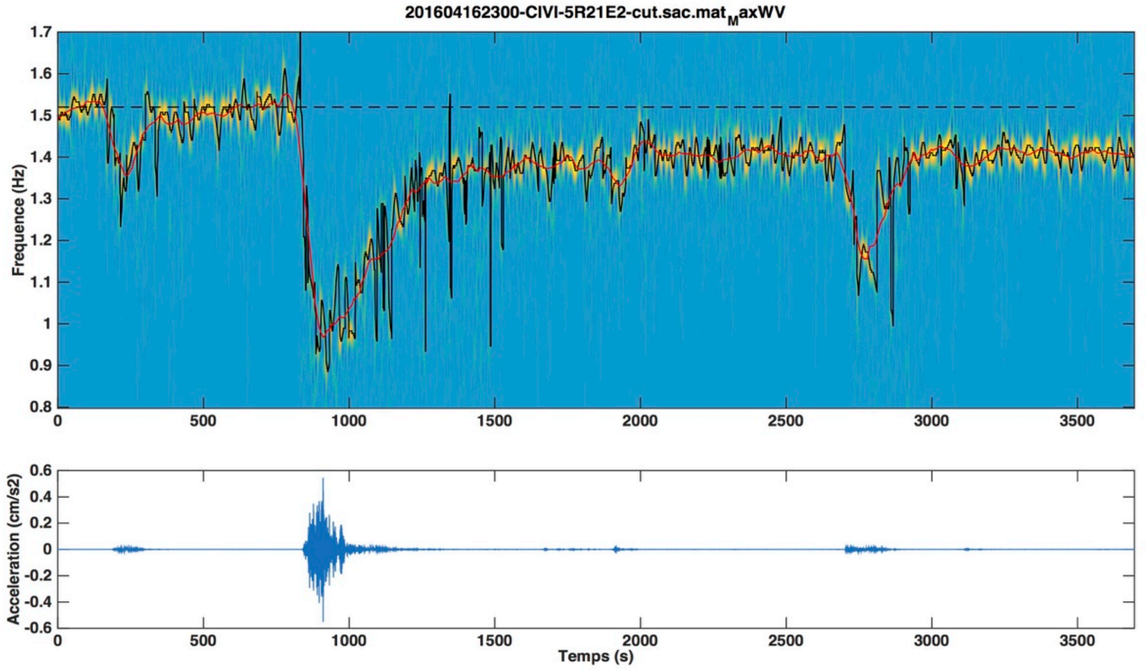
Clayton et al., SRL 2015



2016 Pedernales (Ecuador) Earthquake

10-stories Quito building

Guéguen et al., End. Struct. 2020



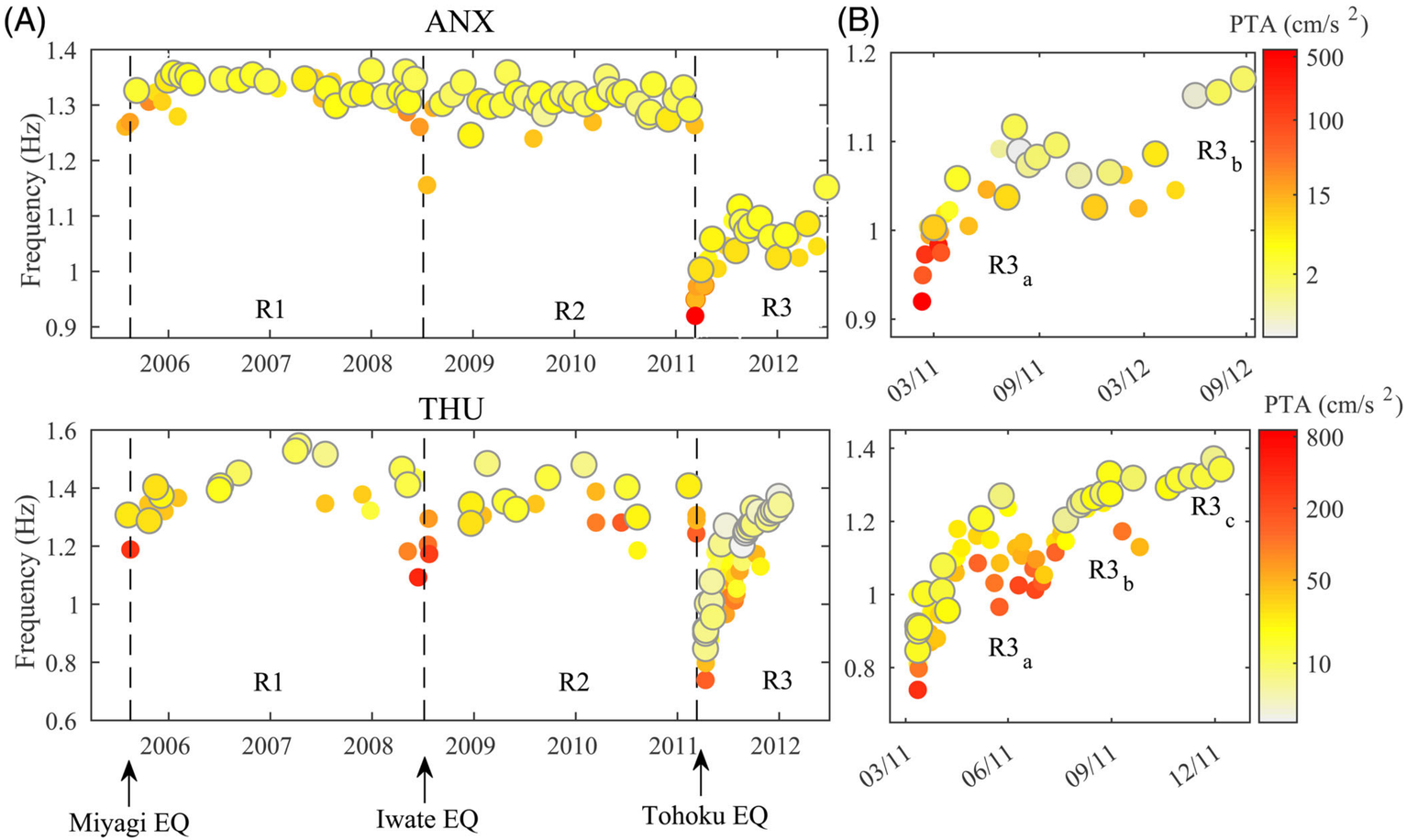
Wave-based or modal based approaches

Continuous, permanent, highly sensitive (I stress highly sensitive) + HPC tools

Co-seismic variation and slow-dynamic of physical properties

BRI Japan
ANX building

BRI Japan
THU building



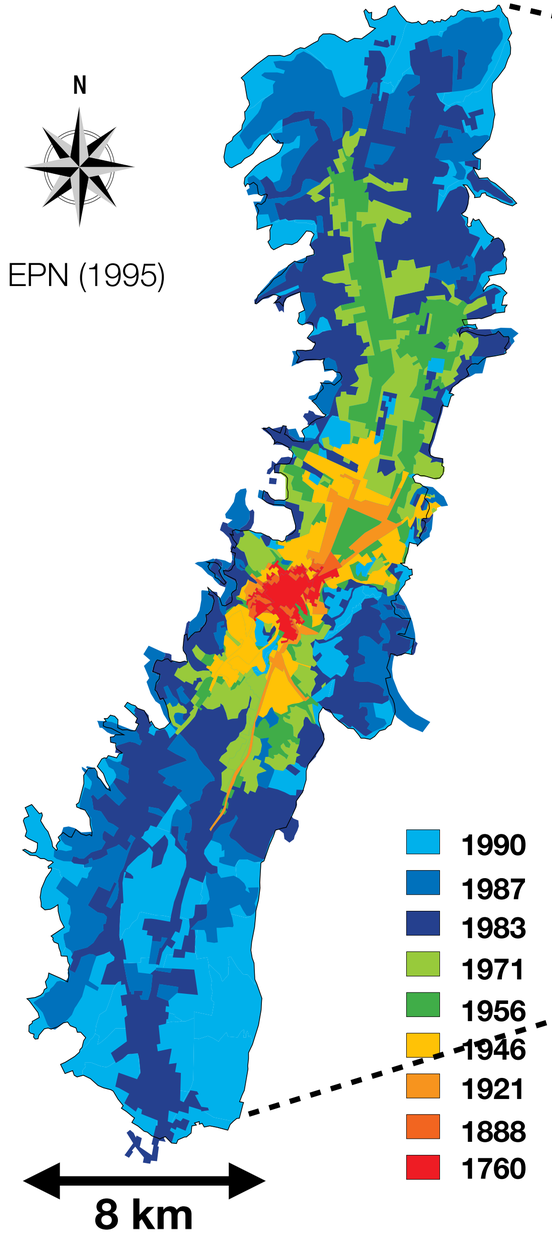
Astorga et al., BSSA 2018, SHM2019, Astorga and Guéguen, Eng. report, 2020

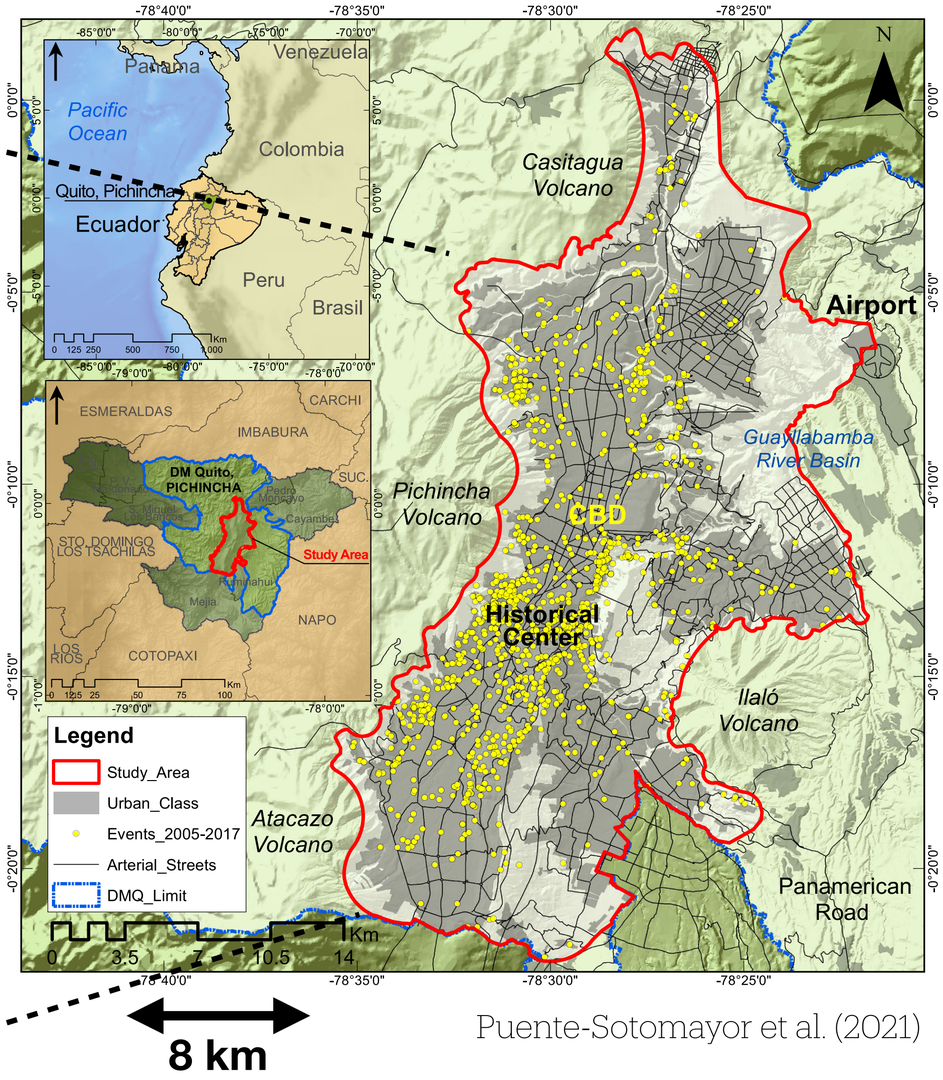
What next?

- Strong velocity changes are observed in the shallow crust
- Velocity changes last longer (several years) at low frequencies (f < 1 Hz). Yet, they are small and mobilize the whole crust
- Near-surface effects are several orders of magnitude larger, and they show a strong variability in space and time
- No need of borehole or reference stations to obtain a proxy of site effects. Can we invert the velocity structure?
- Empirical method could also be used to long-term structural health monitoring of buildings, sediments, rails, dams, etc.

Beyond the fundamental resonance frequency in site characterization

Becoming a megacity: Quito - Ecuador





Puente-Sotomayor et al. (2021)

- 1M in 1990, 2M in 2024
- Growth is not always planned
- Increase of vulnerability

How is a city organized?

Barcelona, Spain

Welcome to the real world...

Bogotá, Colombia

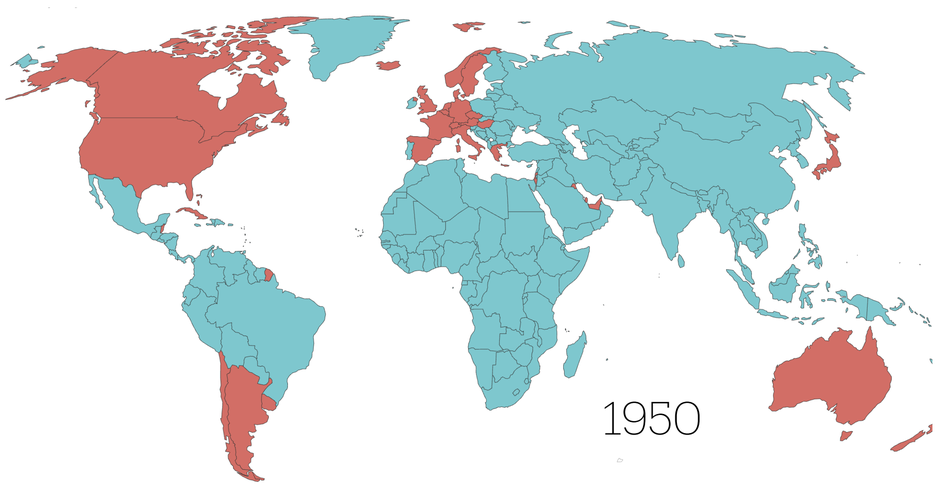
Quito, Ecuador

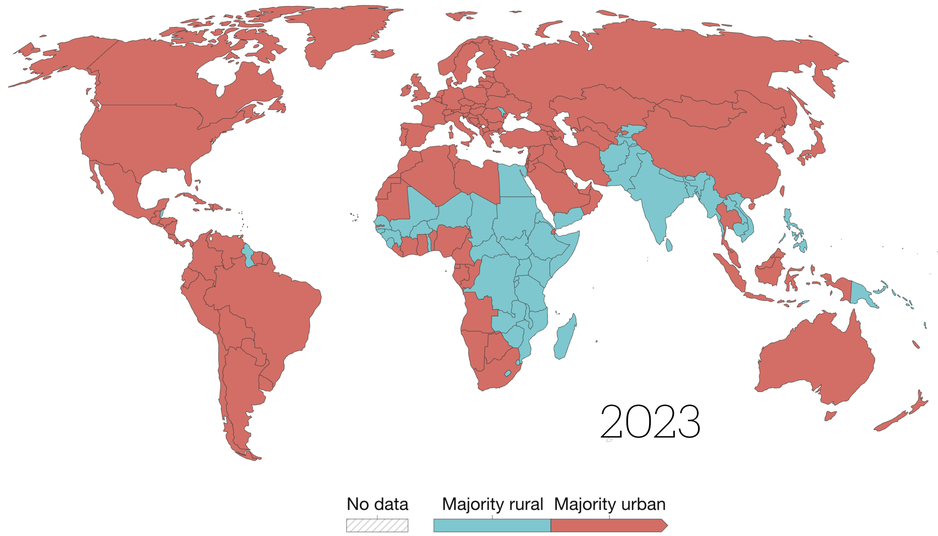
What do you observe?

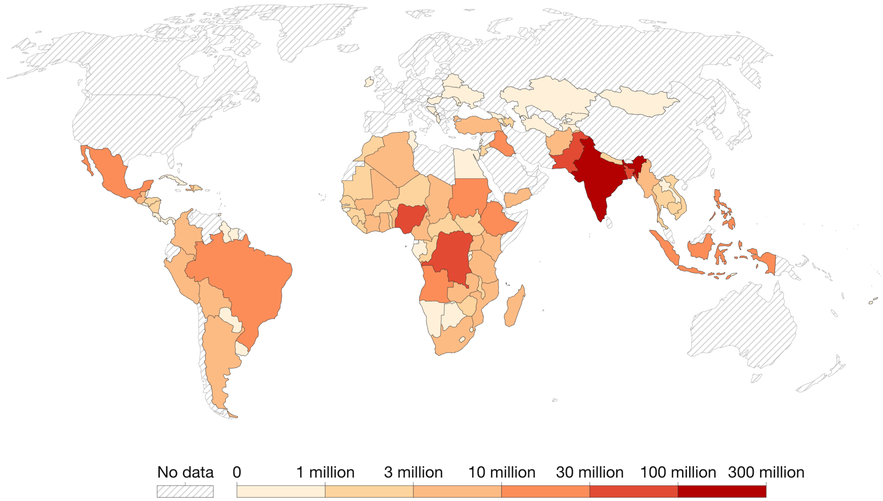
- Homogeneous construction?
- Flat landscape everywhere?

NO!!!

Urbanization of cities (megacities)



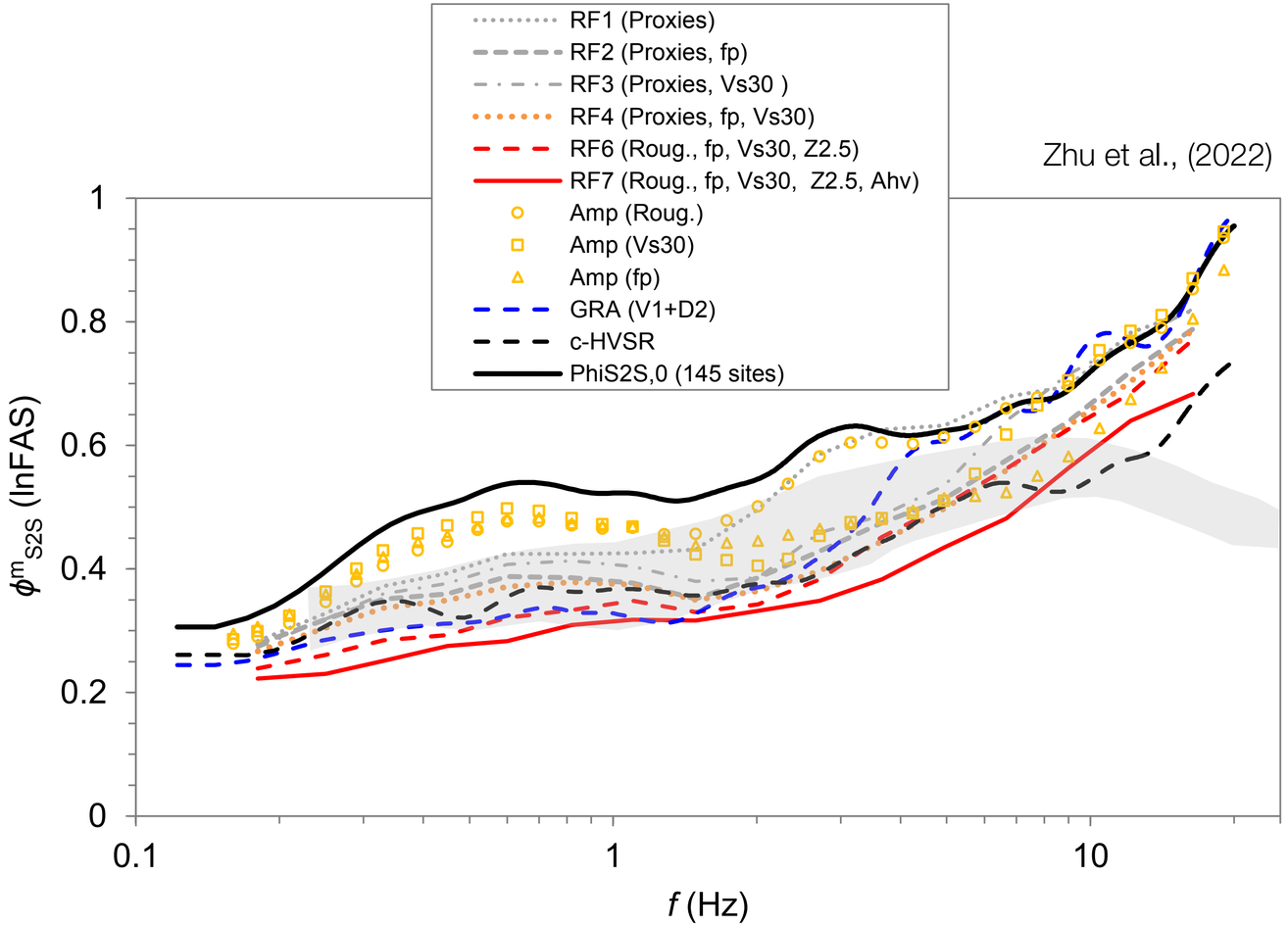




Number of people living in urban slum households, 2020

https://ourworldindata.org/urbanization

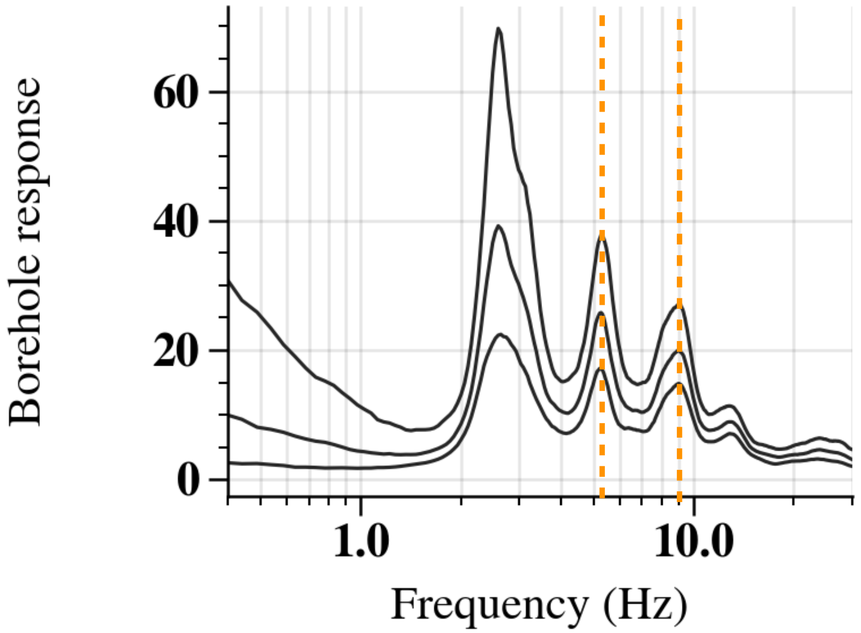
Site characterization as part of seismic hazard



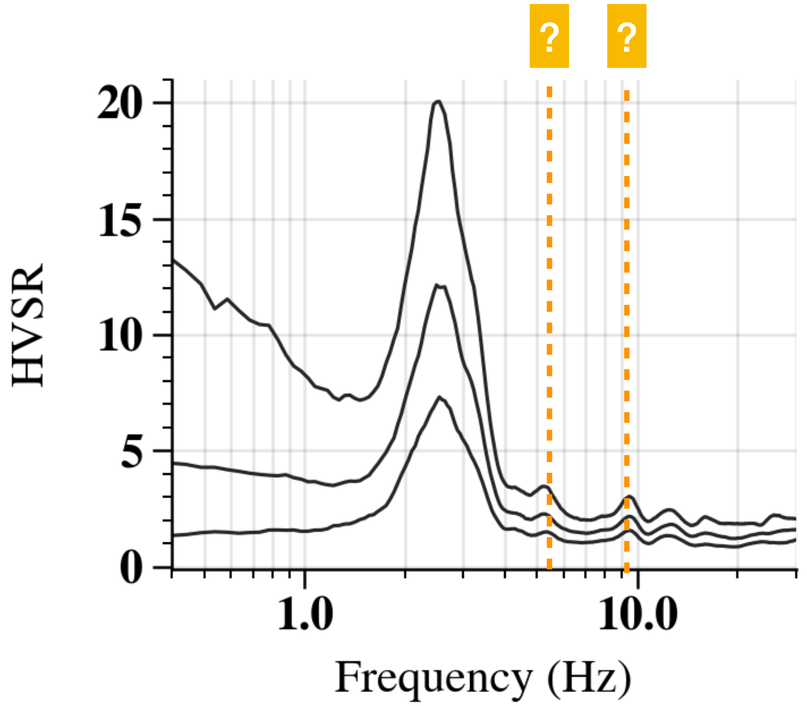
The site-to-site variability generally increases with frequency when predicting the Fourier spectra

Empirical estimation of site effects

Spectral ratios (earthquakes)



H/V (noise)



- Site-to-reference methods provide the amplification as a function of frequency
- HVSR using ambient noise usually identifies the fundamental frequency, but may miss the higher harmonics

Why to go to higher frequencies?

- The spatial variability of the building stock does not necessarily have correlation with the soil fundamental frequency
- Site characterization implies to know what produces the observed response (inversion of the velocity model)
- High frequencies are important because they control Vs30 values, determination of “kappa”, and computation of empirical Green’s functions
- Use of techniques from Seismology (diffuse wave field theory and seismic interferometry) to have a better representation of Green’s functions

DAS data can also clip

Viens et al. (2022)