Seismic Hazard Assessment, 2016

UME School

Seismic Response Analysis: From Site Effects to Site Characterization Techniques

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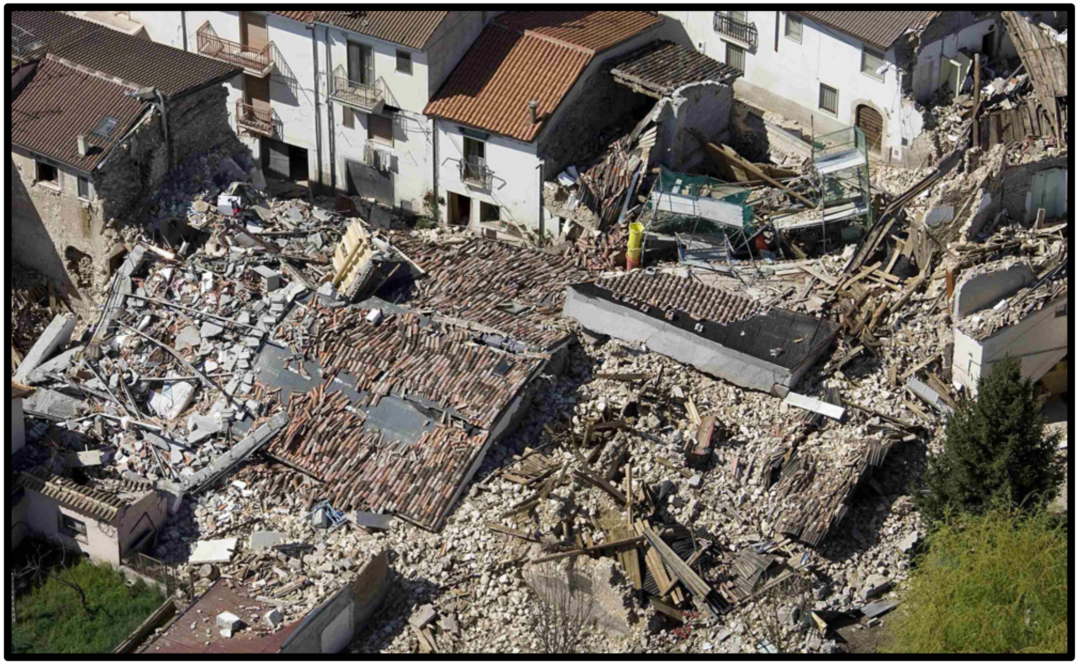
Lecture outline

- Motivation
- Understanding local seismic response and microzonation
- Relevant phenomena for the modification of the ground motion
- Seismic site response evaluation in practice
- Geophysical site characterization techniques (depending on available time)
- Site term in GMPEs
- Concluding remarks

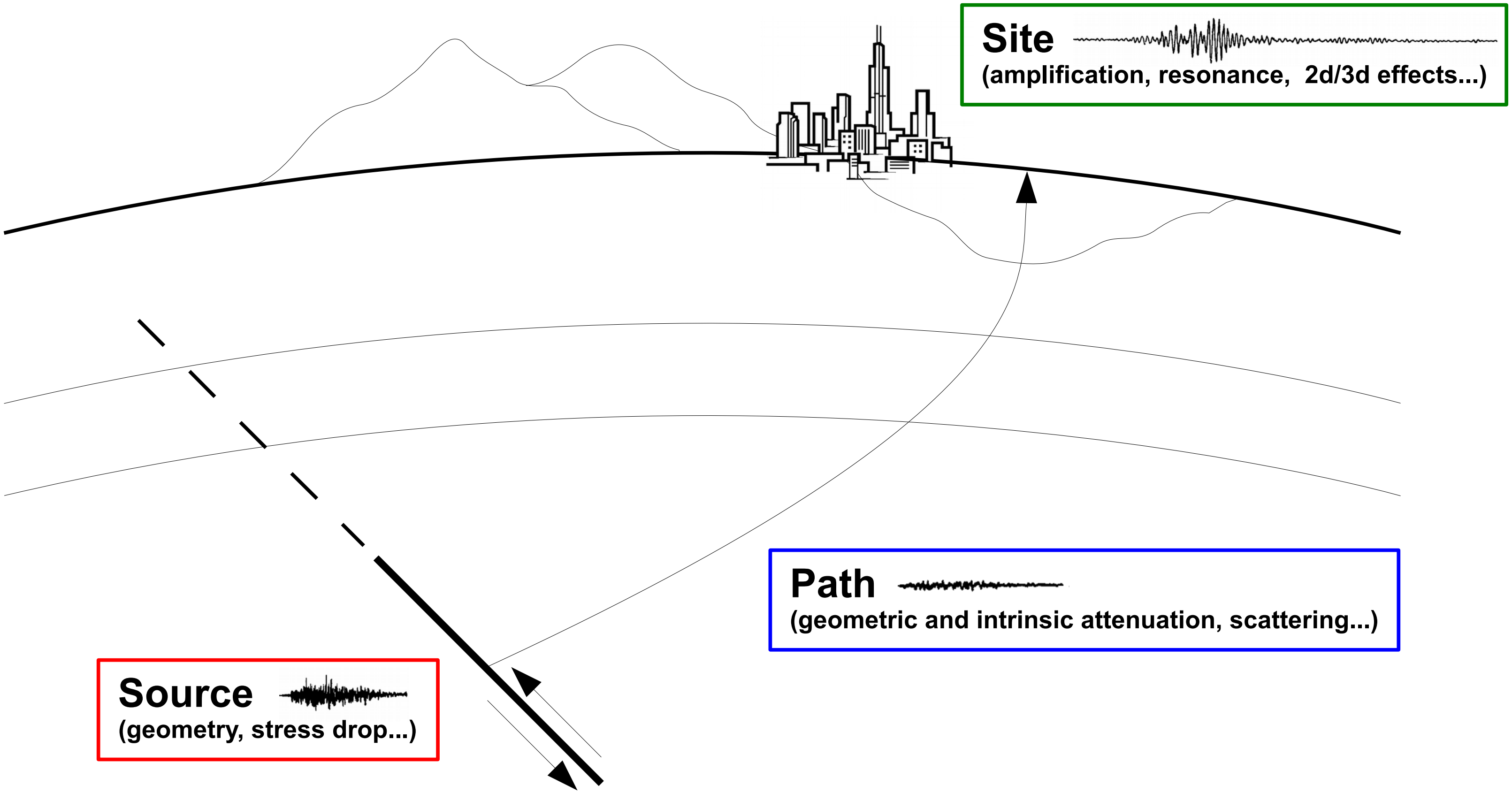


L'Aquila Earthquake 2009,
Magnitude Mw 6.3

Introduction

Factors controlling Ground Motion

- Earthquake signals can be strongly altered during their propagation from the **source** to the **observation point**
- Significant contribution comes from the uppermost **few hundred meters of the earth structure**, where the larger variability of the geological conditions is present
- As a result, the waveform at the recording station is generally very different from that one potentially observed close to the generating fault



Site
(amplification, resonance, 2d/3d effects...)

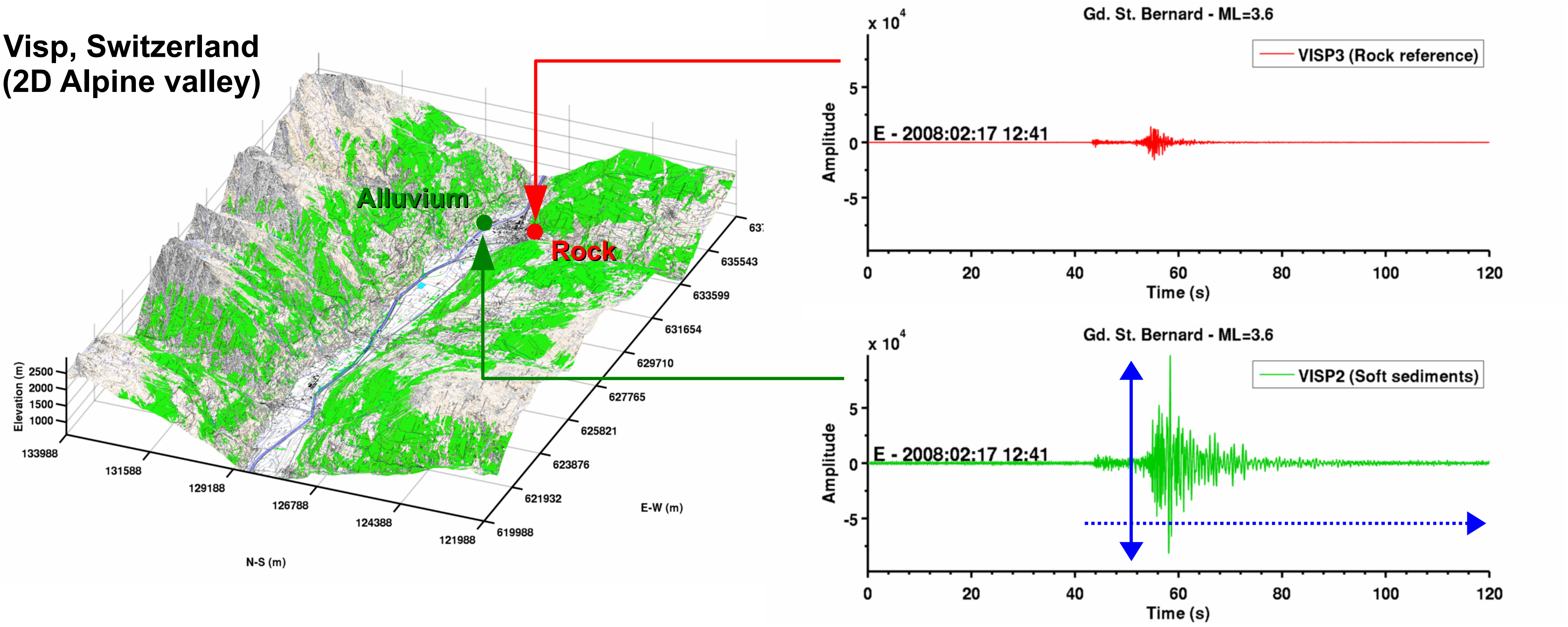
Path
(geometric and intrinsic attenuation, scattering...)

Source
(geometry, stress drop...)

Effect on Ground Motion: Local Seismic Response

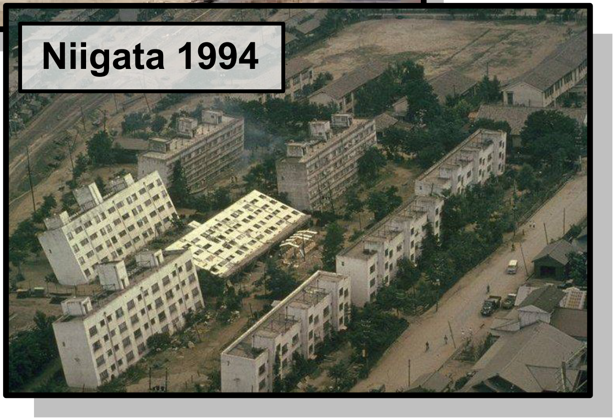
- For a particular site, the **amplitude** and **duration** of the ground motion during an earthquake can significantly be modified by the effect of the *local site conditions*
- On **very soft sediments** on top of a rigid bedrock, the ground motion can be **amplified** by more than a factor of 10, with increase in duration of several tens of seconds...
- Additionally, the energy can be non-evenly redistributed over different *frequency bands* of the spectrum, with a chance of matching the dominant **resonant frequencies of buildings**

Visp, Switzerland (2D Alpine valley)



Effect on the environment: Induced Effects

- The local environment is also vulnerable to certain shake levels, through development of **induced** or **secondary** effects, such as
  - ⇒ **Ground failures**: static displacement (offsets), subsidence, liquefaction, landslides...
  - ⇒ **Indirect or triggered effects**: flooding, tsunamis, snow avalanches..
- All these phenomena concur to the increase in **seismic hazard at local scale**

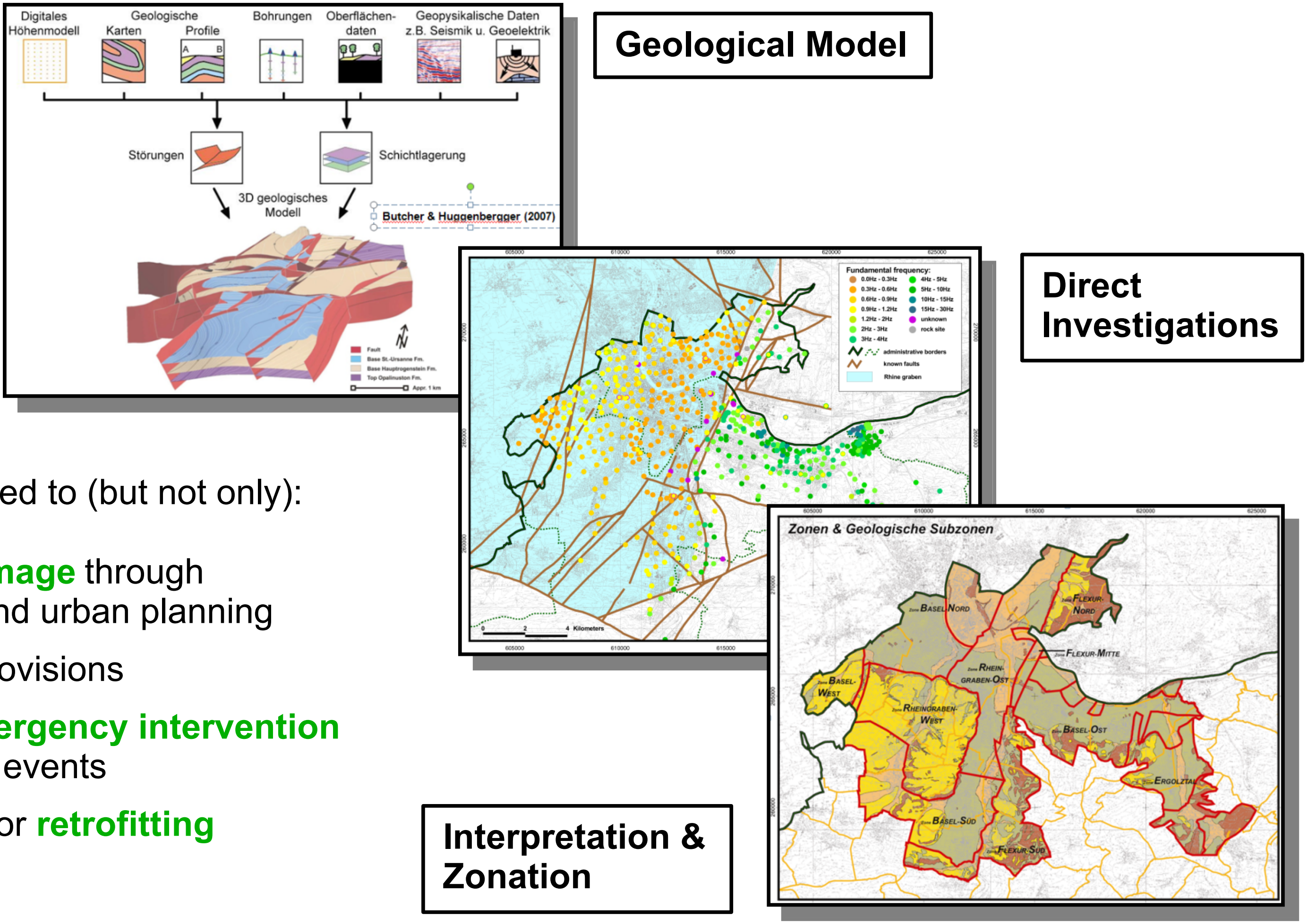


Seismic Microzonation and Site-Response Analysis

Microzonation is the **seismic hazard assessment at local scale**, accounting for both:

❶ the modification of the ground motion (amplitude, duration)

❷ earthquake induced phenomena



Geological Model

Direct Investigations

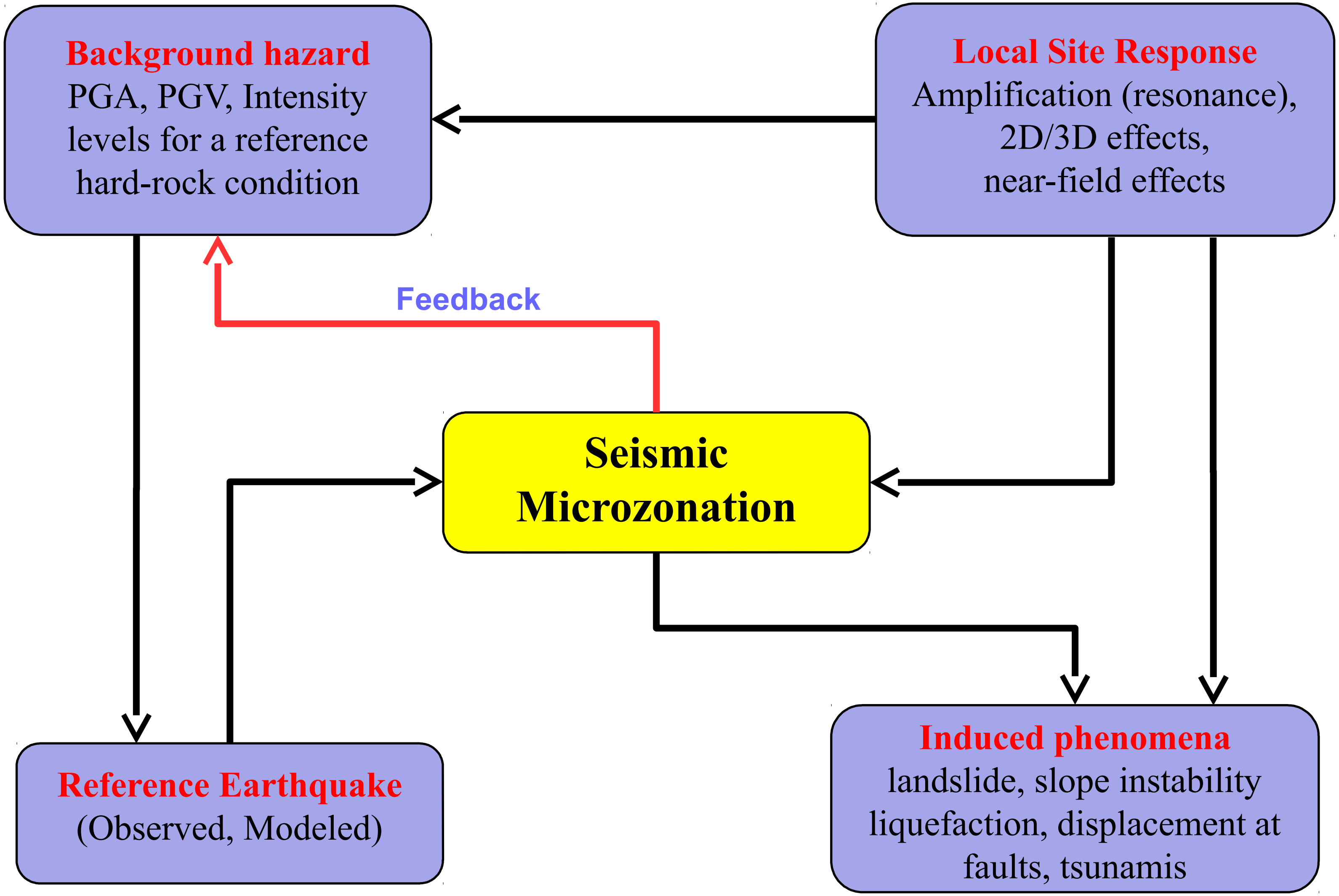
Interpretation & Zonation

Microzonation is aimed to (but not only):

- ✔ **Mitigation of damage** through preventive land and urban planning
- ✔ **Building code** provisions
- ✔ Assistance to **emergency intervention** after catastrophic events
- ✔ Setting priorities for **retrofitting**

Microzonation Workflow

Microzonation strongly depends on the **background regional seismic hazard**, and produces feedback for its computation (iterative refinement)



Background hazard
PGA, PGV, Intensity levels for a reference hard-rock condition

Local Site Response
Amplification (resonance), 2D/3D effects, near-field effects

Feedback

Seismic Microzonation

Reference Earthquake
(Observed, Modeled)

Induced phenomena
landslide, slope instability liquefaction, displacement at faults, tsunamis

Local Site Response

Local Effects influencing the Ground Motion

- Understanding the way local geological structures interact with the ground motion is the first step in site-response analysis
- Different phenomena can contribute to the complexity of the seismic response

❶ **Amplification phenomena** (seismic impedance contrast, resonance effect)

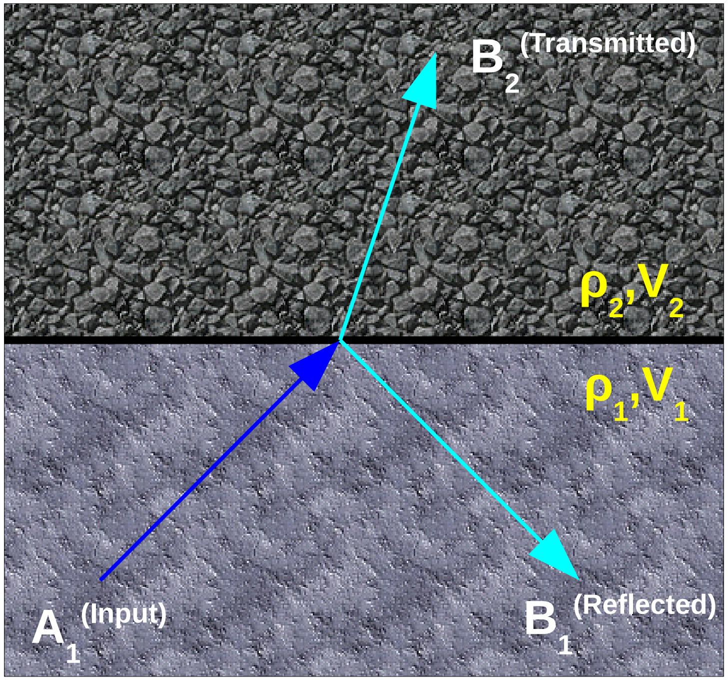
❷ **Geometrical effects** (2d/3d basin geometries, topography)

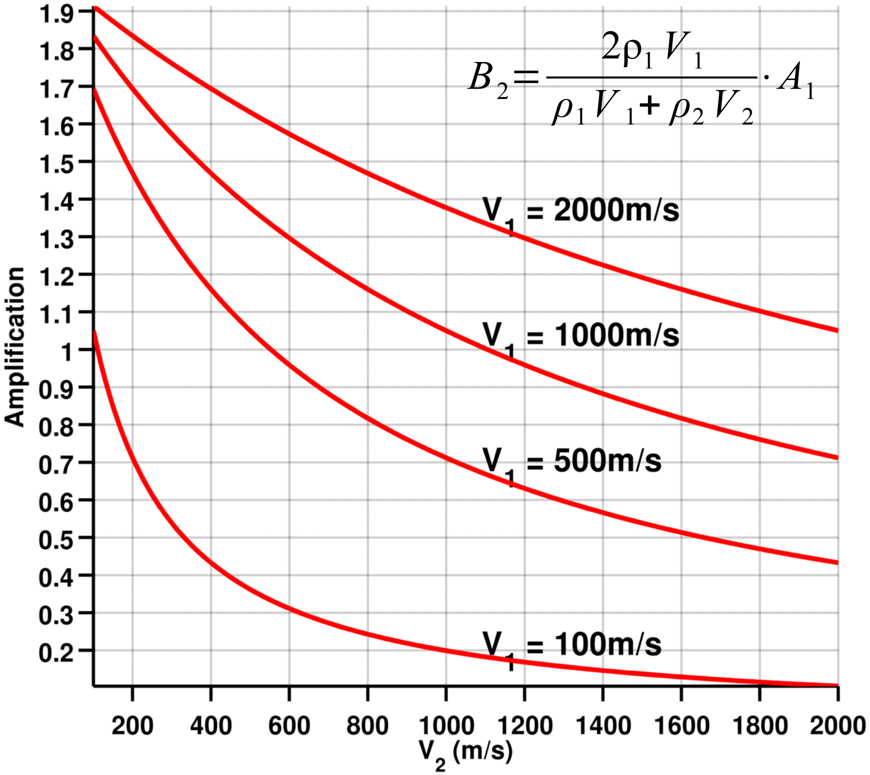
❸ **Soil non-elastic behavior** (anelasticity, scattering, non-linear response)

- Boundaries between these phenomena are overlapping; often one site-effect is controlled by the occurrence of others (e.g. 3d anelastic resonance....)
- Each phenomenon is controlled by a set of **specific ground parameters**, which can be quantified through the use of focused analysis (discussed later)

Seismic Velocity Contrast

Theory of linear elasticity shows that a wave propagating across an interface between two media of different ***seismic impedance*** (*the product of the seismic velocity and the density*) modifies its amplitude and speed to satisfy the conservation of energy principle

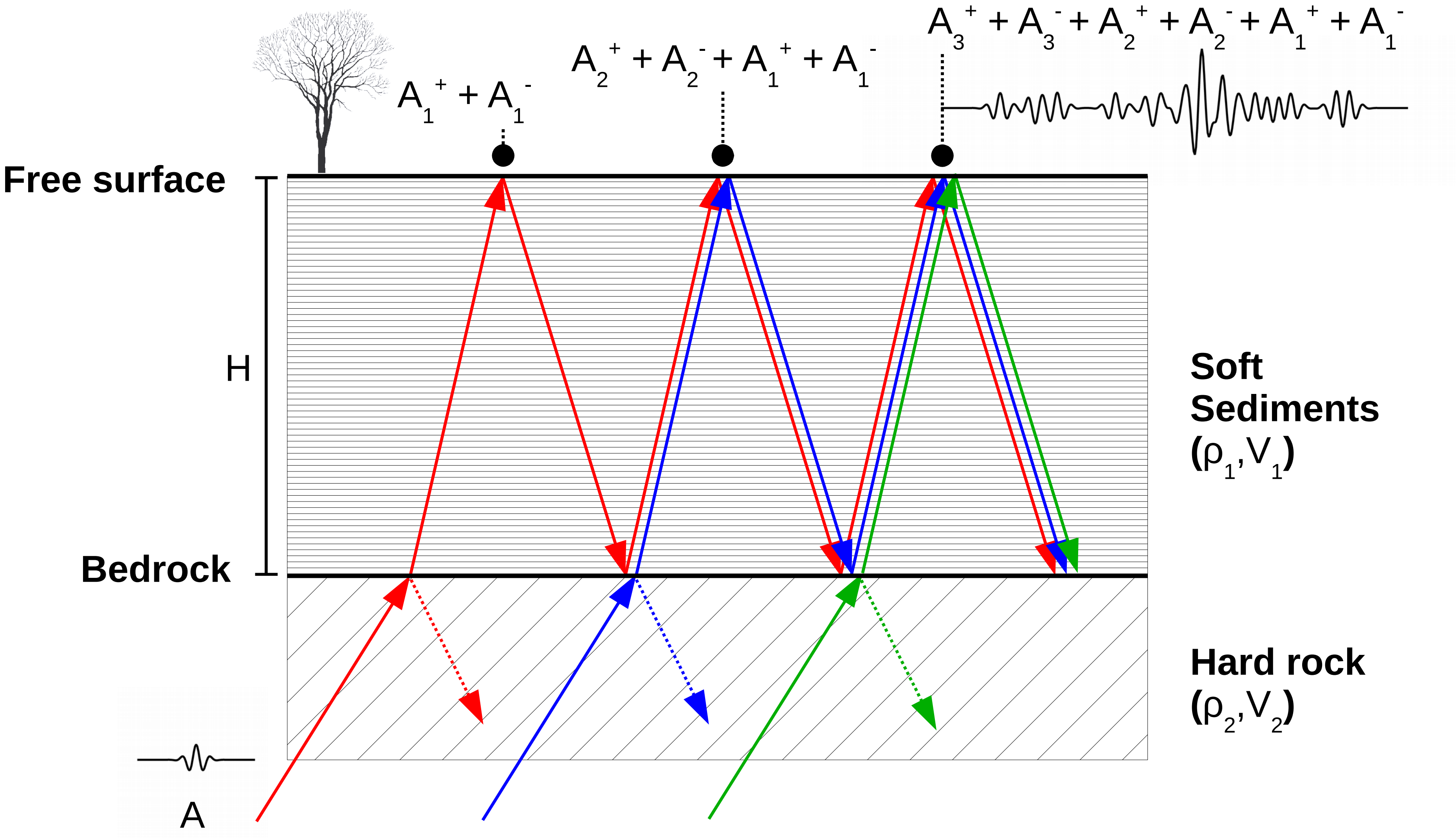




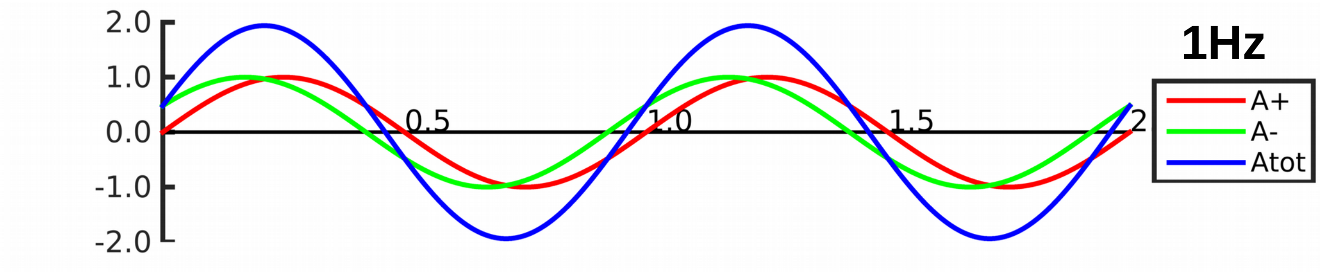
✎ In the case of a sedimentary valley with **soft sediments** (low-velocity) on top of **rigid bedrock** (high-velocity), amplification of the ground motion has to be expected

The resonance amplification

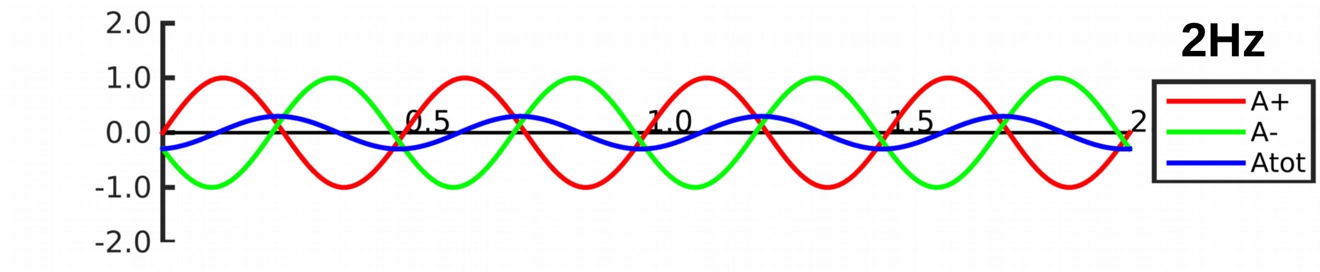
In soft sediment basins it is common a phenomenon of "***trapping***" of the wave-field, due to the multiple reflection and refraction of waves within the layers, which lead to a complex interaction called **seismic resonance**



Constructive Interference

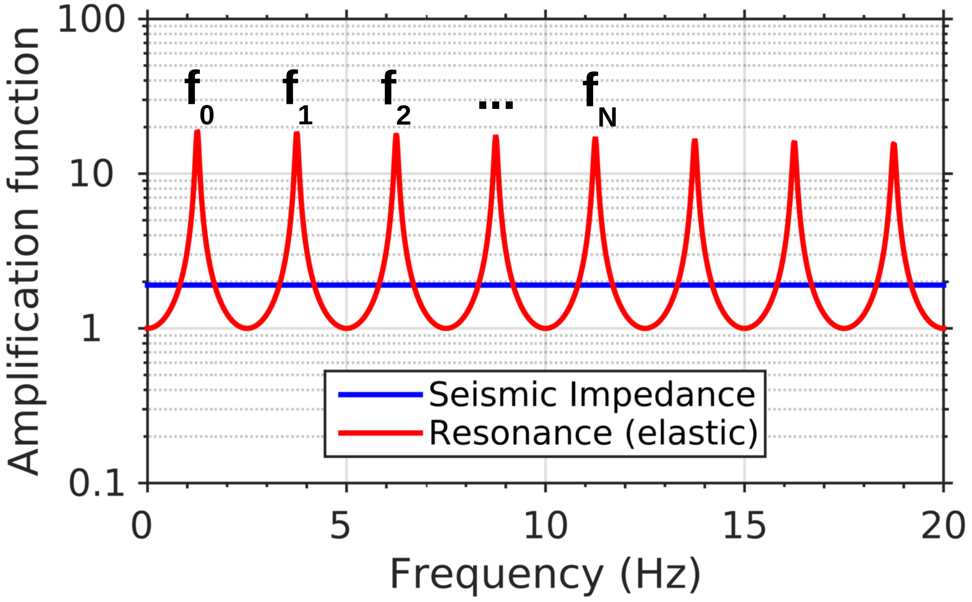


Destructive Interference



The phenomenon is **frequency dependent**, that means ground motion can either be **amplified** or **deamplified** at different frequencies....

The larger amplification is experienced at the **resonance frequencies** ($\mathbf{f_0}$, $\mathbf{f_1}$, **…** $\mathbf{f_n}$), controlled by the geometrical and mechanical properties of the soil

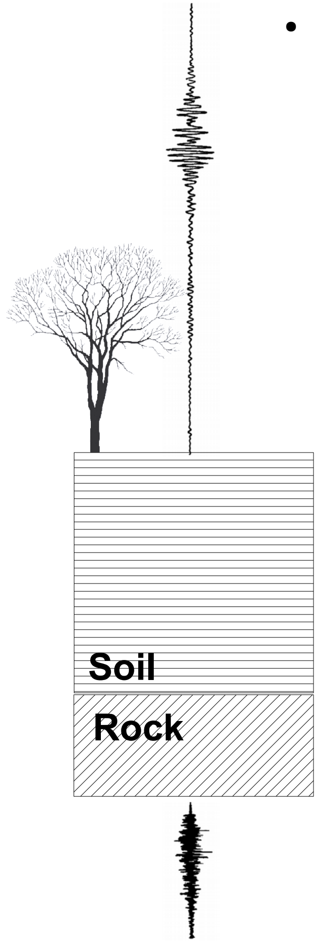


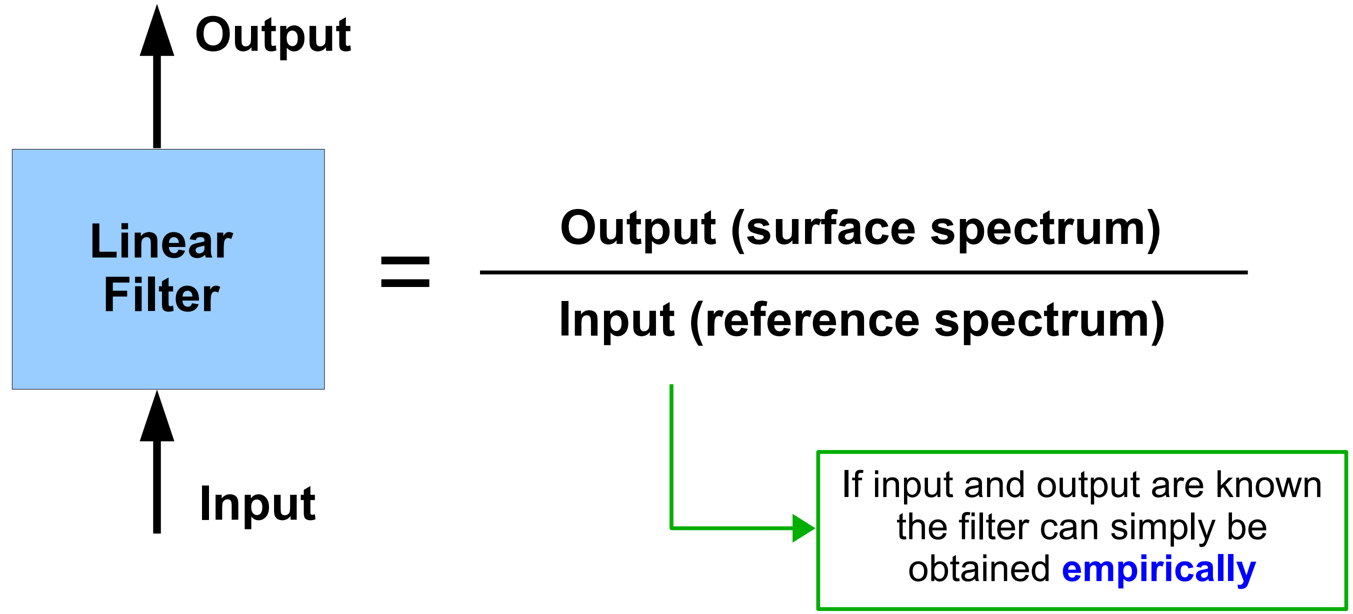
Linear Filter Equivalence

- For small strain levels the soil behaves as a **linear filter**
- Such **Filter** or **transfer function** can be obtained **deconvolving** the output signal (at the free surface) to the input signal (below the bedrock interface)
- Absolute value of the transfer function is the **amplification function**
- Two useful properties:

☞ In frequency domain, deconvolution is just a **spectral ratio**

☞ If input is a white spectrum (impulse), the output is equal to the filter itself!





Output

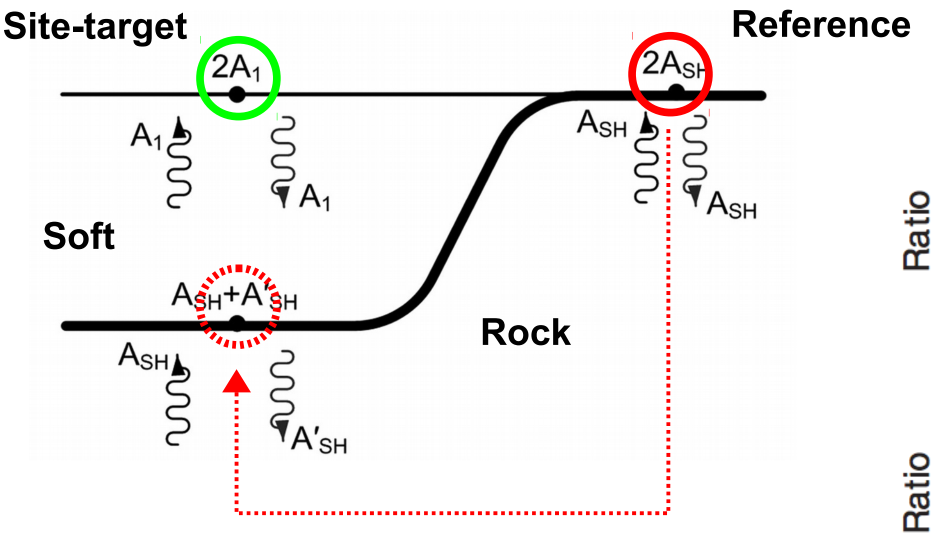
Linear Filter

Input

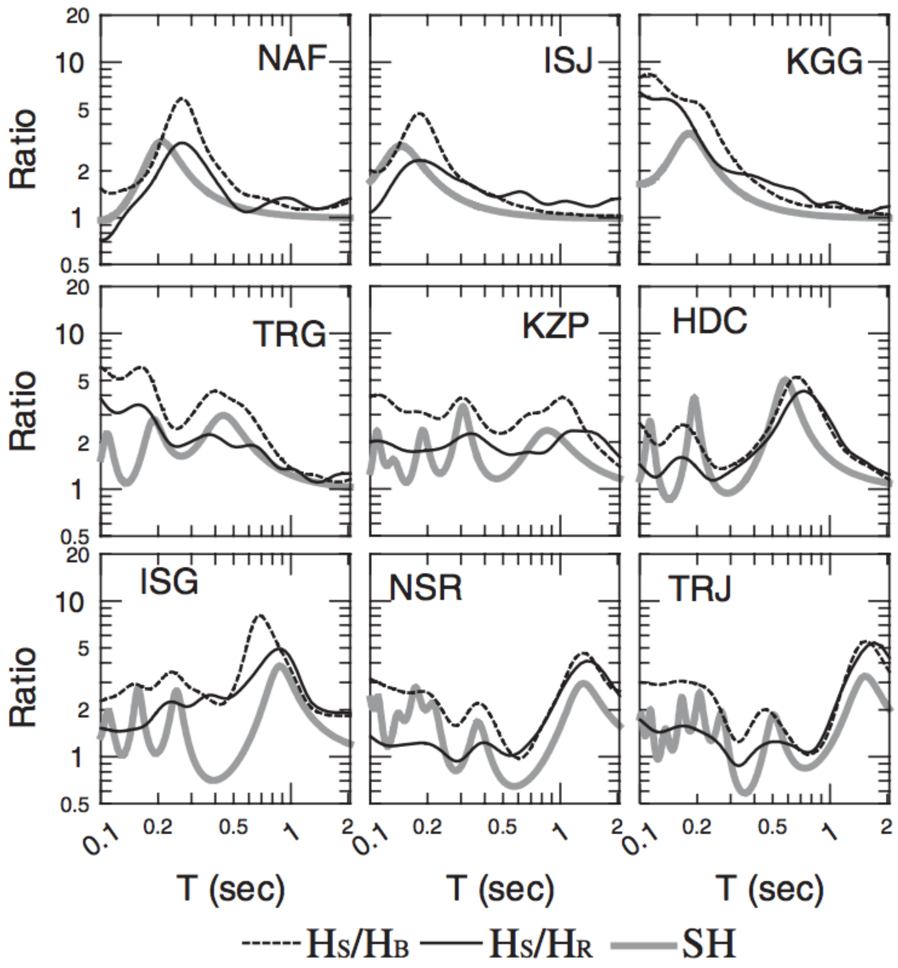
$$\text{Linear Filter} = \frac{\textbf{Output (surface spectrum)}}{\textbf{Input (reference spectrum)}}$$

If input and output are known the filter can simply be obtained **empirically**

Empirical Site-to-Reference Spectral Ratios



SSR amplification



Rodriguez& Midorikawa (2003)

- Also called **Standard Spectral Ratios** (SSR)
- The signal at the target site is **deconvolved** by the signal at a nearby rock station (**the reference**), which is assumed:

  ❶ free from site-effects (questionable...)

  ❷ similar to the motion at the bedrock (also questionable...)

Analytical SH-wave Transfer Function

If input is unknown (very often), the solution can be obtained **analytically** or **numerically**

In such cases, a sufficient knowledge of the soil properties is required

For example, by assuming:

- Plane waves with vertical incidence
- One-dimensional soil profile consisting in one layer over homogeneous half-space
- Perfectly elastic soil behavior

the soil amplification function A(f) can easily be calculated as:

$$A(f)=\left|\frac{1}{\cos\left(\frac{2\pi f H}{V_S}\right)+j\,I^c\sin\left(\frac{2\pi f H}{V_S}\right)}\right|$$

$$I^C=\frac{\rho_R\cdot V_R}{\rho_S\cdot V_S}$$

Impedance contrast

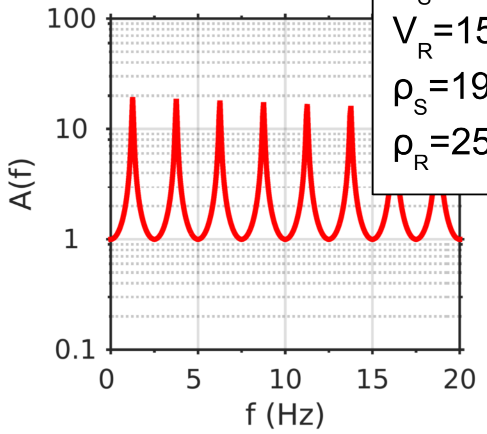
$$f_0=\frac{Vs}{4H}$$

Fundamental

$$f_n=(2n+1)*f_0$$

Overtones

H=20m
V_S=100m/s
V_R=1500m/s
ρ_S=1900Kg/m^3
ρ_R=2500Kg/m^3



Well, site response analysis seems to be relatively easy to perform....

True; however this is mostly because of the simplification introduced
by using **very simplified model assumptions**
(e.g. basin is single layer, one-dimensional, perfectly elastic materials....)

AND

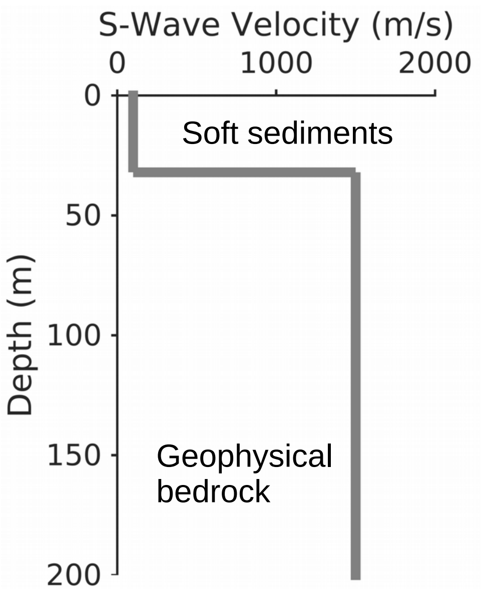
oversimplification often leads to increase in uncertainty of the solution,
the so called **epistemic uncertainty**

...

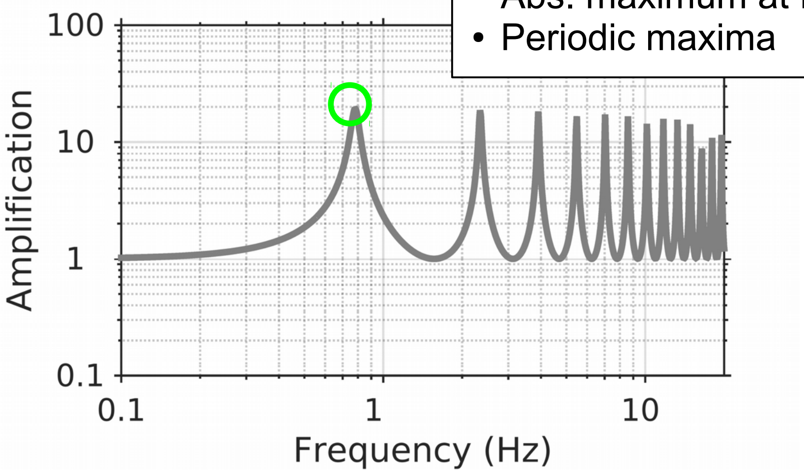
Obviously, things are getting more and more complicated when dealing with
real geological structures and **realistic velocity profiles**

Let's see few examples....

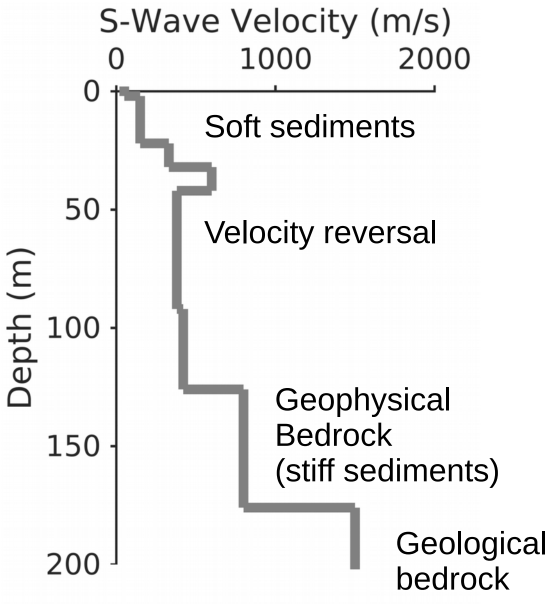
Using realistic velocity profiles



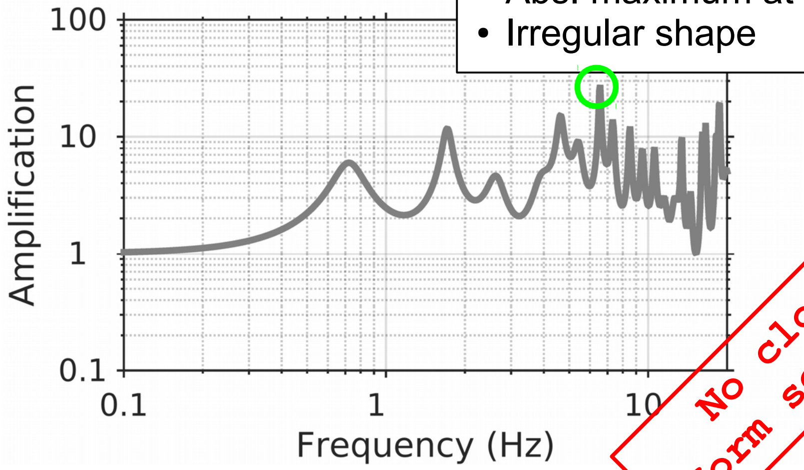
Simple case....



- Easy prediction
- Abs. maximum at f_0
- Periodic maxima



...reality

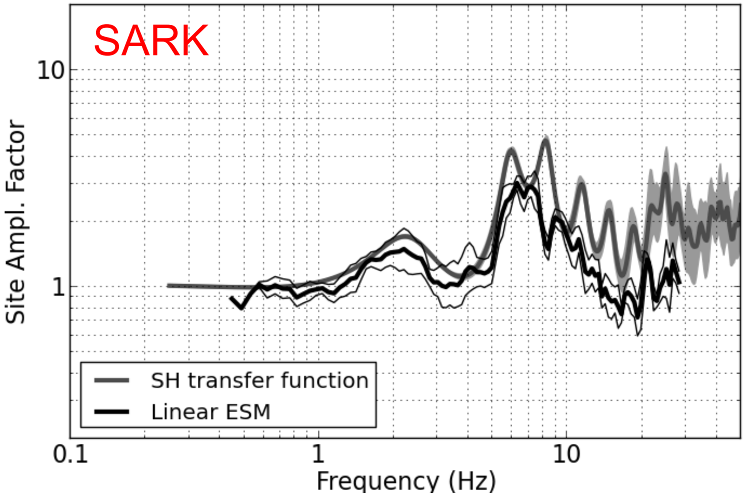


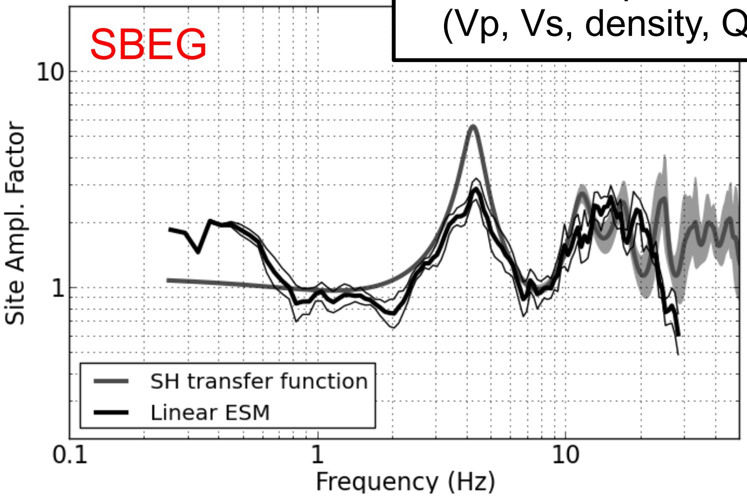
- More complex prediction
- Abs. maximum at f_n
- Irregular shape

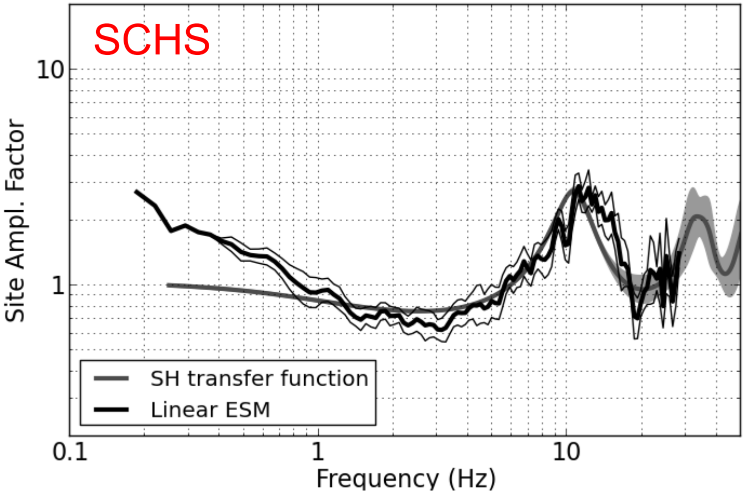
No closed form solution!

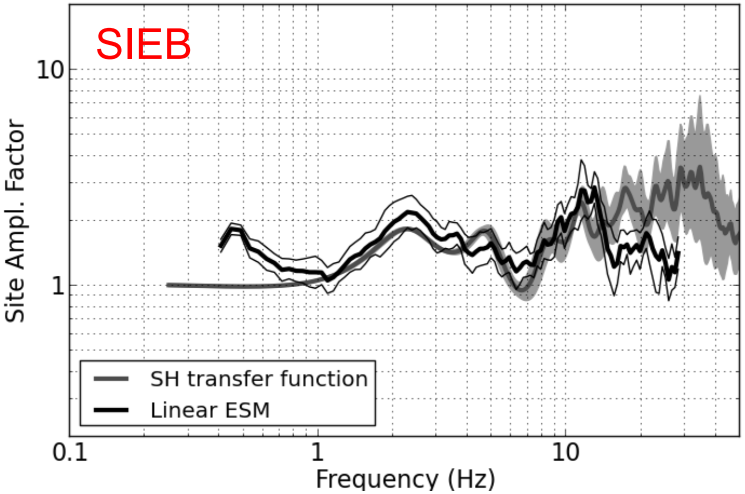
...nonetheless, good results can still be obtained with 1D modeling

Require accurate knowledge of soil parameters (Vp, Vs, density, Qp, Qs...)



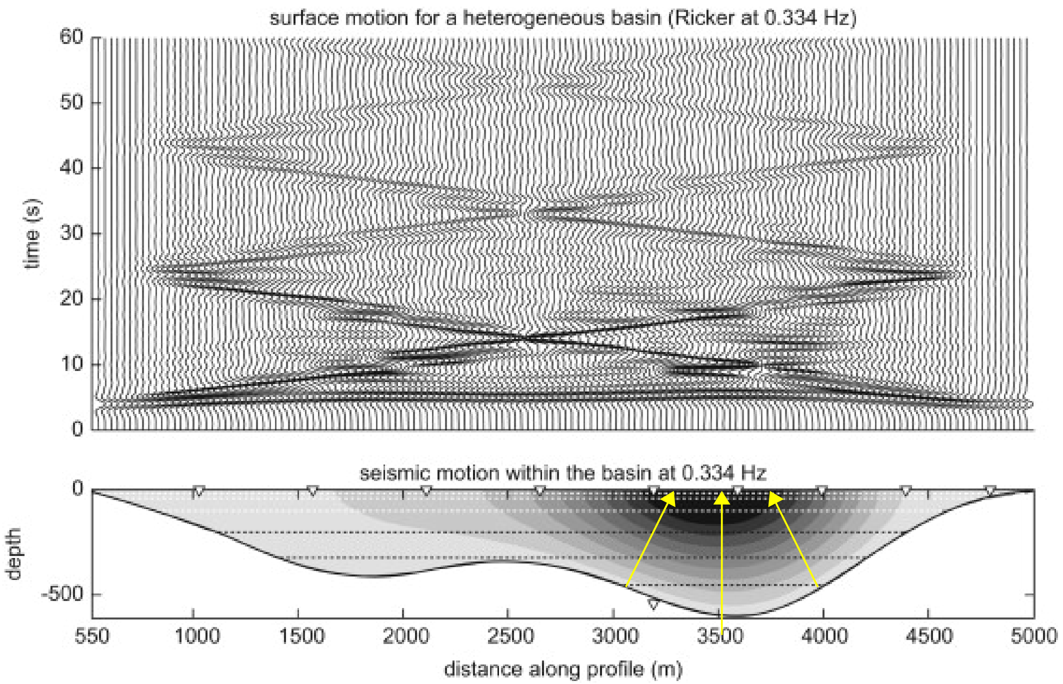






2D/3D basin effects

Sedimentary basins with complex **2D/3D geometry and topography** suffer the additional interaction of the structure with the earthquake wave-field

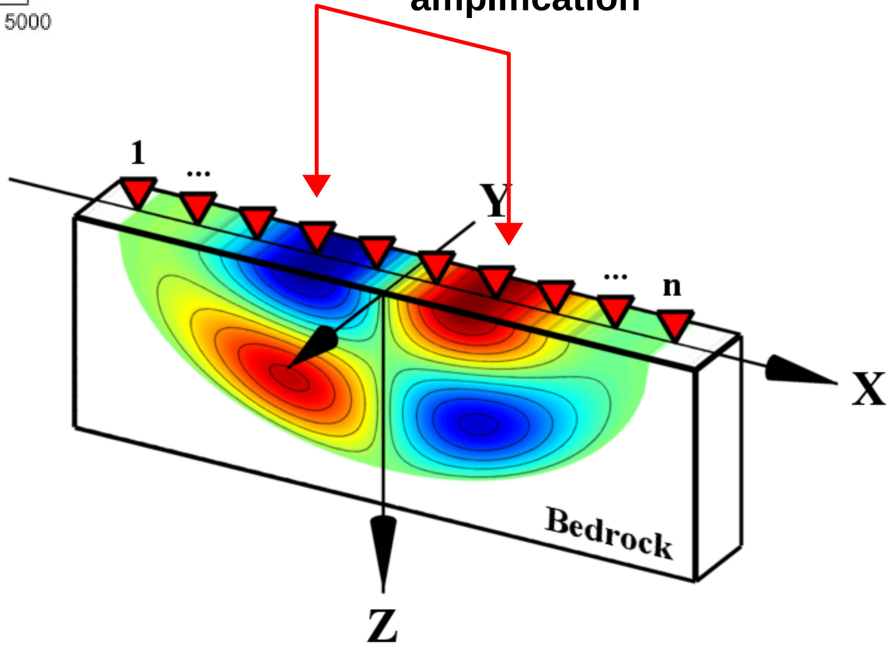


Delépinea and Semblat., SDEE, 2012

Site effects affecting the ground motion:

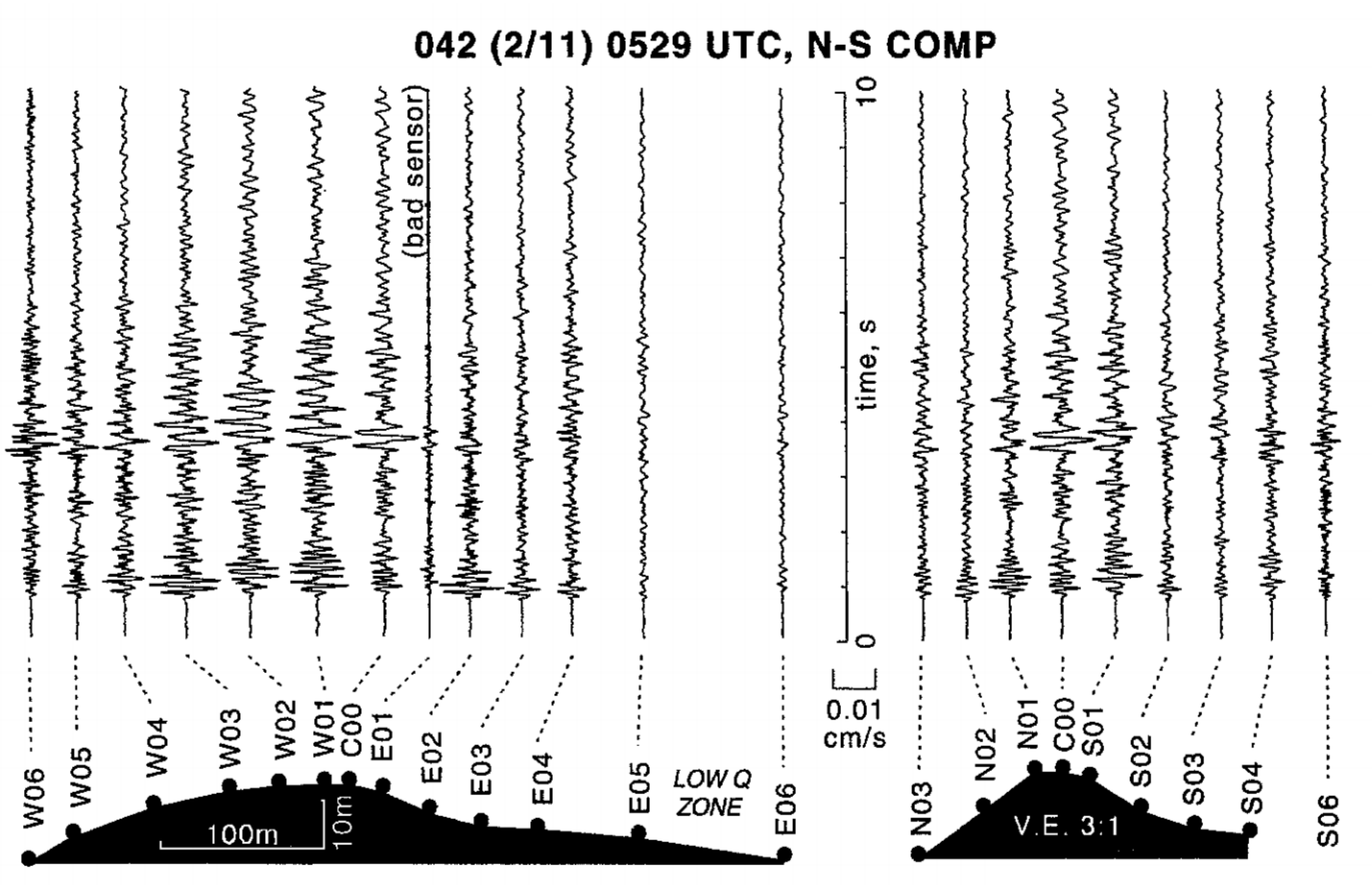
- Wave focusing and defocusing
- Wave diffraction and scattering
- **2D/3D resonance amplification**

Regions of larger amplification



2D/3D topographic effects

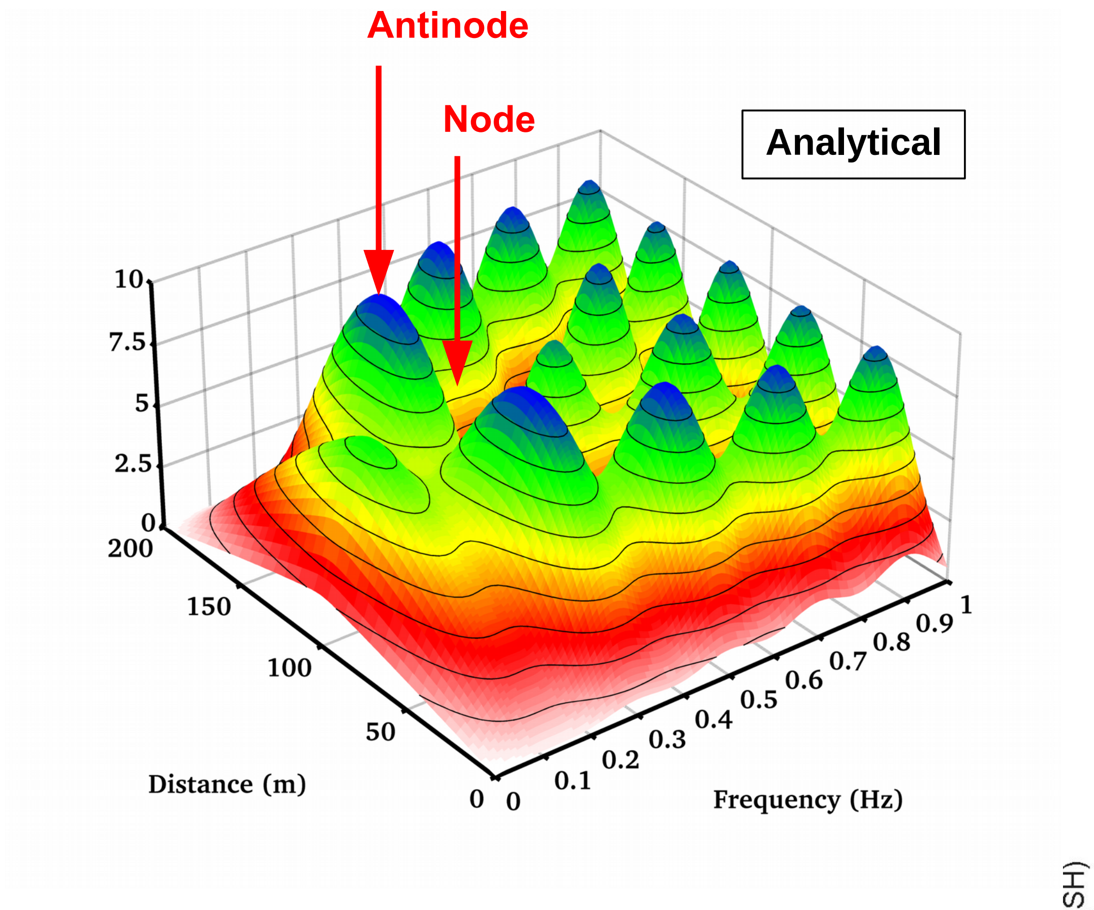
These are considered nowadays a **minor contribution** to the total amplification, but can still be relevant in combination with particular soil conditions (e.g. **weathering, fracturing**).



Spudich et al., BSSA, 1996

2D/3D resonance amplification

In the 2D/3D case, the resonance effect on the ground motion can be severe, but **well localized in delimited areas of the basin**



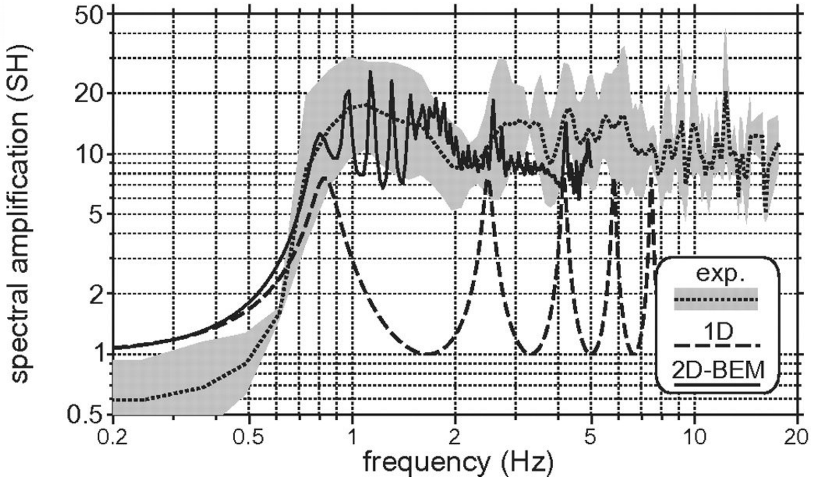
Analytical

Quantifying resonance amplification is not easy:

- ⇨ Analytical solutions (nearly) impossible
- ⇨ Numerical analysis very complex
- ⇨ Empirical estimation problematic....

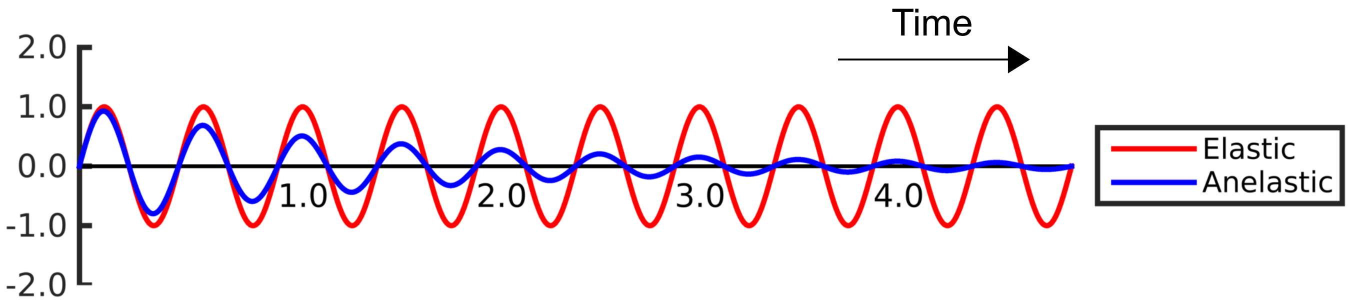
Empirical

Semblat and Bard., BSSA, 2008



Anelastic attenuation

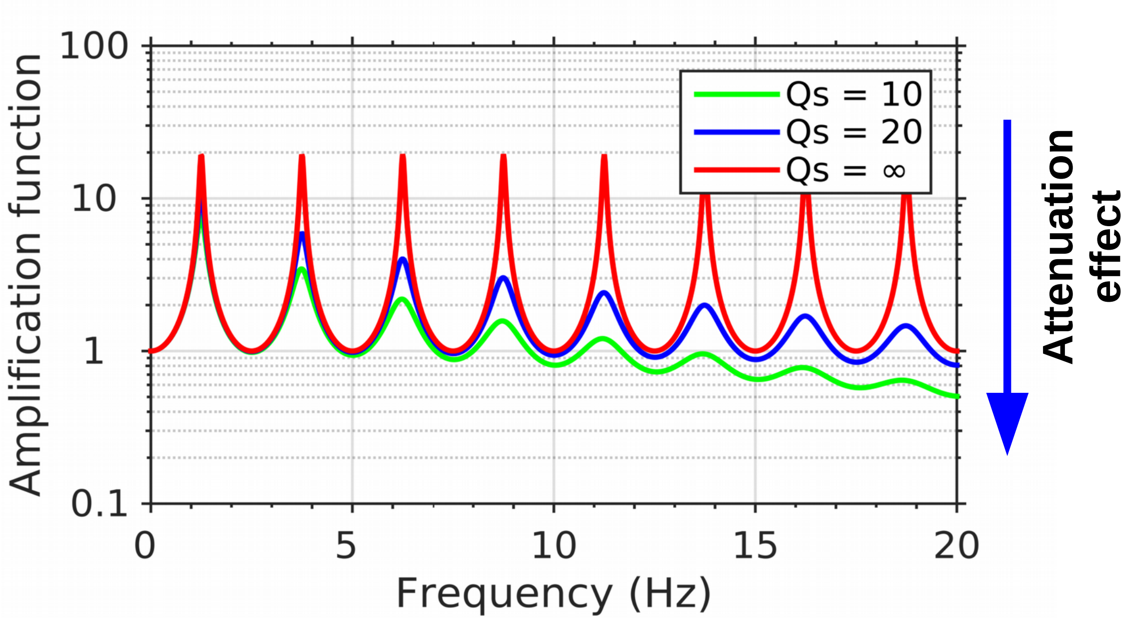
Anelastic (or intrinsic) attenuation is a property of the **visco-elastic materials**, where the energy of the propagating wave is dissipated by the effect of friction of the constituting elements (minerals, sedimentary grains, etc.)



$$A_{Att}(f) = |A(f)| \cdot e^{-\pi f \frac{H}{V_S Q_S}}$$

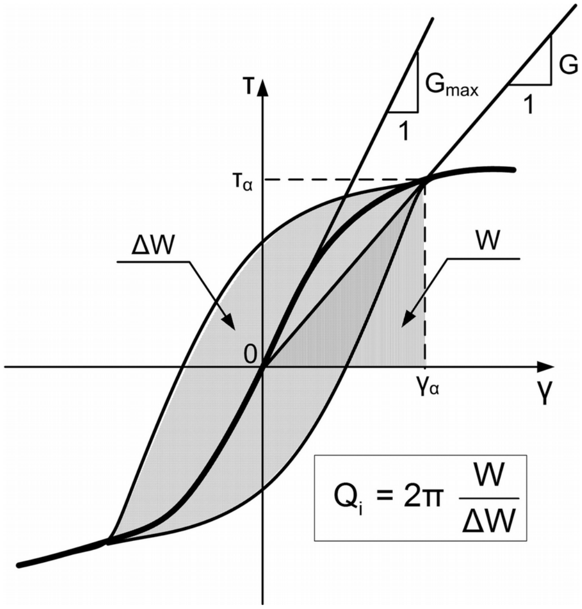
Anelastic attenuation has basically the effect of a **low pass filter**

Qs calibration not easy!



Non-linear soil behavior

As the excitation level increases during strong earthquakes, some loose soils start behaving following a **non-linear stress-strain relation**



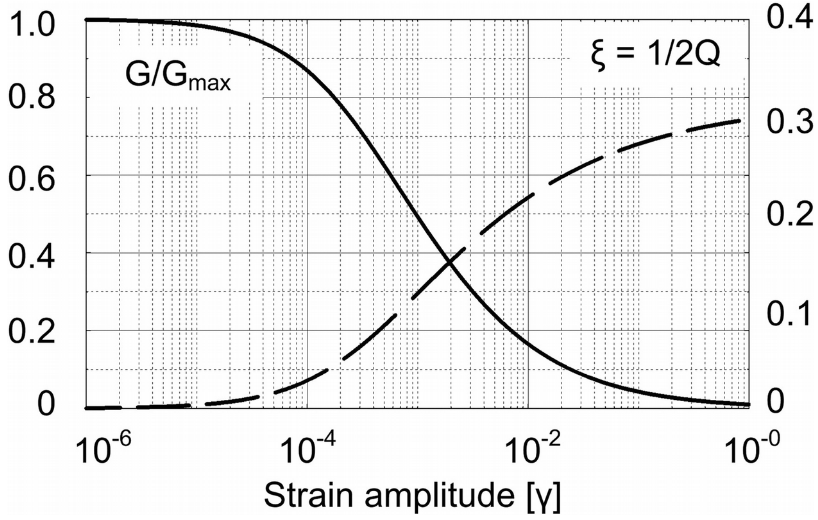
$$Q_i = 2\pi \frac{W}{\Delta W}$$

Non-linear soil response is characterized by simultaneous:

❶ **increase in damping** (attenuation)

❷ **reduction of the shear modulus** (and thus the seismic velocity)

Assimaki et al., BSSA, 2008



As a result, the signal amplitude is simultaneously:

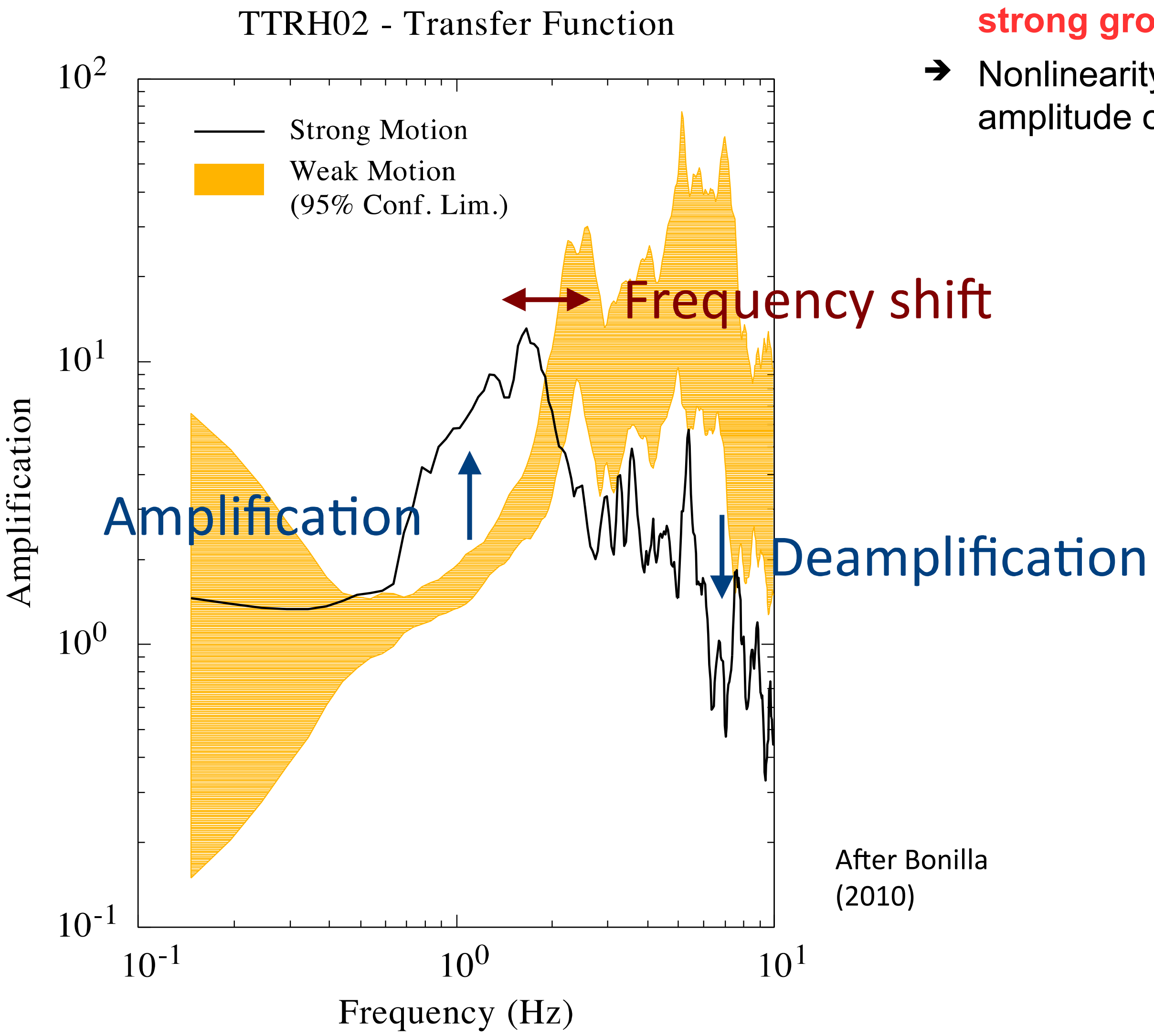
❶ **decreased** by attenuation

❷ **increased** by increase in velocity

Result depends on the intensity of the shaking, the signal duration...

The problem of soil non-linearity

- Soil can develop a nonlinear behaviour under **strong ground motions**
- Nonlinearity changes the shape and amplitude of the **soil transfer function**

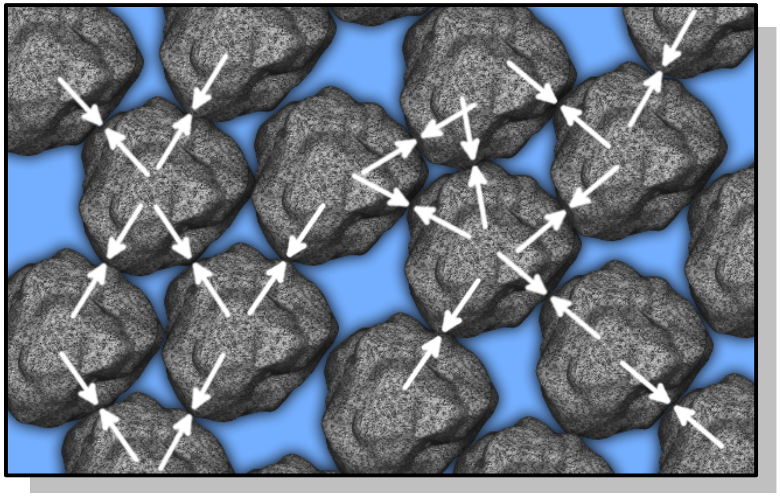


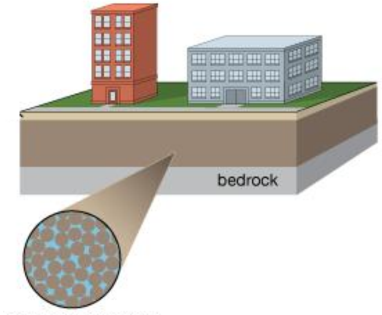
After Bonilla (2010)

Soil Liquefaction

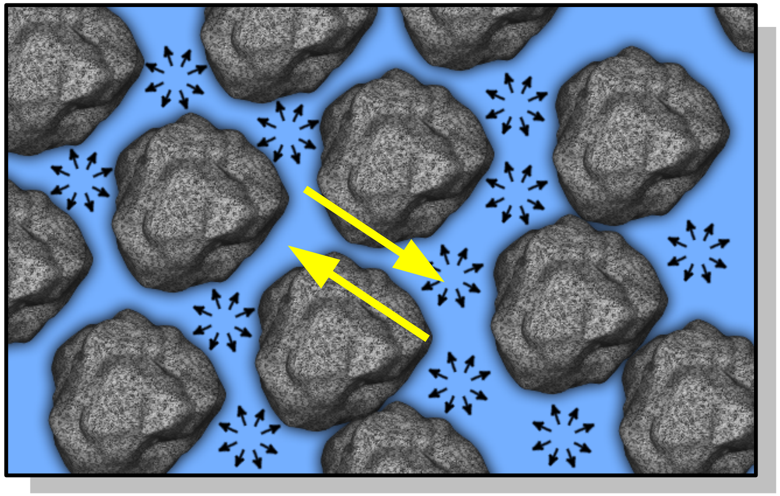
- Liquefaction occurs in porous, water-saturated soils when the **shear strength** of the sediment is reduced by a temporary increase in **water pressure** induced by the stress-field of the earthquake
- Important for lifelines (gas, water, electricity), sewage system, earth dams, rail , roads, landfill areas (harbors), …

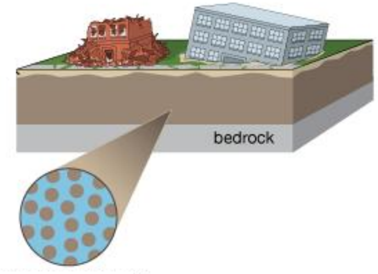
Static conditions





! Under dynamic loading !





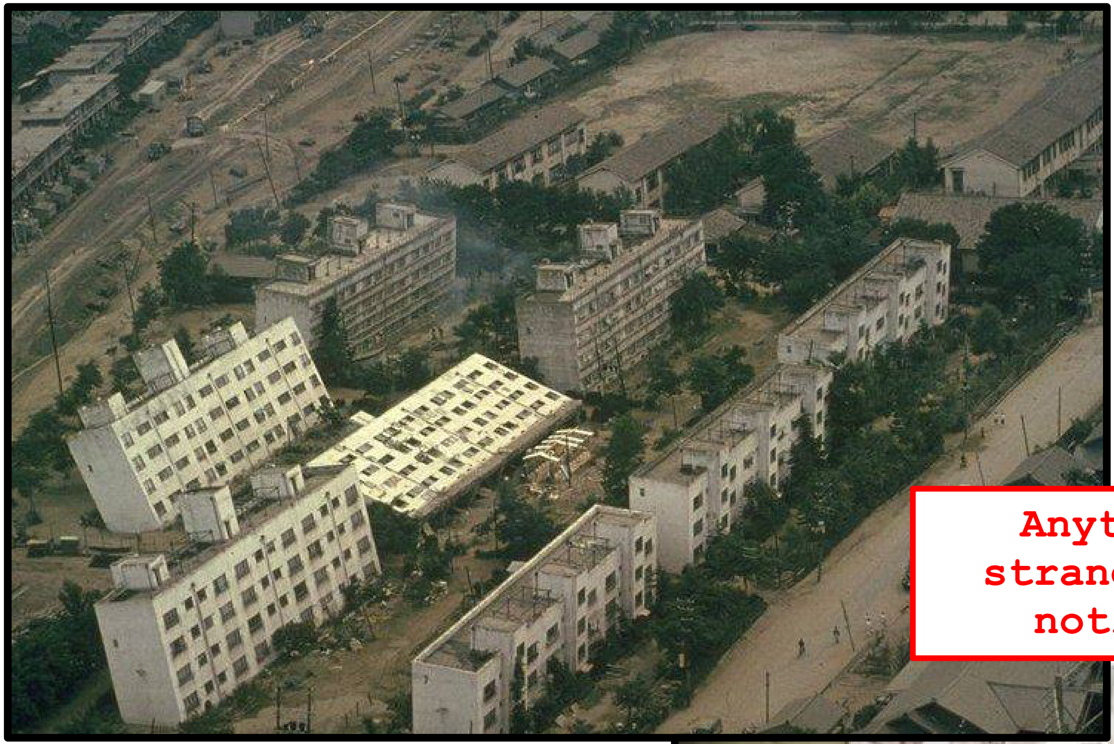
Soil Liquefaction

Some example of the effects at local scale….

Kobe, Japan 1995
Mw 6.9

Emilia, Italy
2012
Mw 6.1

Christchurch, New Zealand 2010
Mw 7.1



Niigata, Japan 1964

Mw 7.5~7.6

Anything strange you notice?

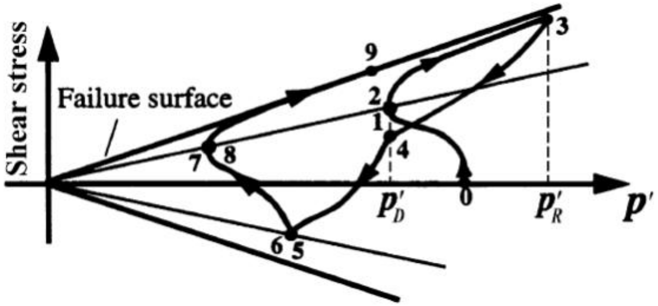
Izmit, Turkey 1999

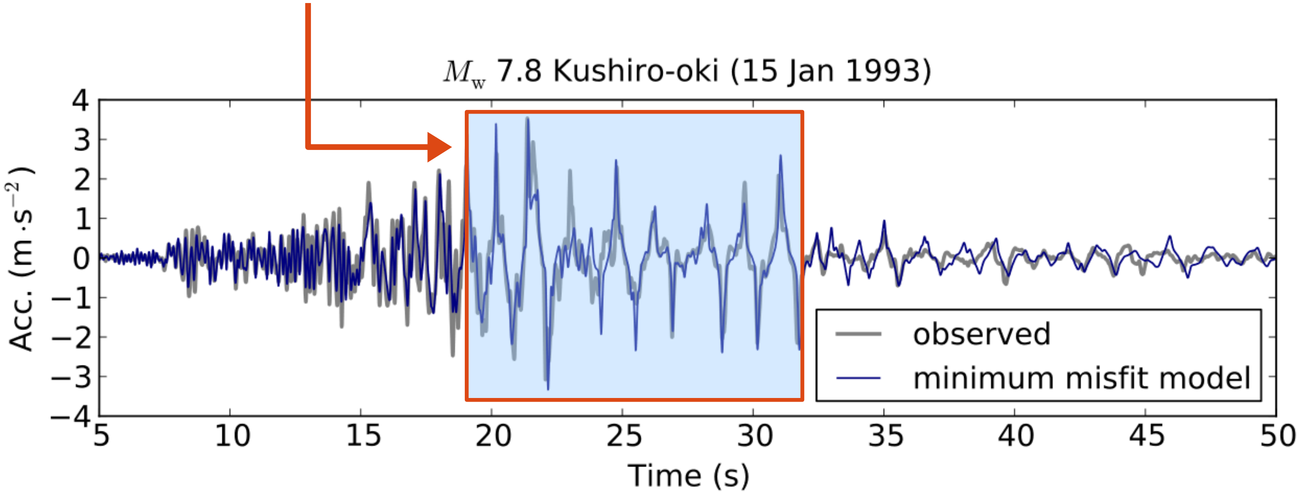
Mw 7.6

Cyclic Mobility

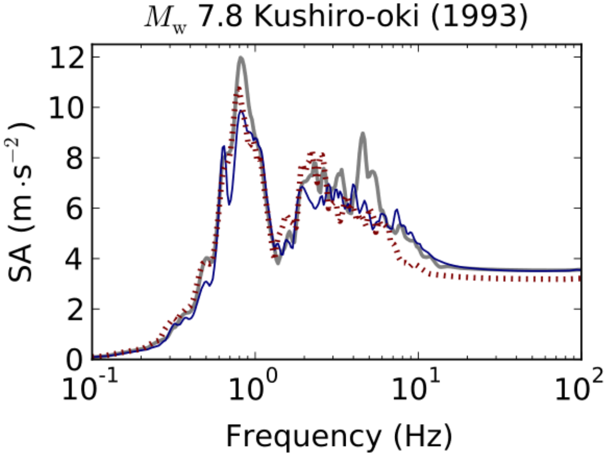
- It occurs in dense, cohesionless saturated soils when **cyclic loading-unloading** is applied
- The material experiences several cycles of **softening** (decrease in shear resistance) and **stiffening**
- Soil failure may occur after several cycles of loading
- Earthquake signal can heavily be altered by development of **large high-frequency pulses in acceleration**

Complex stress path!





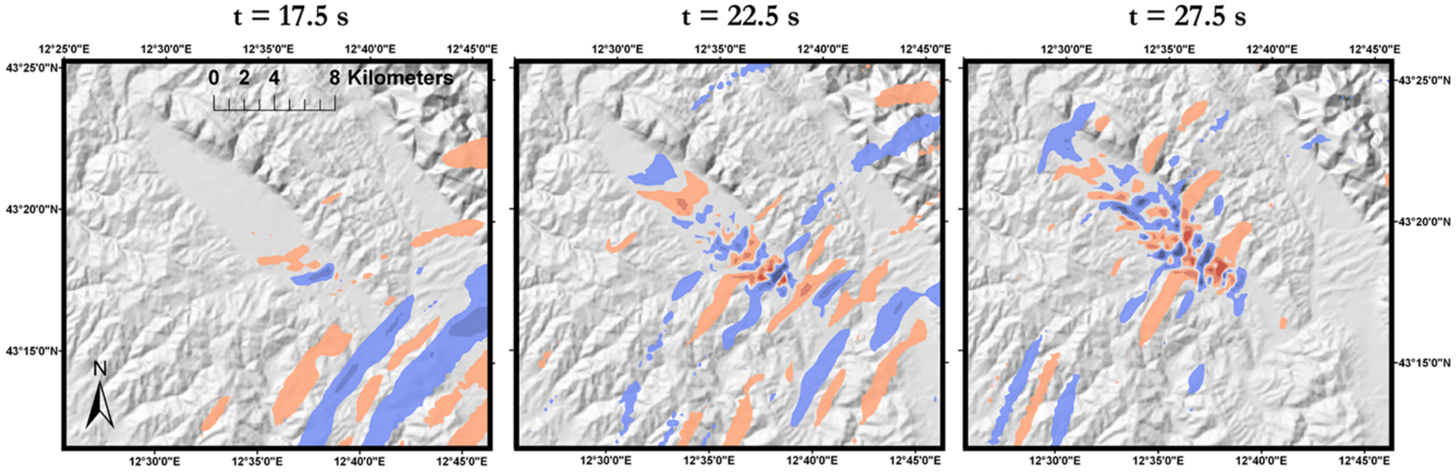
Very difficult to model!



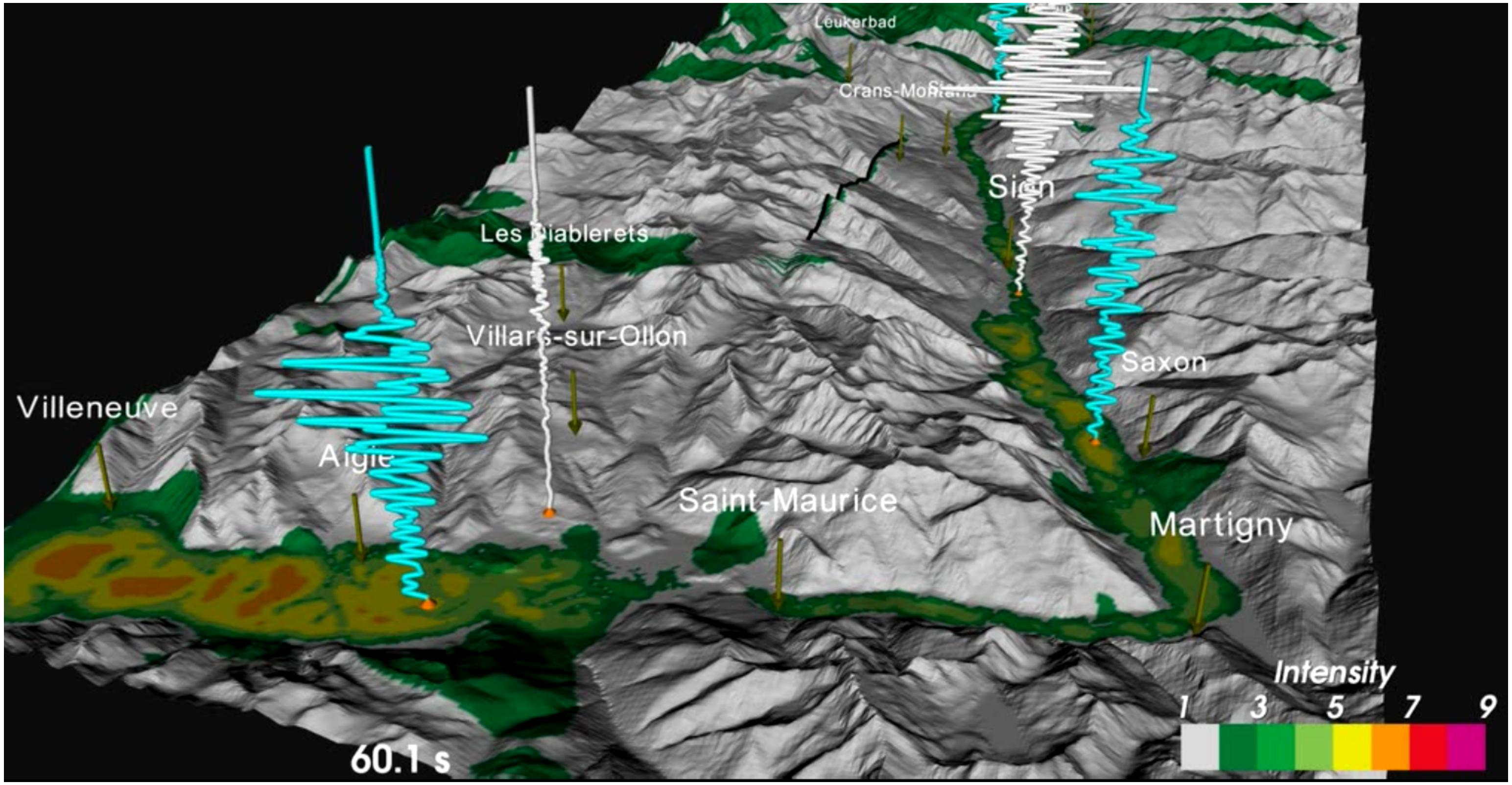
Indirect modeling methods

- When the complexity of the model and of the phenomena to simulate is too large, analytical methods are not feasible anymore
- Complex wave-field modeling is nowadays done though the use of highly sophisticated numerical techniques
- Quality of the solution depends on many factors:
  - ✰ Assumptions and approximation of **simulated the physical laws**
  - ✰ Assumptions and approximation / available knowledge of the **model parameters**
  - ✰ **Computation costs** (large simulations might require days on computer clusters)

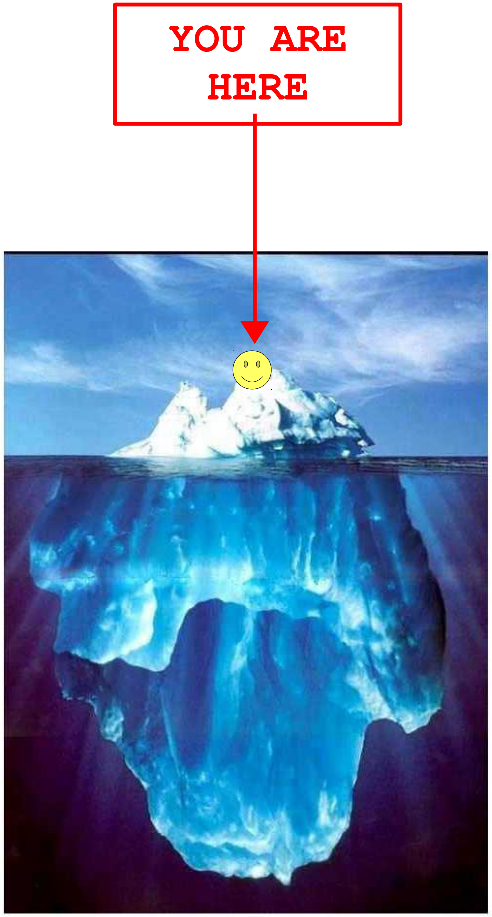
Gubbio basin (M=6)



Paolucci & Smerzini, esg4, 2012



Time to watch a movie...



Some concluding remarks

- What you just learned is only *the tip of the iceberg...*
- Many other phenomena are relevant at local scale and a variety of analysis techniques available
- Seismic response analysis can be very complex (and very useful) if properly done

Nonetheless....

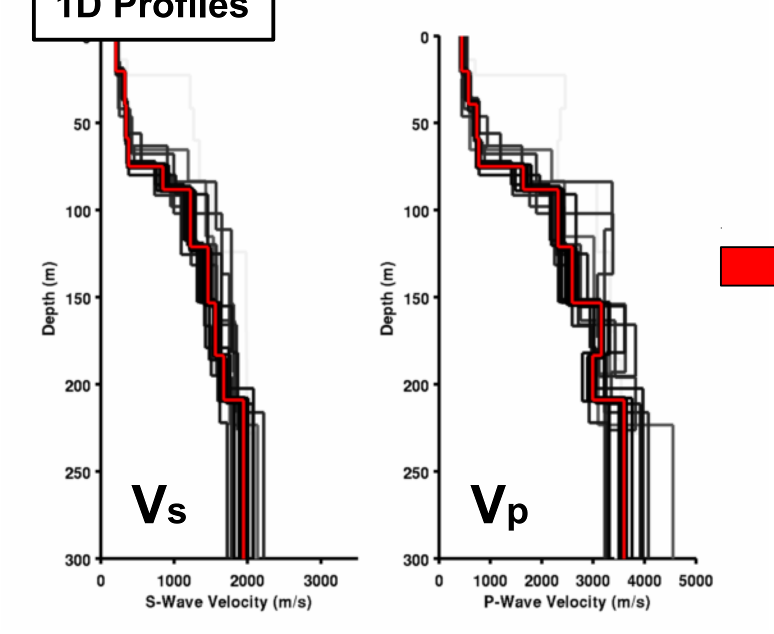
- Local response is often neglected or analyzed too simplistically
- **Why?** Basics are not well-understood by practitioners (and in some cases also by scholars)
- As result, many present studies are affected by considerable uncertainty, which then propagates into other studies......

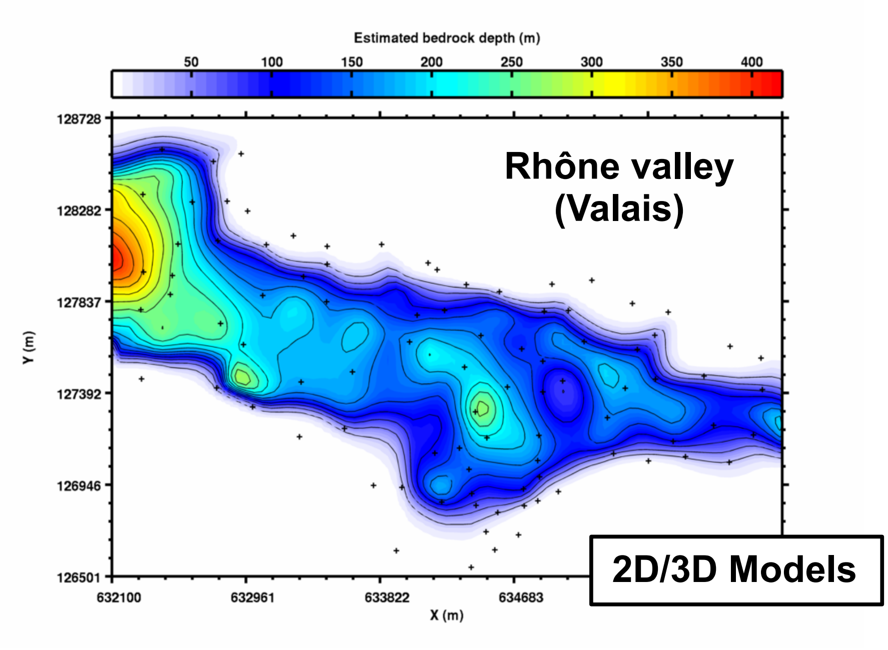
Site Characterization Techniques

Ground Parameter Overview

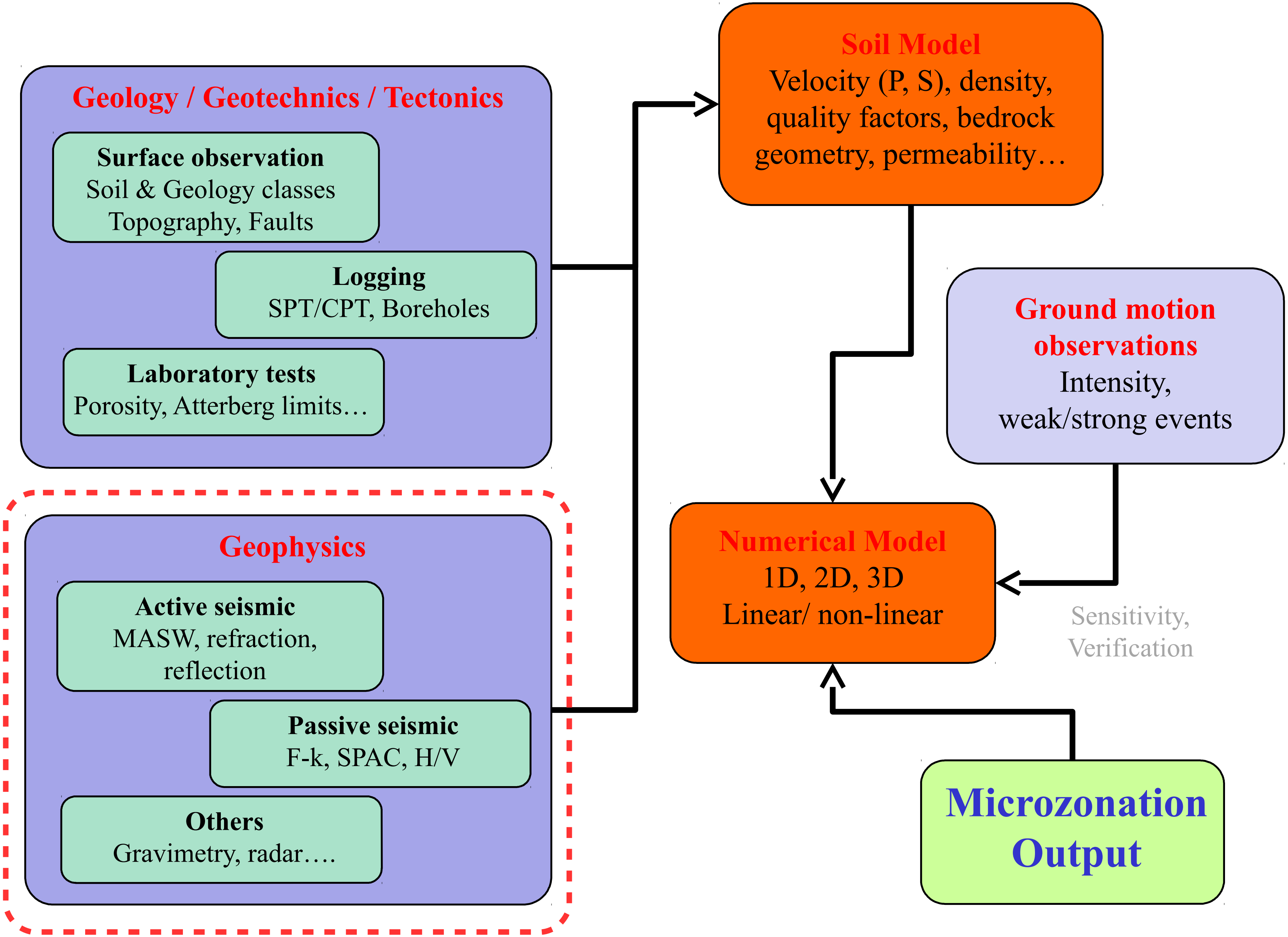
- The most relevant parameters to characterize the soil behavior are the **seismic velocity of body waves** (Vp and Vs), the **density** (ρ) and the **attenuation factors** (Qp and Qs)
- The way these parameters are geometrically distributed controls the modification of ground-motion during an earthquake
- **Shear wave velocity**, in particular, is the most important property in engineering applications
- A sufficient knowledge of these parameters is essential for any **interpretation of recorded earthquake ground motion**

1D Profiles





2D/3D Models



Geology / Geotechnics / Tectonics

Surface observation
Soil & Geology classes
Topography, Faults

Logging
SPT/CPT, Boreholes

Laboratory tests
Porosity, Atterberg limits…

Geophysics

Active seismic
MASW, refraction,
reflection

Passive seismic
F-k, SPAC, H/V

Others
Gravimetry, radar….

Soil Model
Velocity (P, S), density,
quality factors, bedrock
geometry, permeability…

Ground motion observations
Intensity,
weak/strong events

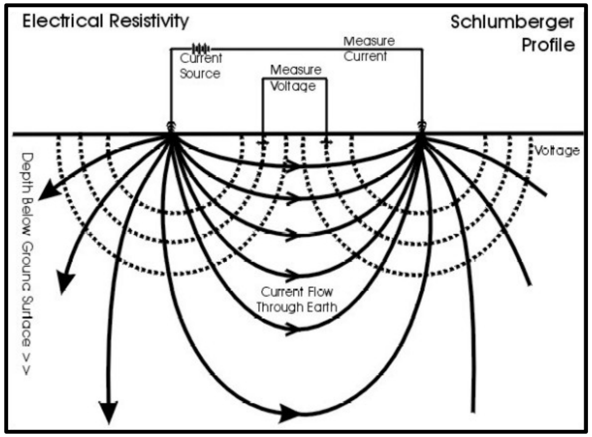
Numerical Model
1D, 2D, 3D
Linear/ non-linear

Sensitivity,
Verification

Microzonation Output

Indirect (geophysical) investigations

Indirect investigation techniques (or **geophysical methods**) use the properties of the **physical fields** (electric, magnetic, gravity, seismic) to infer information on the soil structure remotely (water table, bedrock depth)



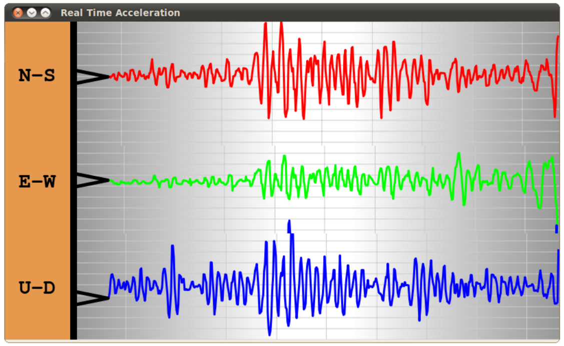
(http://www.earthdyn.com)

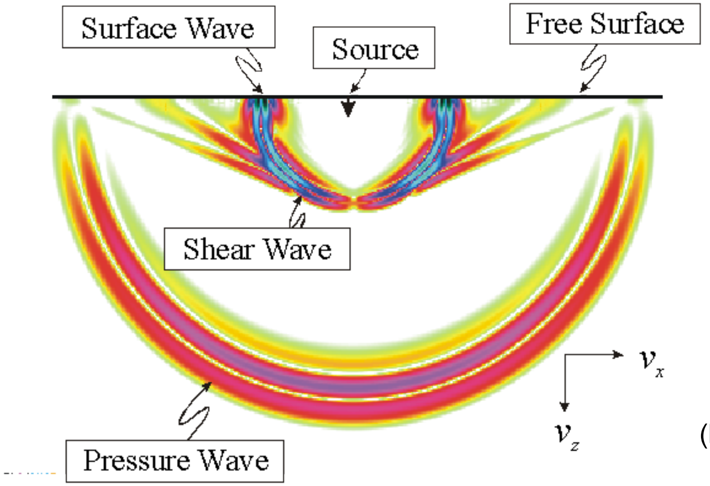
Static-field methods:

- Electrical methods (resistivity, self-potential)
- Magnetic method (magnetic susceptibility)
- Gravimetric method

Wave-field methods:

- Electromagnetic methods (radar)
- Seismic methods (active and passive)





(http://acoustics.org/)

Active seismic methods

→ Make use of an **artificial sources** to generate a seismic signal
→ Two major categories: the **travel-time** and **surface wave methods**
→ The receivers can be located at the surface or in boreholes

Advantages:

- Good signal quality in noisy environments
- Good resolution on the velocity profile

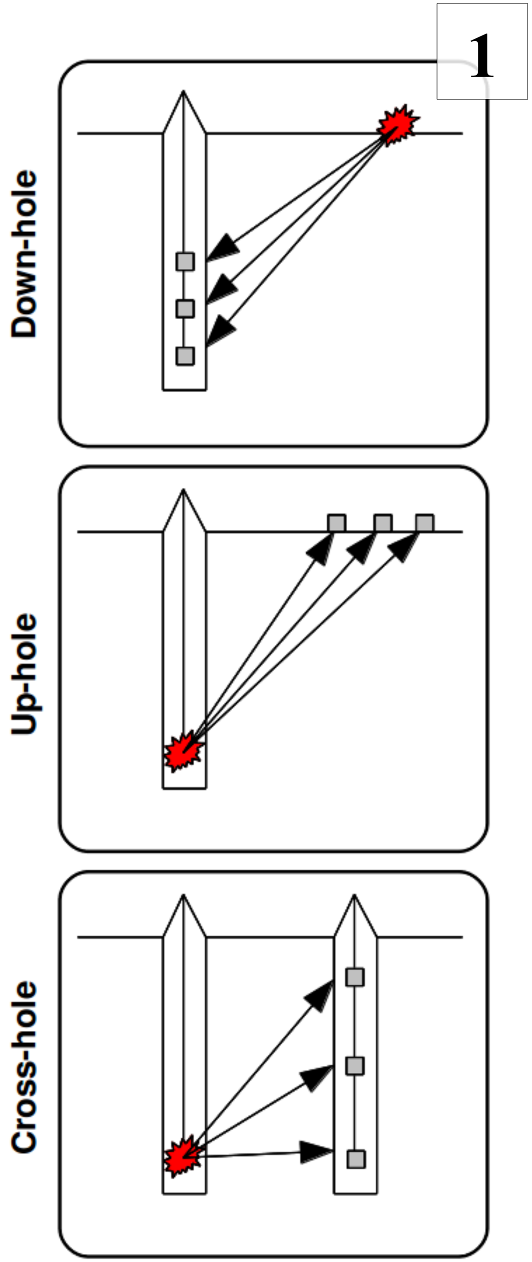
Disadvantages:

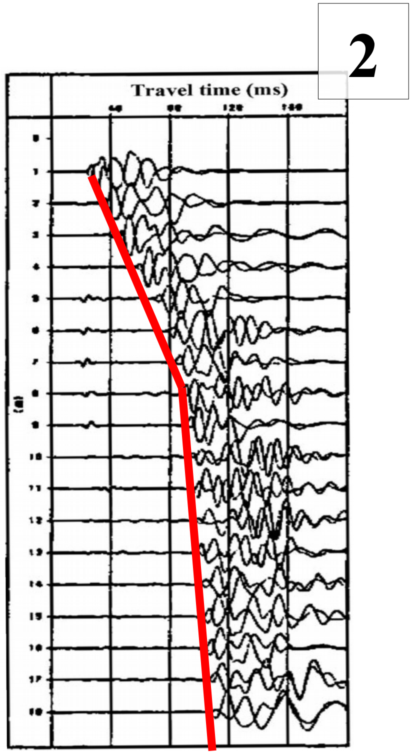
- Scarce penetration depth with conventional sources (e.g. hammer, minigun)
- Relatively high costs of implementation
- They can hardly be used in urban environment

(http://www.earth.ox.ac.uk)

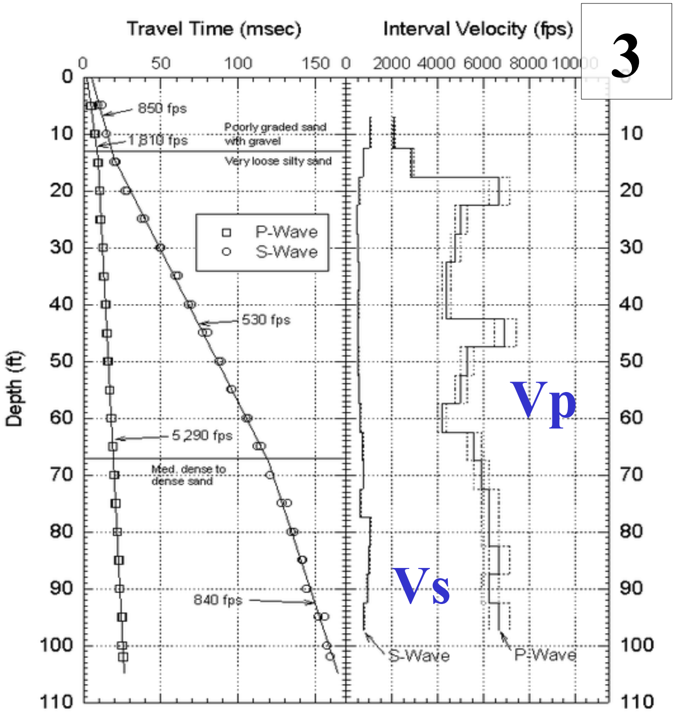
Borehole seismic

(Travel-time analysis)





Takahashi et al. IJRMMS. 2006



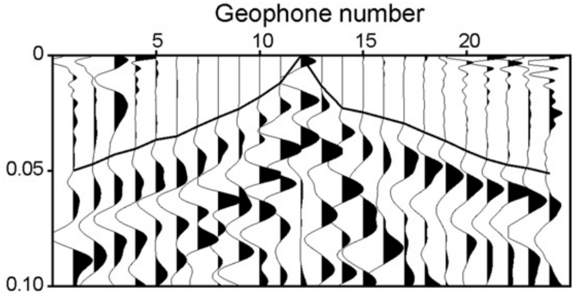
Typical results from downhole seismic survey

(http://www.earthdyn.com)

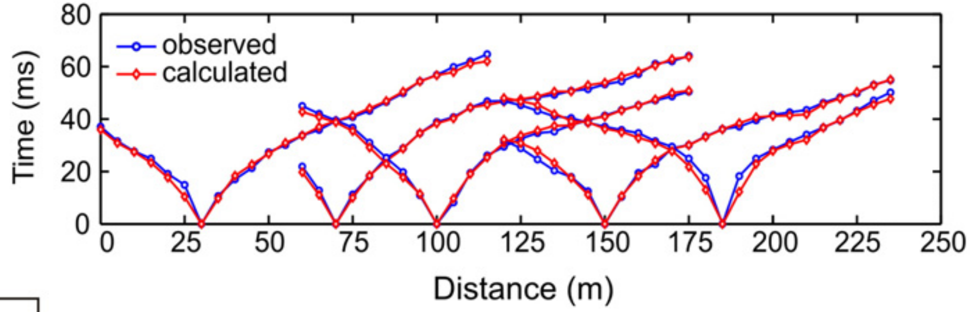
Seismic refraction analysis

(travel-time tomography)

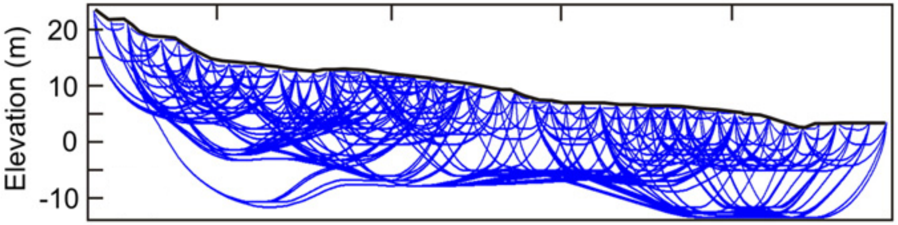
Acquisition



Travel time analysis

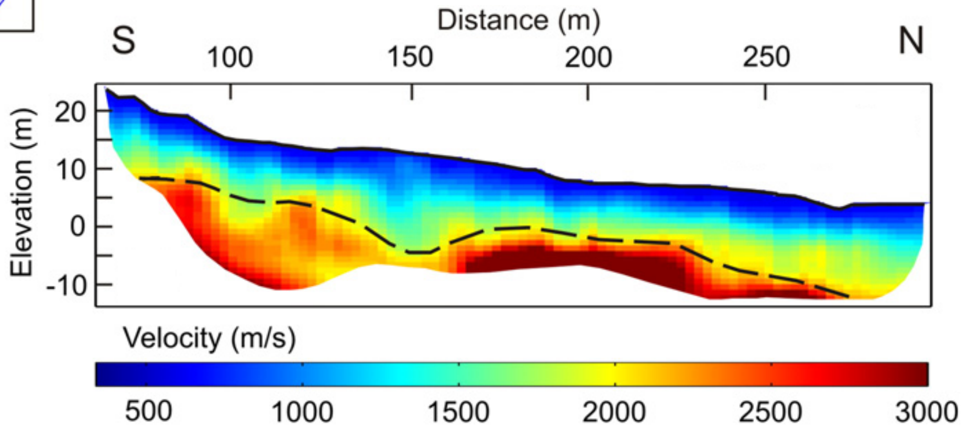


Ray-path modeling



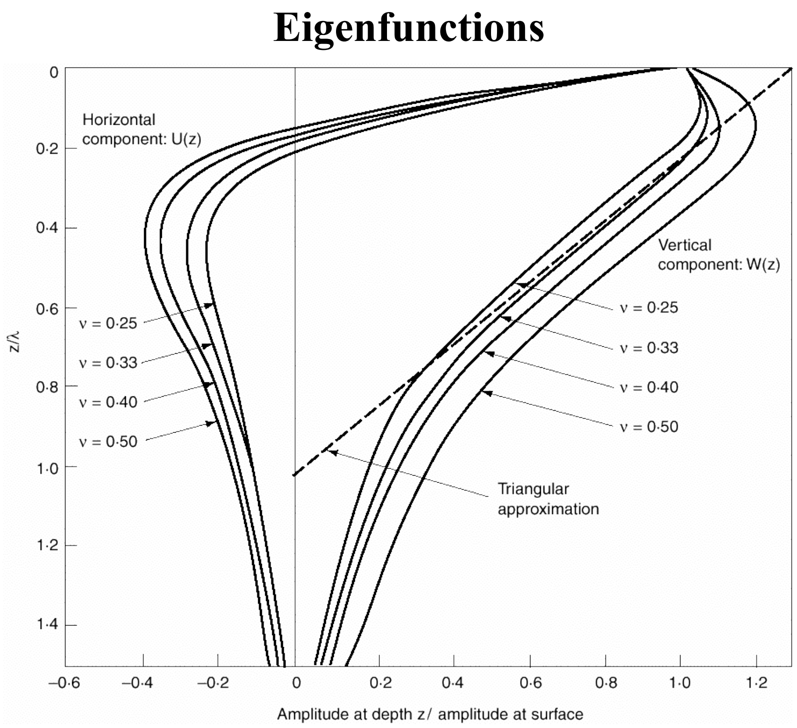
Göktürkler et al., JAG, 2008

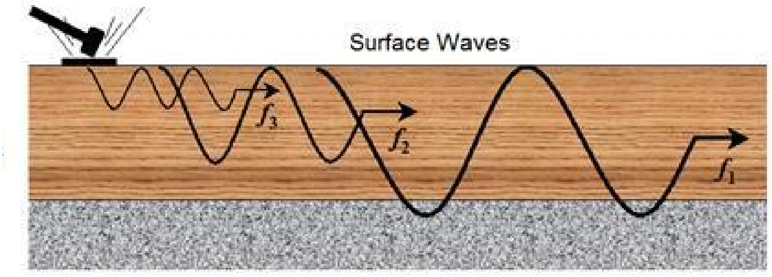
Velocity analysis



Surface waves

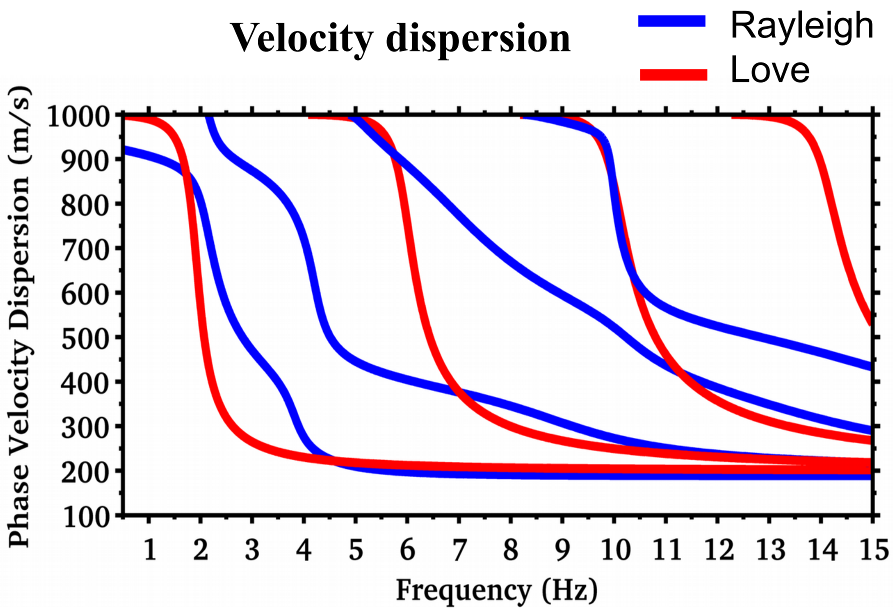
Displacement (**mode eigenfunction**) vanishes with depth


Eigenfunctions



$V_3 < V_2 < V_1$

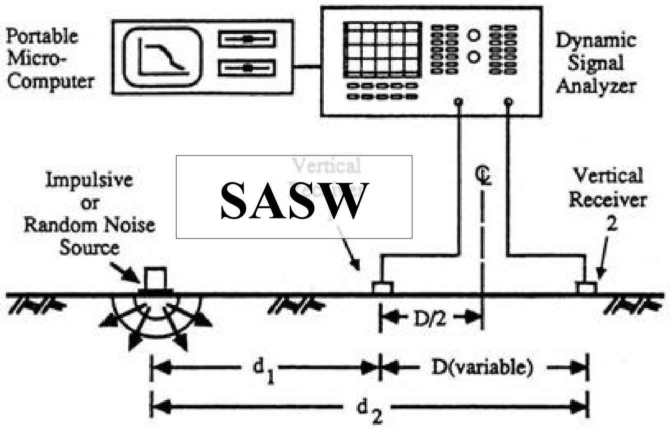
- Velocity is frequency dependent (***velocity dispersion***)
- **Multiple modes** of propagation exist at the same time


Velocity dispersion

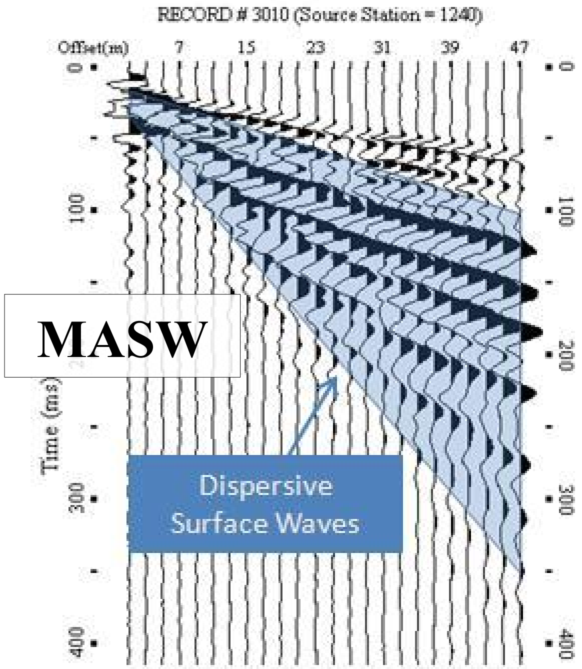
Active surface wave analysis

SASW → Spectral Analysis of Surface Waves (relative phase delay between pairs of receivers)

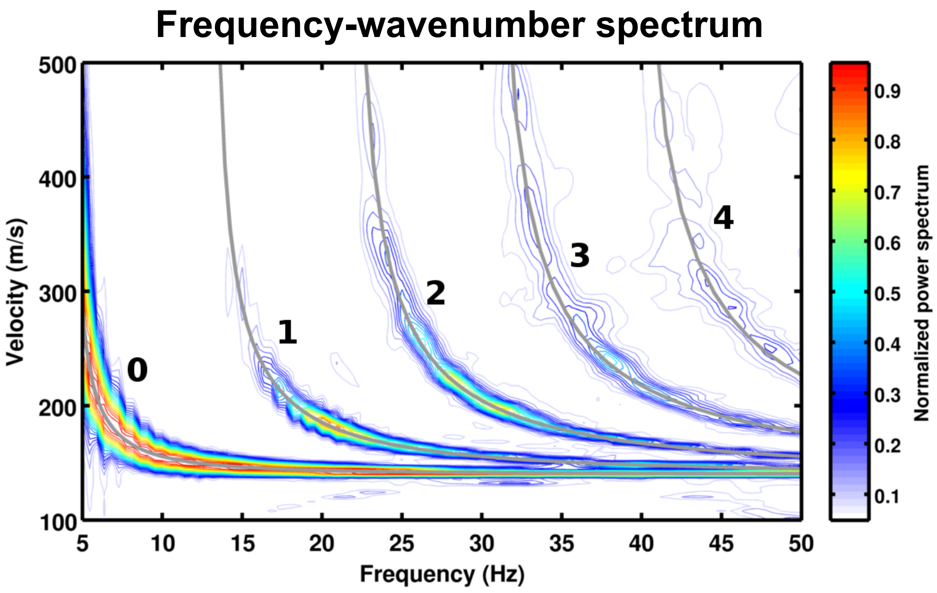
MASW → Multichannel Analysis of Surface Waves (frequency-wavenumber analysis)



From Rix et al. (1991)



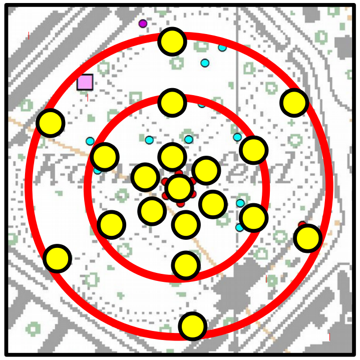
(http://www.parkseismic.com)


Frequency-wavenumber spectrum

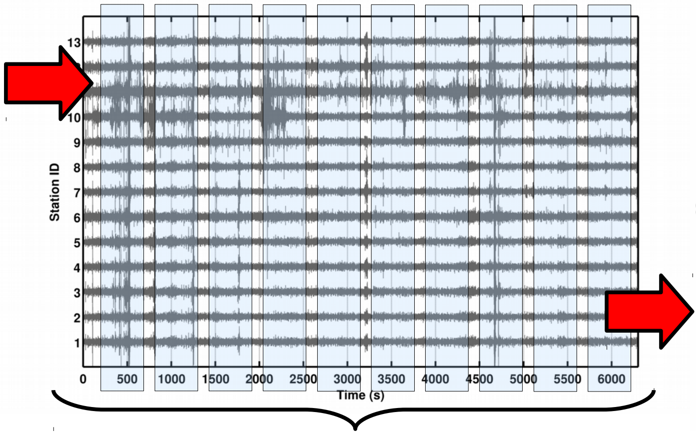
Ambient vibration seismology

(Array analysis)

Array deployment

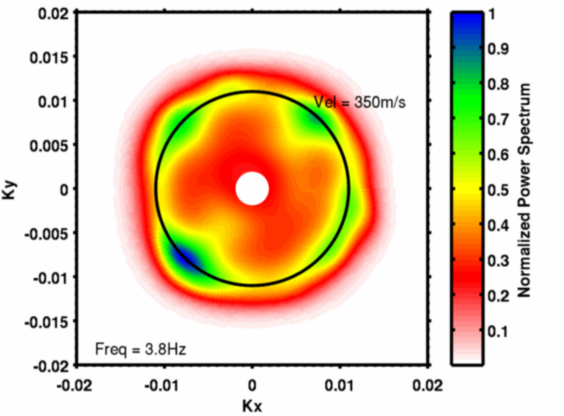


Noise recording

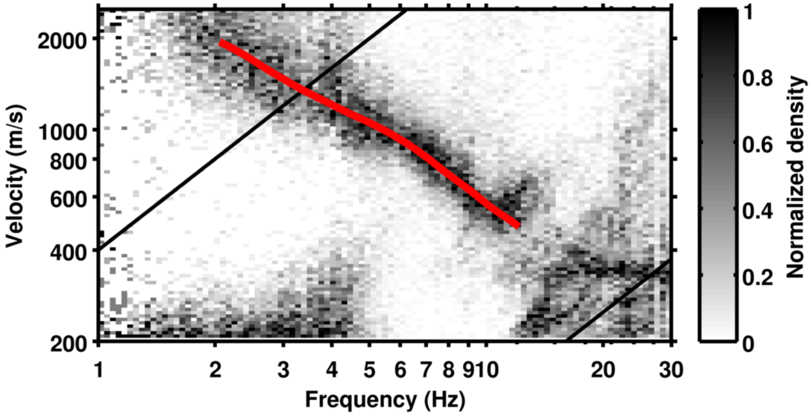


1h40m

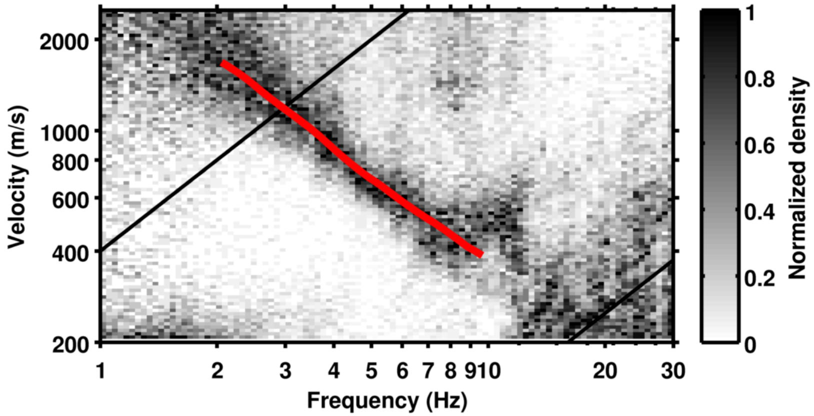
f-k analysis



Vertical Component



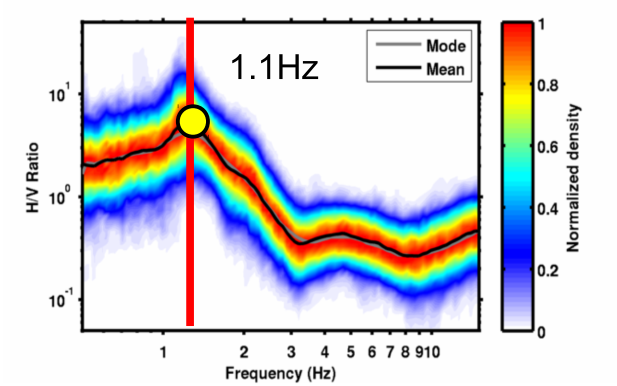
Transversal Component



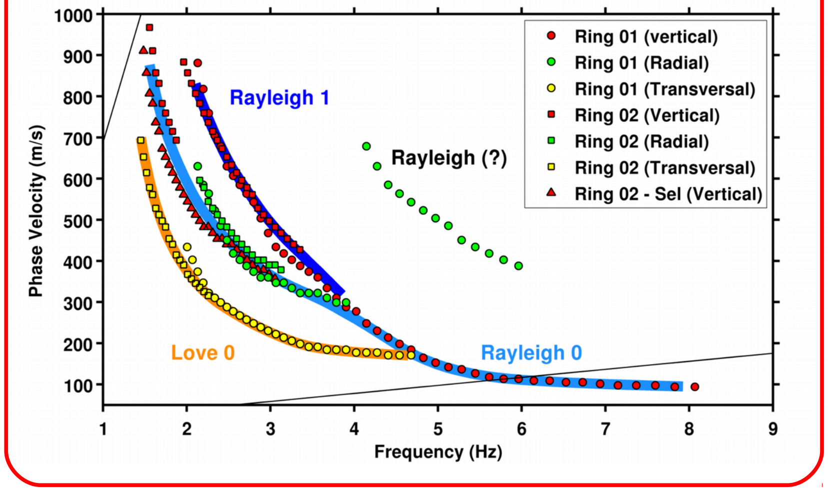
Building the Model

Surface-wave Data

Rayleigh Ellipticity - f_0

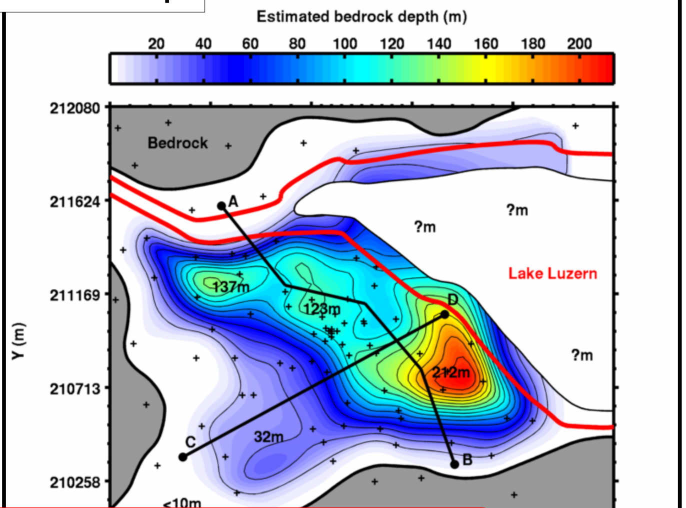


Surface Wave Dispersion

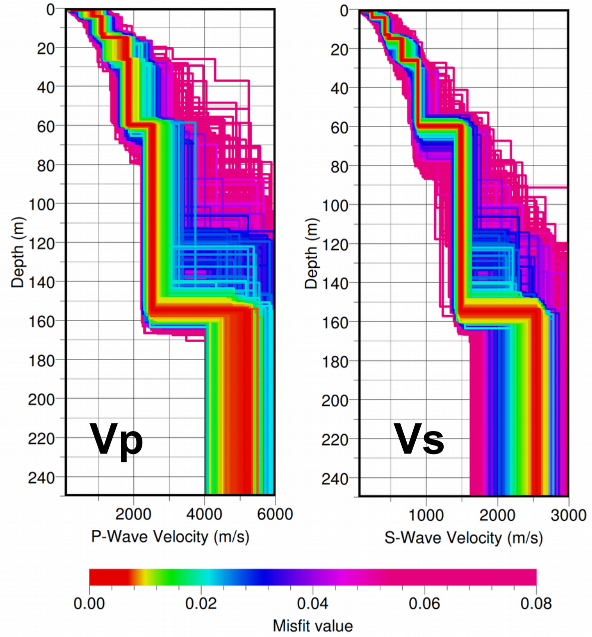


Inversion

Bedrock Map



Velocity Model

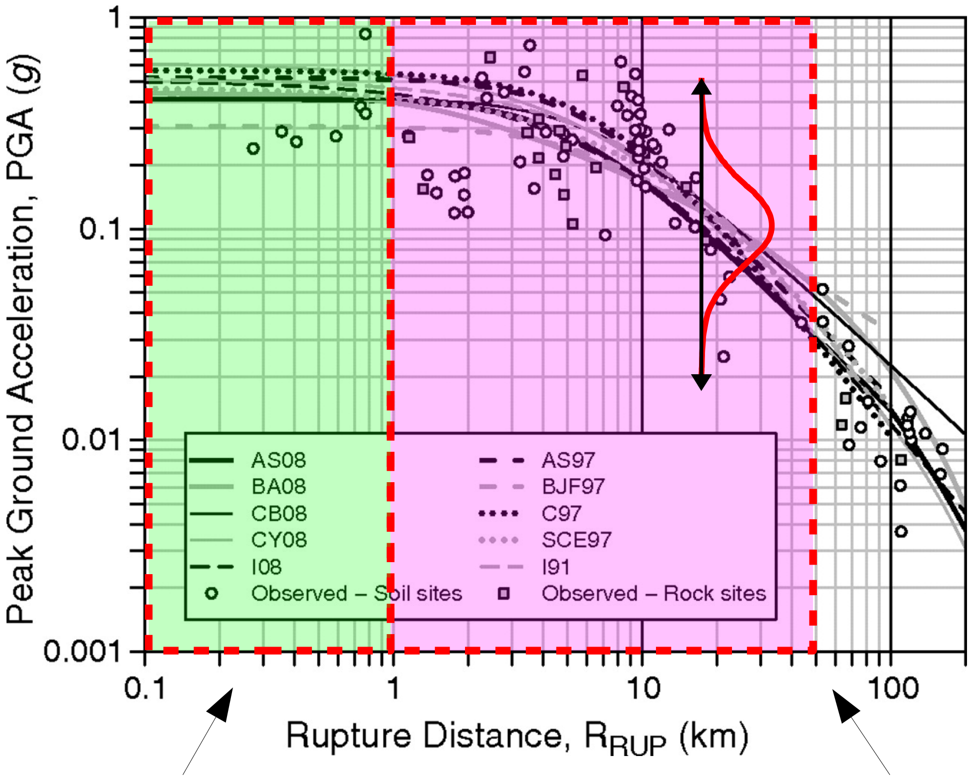


GMPE site term and Soil Proxies

GMPE - Ground Motion Prediction Equations

Given a specific source scenario (e.g. magnitude, fault mechanism...), GMPEs predict the shaking level at a given location (e.g. at distance R)

GM Amplitude = **Source term** * **Path term** * **Site term**



Lack of data in near field...

Important distances < 50Km

Often source, path and site terms are described by a simple **regressive model** (e.g. high order polynomials) using a merely empirical approach and **single predictors** (**PGA, PGV, Intensity**)

PRO: generally quite easy to use, often calibrated on world-wide datasets

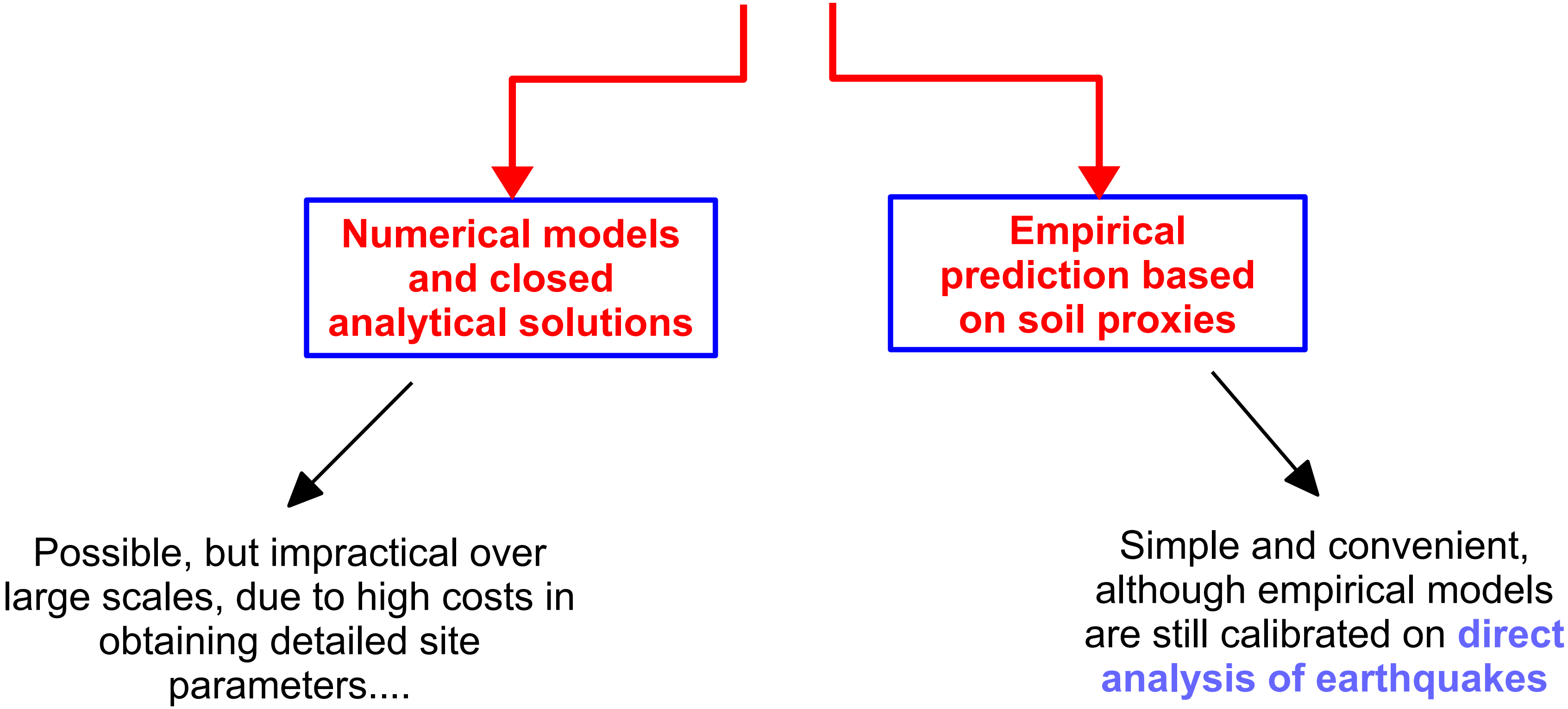
CONS: based just on observation, (little) physical justification, large epistemic uncertainty

The Generic Site Amplification Term

GMPEs represent a simple and convenient way to predict ground motion level over wide areas and sites of different characteristic

In order to predict site response for a specific site and in case of **lack of direct recordings**, a **site amplification model** is then necessary

This can be done in two ways, using:



Numerical models and closed analytical solutions

Empirical prediction based on soil proxies

Possible, but impractical over large scales, due to high costs in obtaining detailed site parameters....

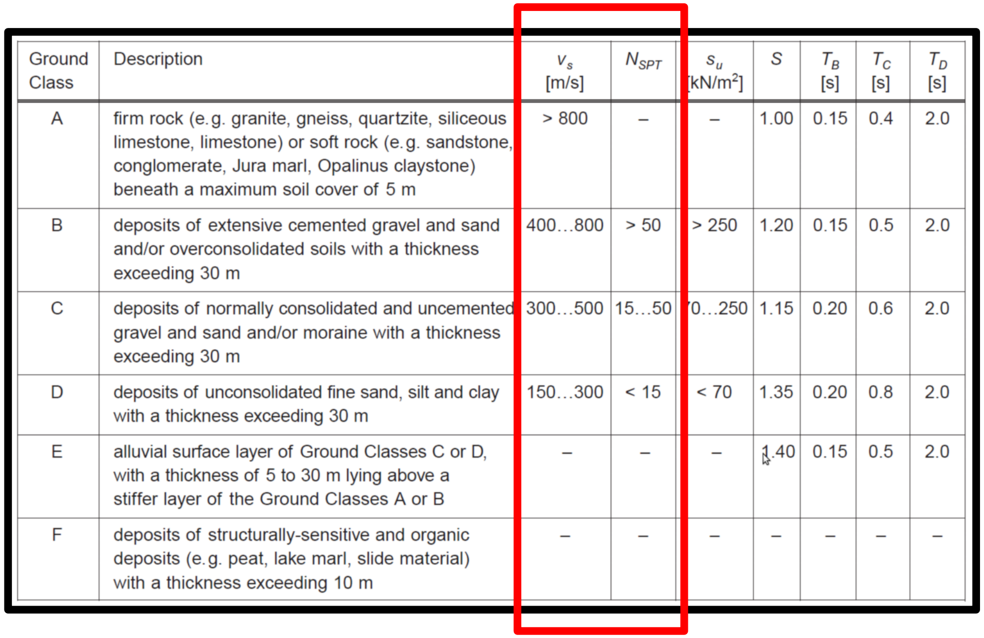
Simple and convenient, although empirical models are still calibrated on **direct analysis of earthquakes**

Soil classification and proxies

Present **GMPEs** and **building codes** use simplified approaches to map the variability of local site response over wide areas by means of **statistical models** based on **ground types** (or classes) and **empirical observations**

Ground types are identified by appropriate **near-surface proxies**, such as:

→ **the average velocity over the first 30 meters (Vs_{30})**
→ the fundamental frequency of resonance
→ results from SPT/CPT tests
→ geological/geotechnical classification...



Ground Class	Description	v_s [m/s]	N_{SPT}	s_u [kN/m^2]	S	T_B [s]	T_C [s]	T_D [s]
A	firm rock (e.g. granite, gneiss, quartzite, siliceous limestone, limestone) or soft rock (e.g. sandstone, conglomerate, Jura marl, Opalinus claystone) beneath a maximum soil cover of 5 m	> 800	–	–	1.00	0.15	0.4	2.0
B	deposits of extensive cemented gravel and sand and/or overconsolidated soils with a thickness exceeding 30 m	400…800	> 50	> 250	1.20	0.15	0.5	2.0
C	deposits of normally consolidated and uncemented gravel and sand and/or moraine with a thickness exceeding 30 m	300…500	15…50	70…250	1.15	0.20	0.6	2.0
D	deposits of unconsolidated fine sand, silt and clay with a thickness exceeding 30 m	150…300	< 15	< 70	1.35	0.20	0.8	2.0
E	alluvial surface layer of Ground Classes C or D, with a thickness of 5 to 30 m lying above a stiffer layer of the Ground Classes A or B	–	–	–	1.40	0.15	0.5	2.0
F	deposits of structurally-sensitive and organic deposits (e.g. peat, lake marl, slide material) with a thickness exceeding 10 m	–	–	–	–	–	–	–

SIA261 - Example of soil classification using Vs_{30}

Some Considerations on the Use of Soil Proxies

⇨ Proxies are a convenient way to characterize soil types of "*expected*" similar seismic response using just a single parameter

⇨ Soil proxies can be obtained by direct measure or (very often) by **indirect extrapolation** from other direct observations (e.g. geology, topography)

⇨ However, despite of their simplicity, these proxies:

① do not fully describe the **vertical/lateral variability** of the soil structure

② can hardly describe the **frequency dependent** amplification behavior

③ cannot account for site-specific phenomena like **soil non-linearity** and **resonance amplification**

What Vs_{30} actually is?...

- Vs_{30} is the **travel-time average shear-wave velocity** over the first 30m.
- It is computed in such a way:

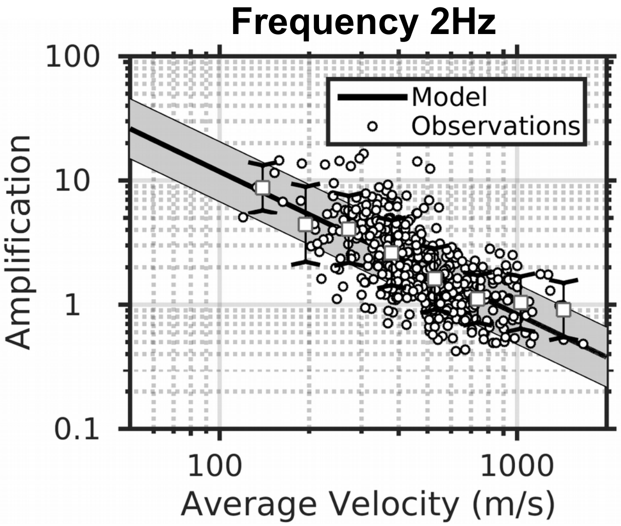
$$\boxed{Vs30 = \frac{30}{\sum_{i=1,N} \frac{h_i}{v_i}}}$$

...but why using 30m, and not 10, 25 or 50m?

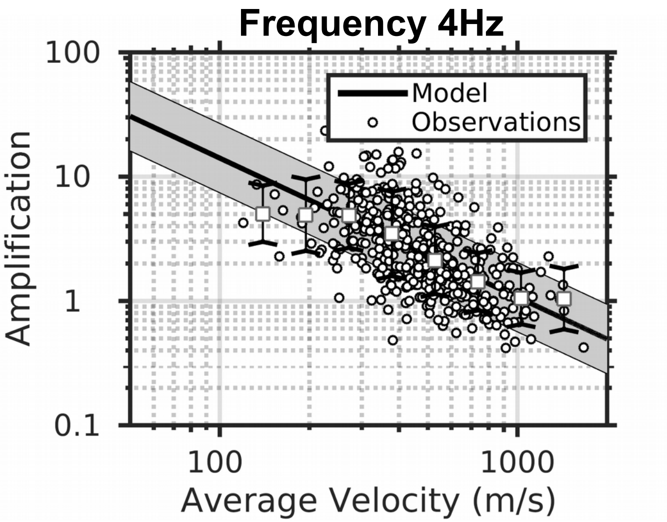
- Simply because ~30m (**100ft!**) was the standard penetration depth of most of the direct logging techniques of the past (at least in US).

Consequently...

- The large availability of log data within this depth range imposed this parameters as **de facto standard** (but without a clear **physical meaning**)

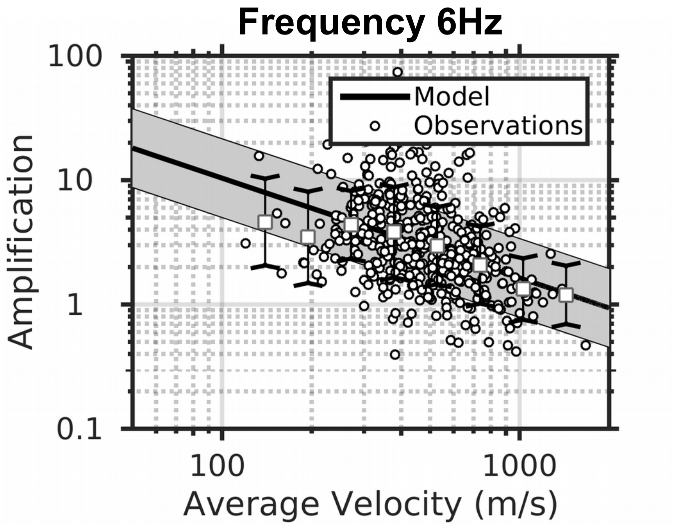


Frequency 2Hz

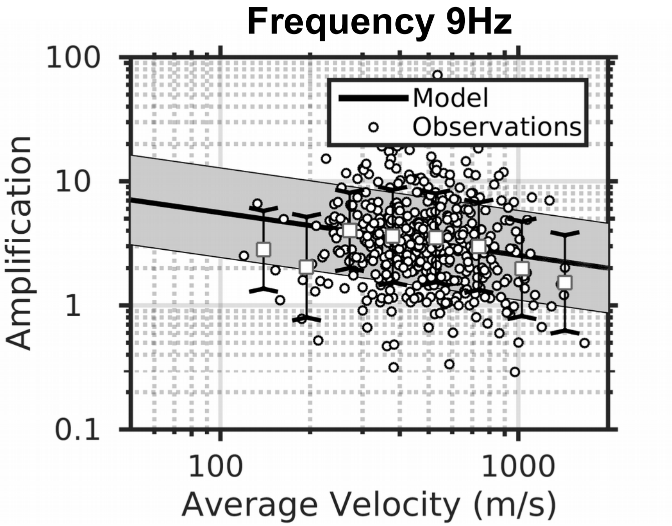


Frequency 4Hz

Nonetheless Vs_{30} is a
parameter **highly correlated**
with site amplification...



Frequency 6Hz



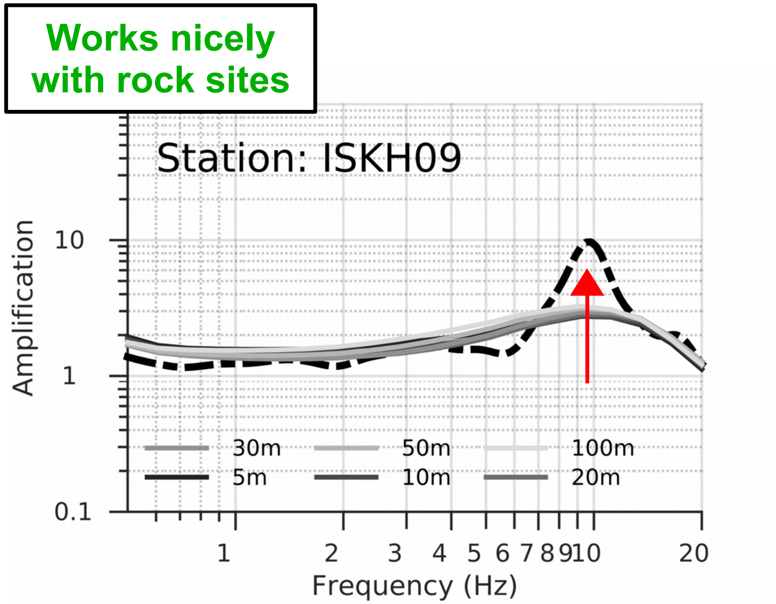
Frequency 9Hz

...even if prediction **uncertainty** is
quite large

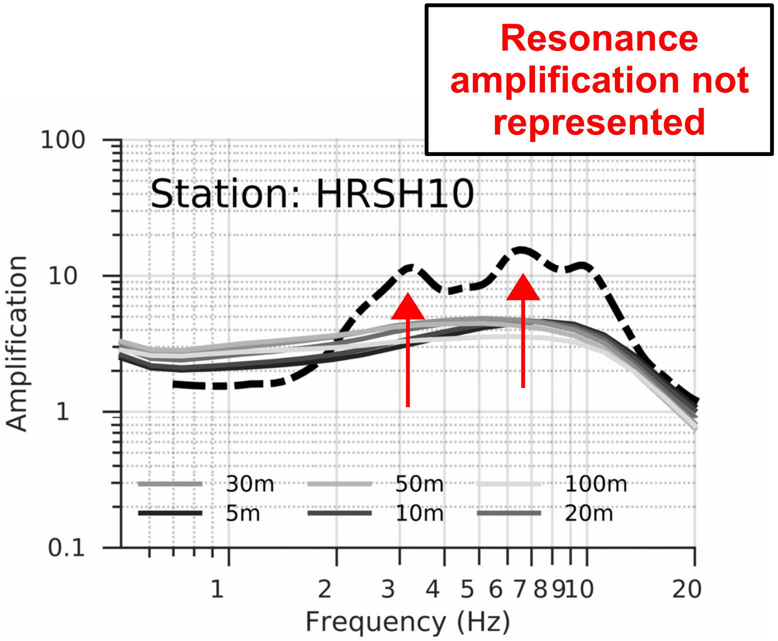
Source of Uncertainty of the Predictor

- Vs_{30} is basically a proxy for the contrast of seismic impedance between the **basement** (source condition) and the **uppermost (average) soil**, which is controls the average amplification level of the site

- However, Vs_{30} cannot explain those complex phenomena developing *“within”* the profile...

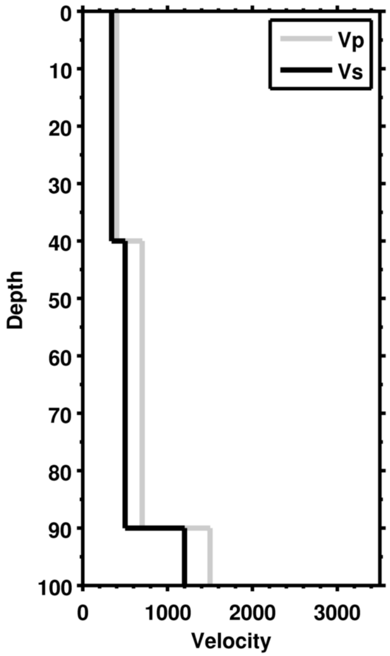


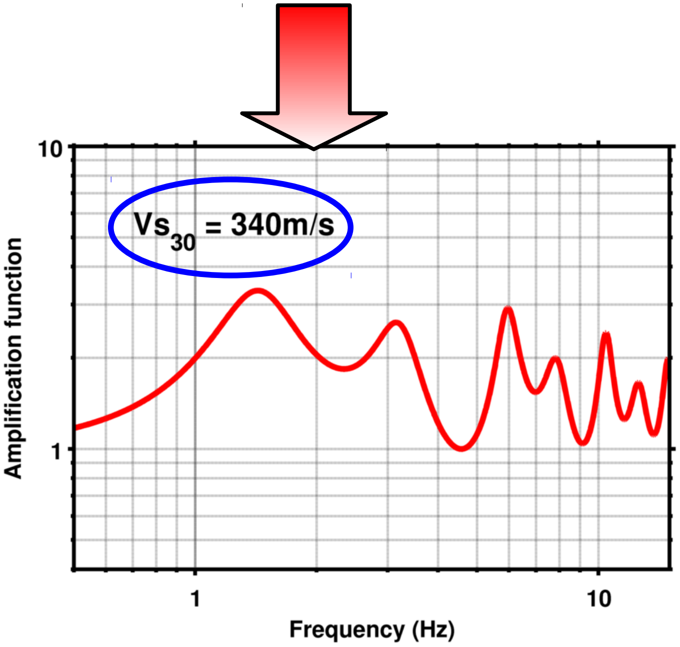
Works nicely with rock sites

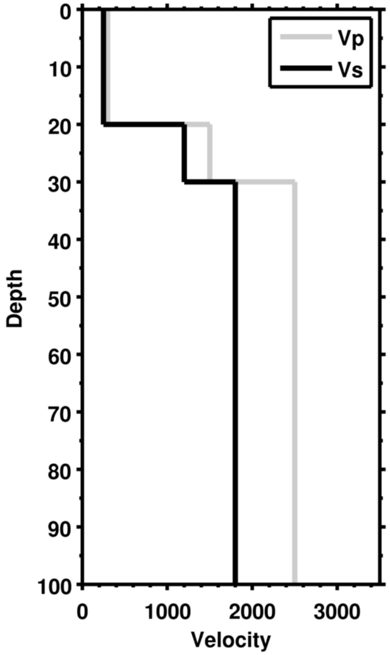


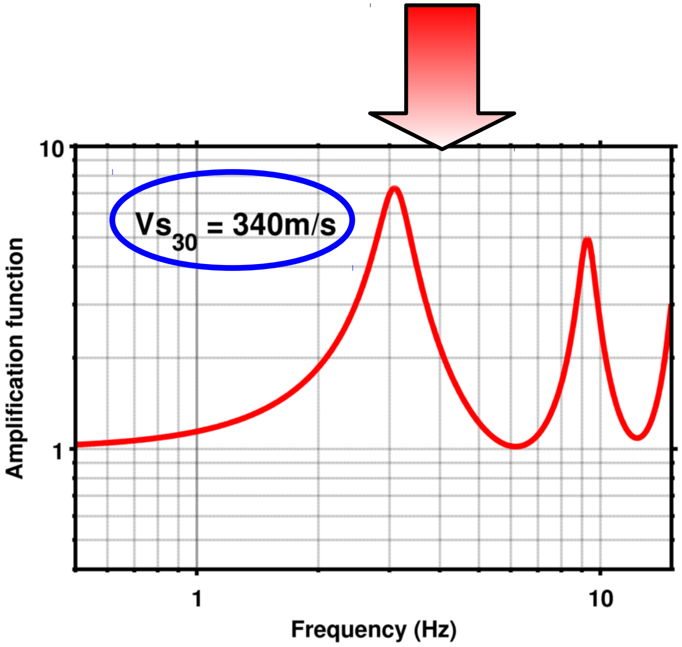
Resonance amplification not represented

A simple synthetic example: profiles with same V_{30}









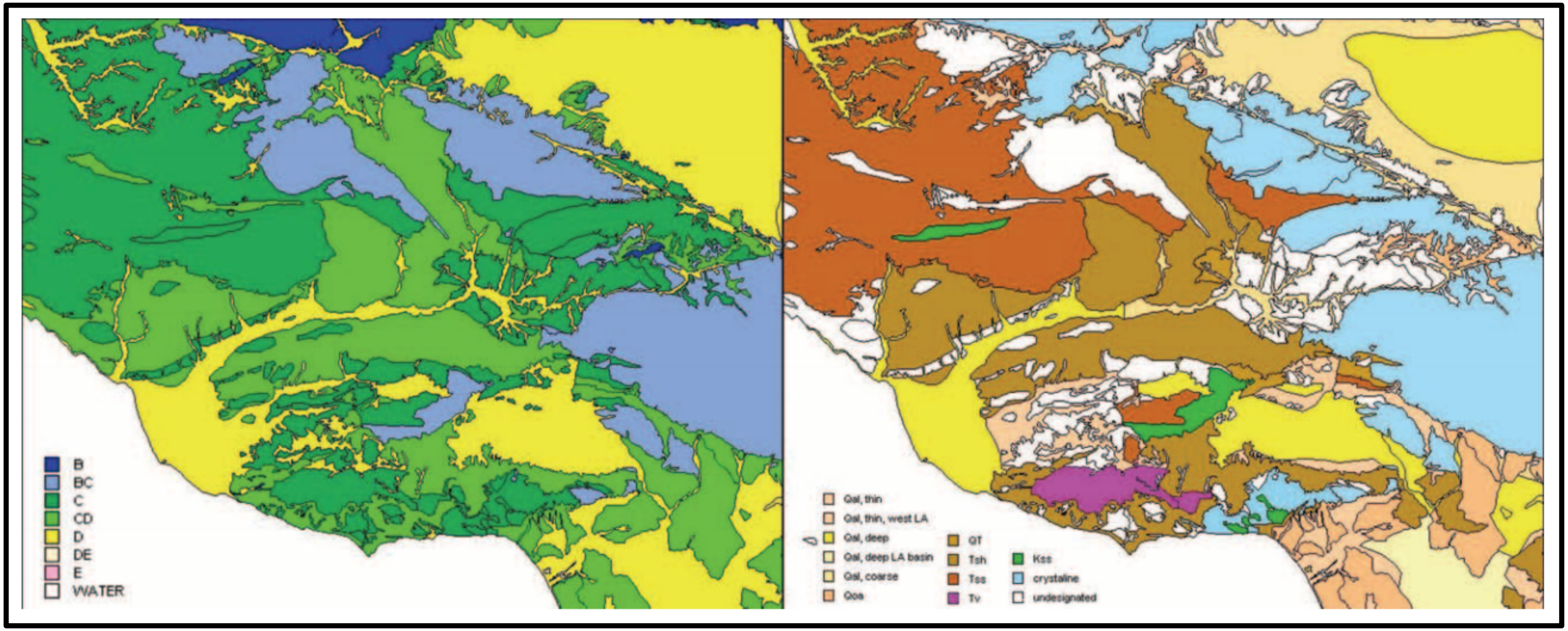
Additional Source of Uncertainty

- Vs_{30} can also be biased by the way it is obtained, often not from direct measurement but **extrapolated** from other surface proxies (geology, geotechnical classification, CPT tests….)

- The conversion introduces an additional contribution to the uncertainty, which sum to the final error in the prediction

Geology

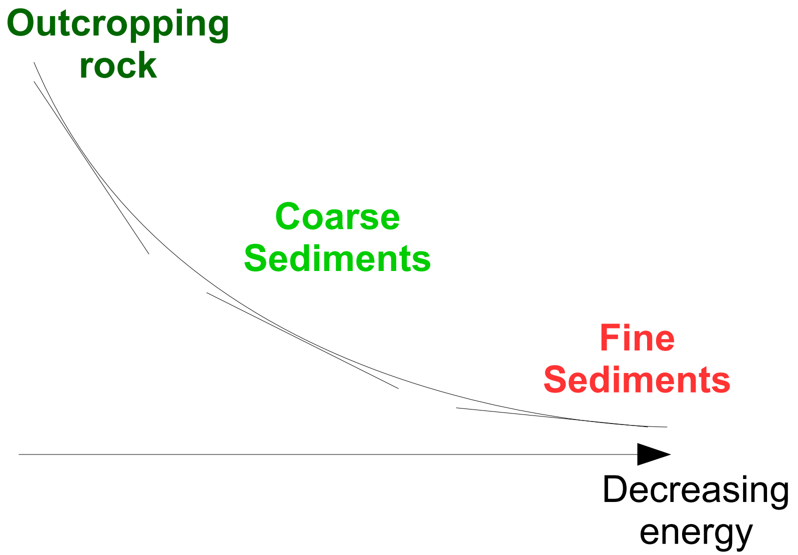
Vs30

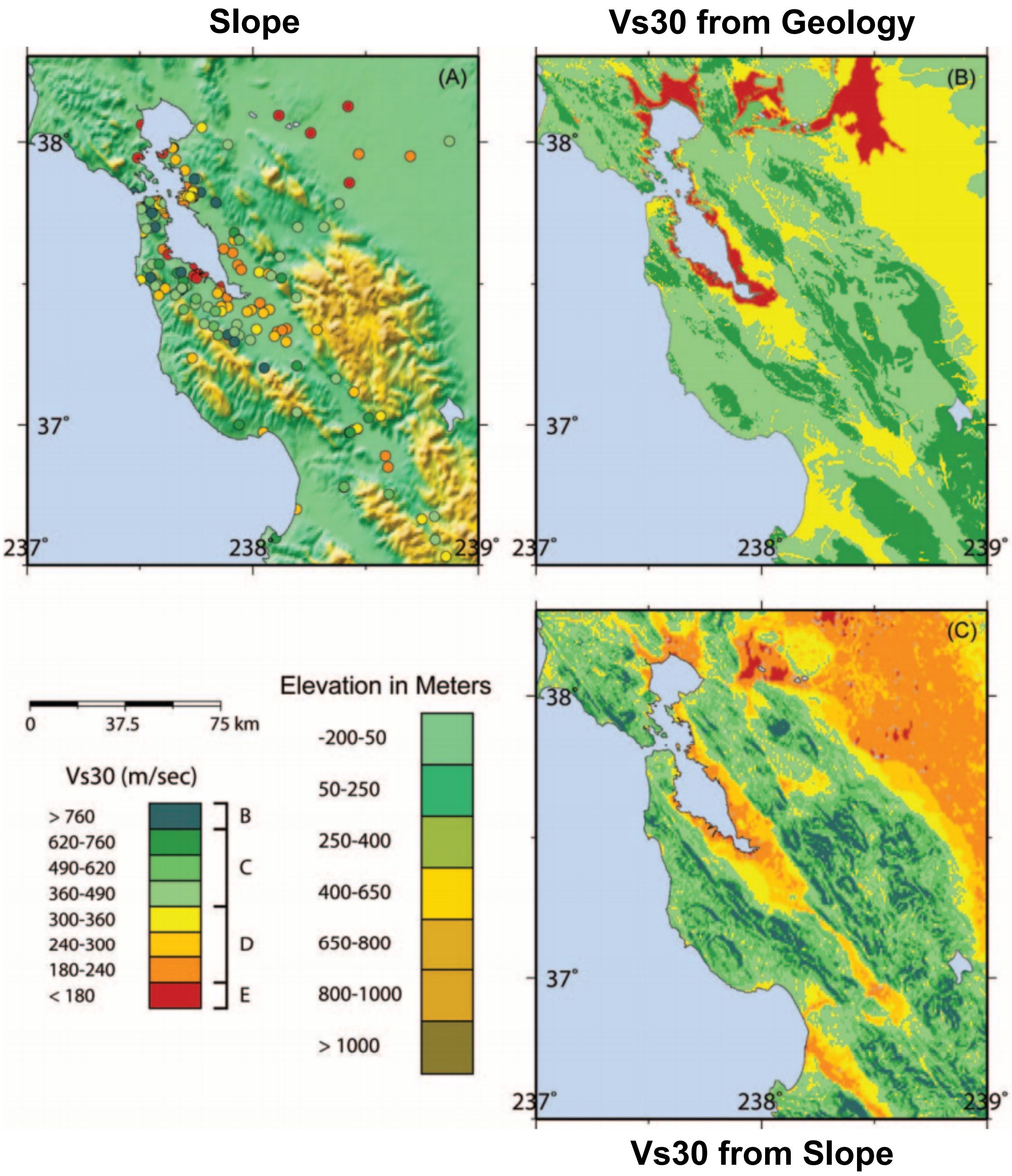


Willis and Clahan (2006)

Vs_{30} from Topography

- Nowadays, a popular way to map Vs_{30} over large areas is the use of **topographic slope** from geodetic observations (Wald and Allen, 2007, 2009)
- The relation is based on the concept of **“depositional energy”** of the sediments



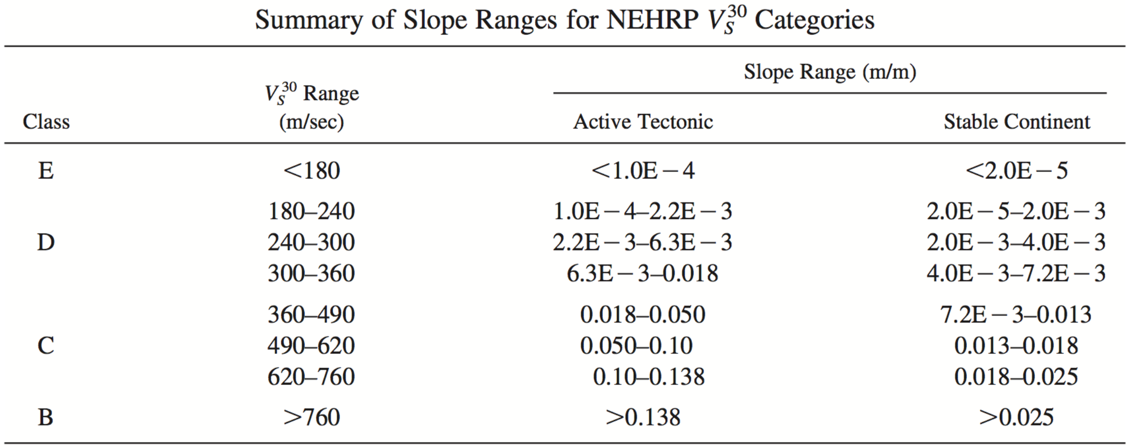

Slope

Vs30 from Geology

Vs30 from Slope

Vs_{30} from Topography

The slope-Vs_{30} relationship is based on the **National Earthquake Hazard Reduction Program** (**NERHP**) Vs_{30} boundaries (arbitrary?)

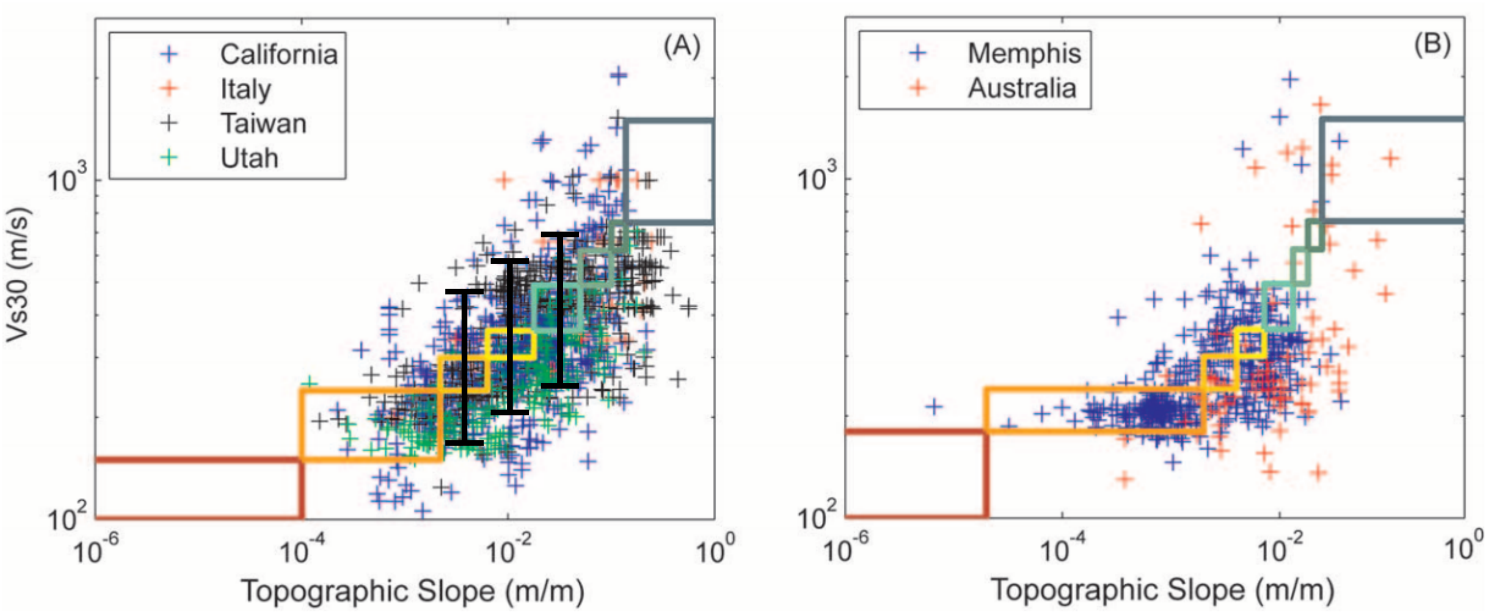


Summary of Slope Ranges for NEHRP V_S^{30} Categories

Class	V_S^{30} Range (m/sec)	Slope Range (m/m)	
		Active Tectonic	Stable Continent
E	<180	<1.0E − 4	<2.0E − 5
D	180–240	1.0E − 4–2.2E − 3	2.0E − 5–2.0E − 3
	240–300	2.2E − 3–6.3E − 3	2.0E − 3–4.0E − 3
	300–360	6.3E − 3–0.018	4.0E − 3–7.2E − 3
C	360–490	0.018–0.050	7.2E − 3–0.013
	490–620	0.050–0.10	0.013–0.018
	620–760	0.10–0.138	0.018–0.025
B	>760	>0.138	>0.025

Calibration databases from different regions:

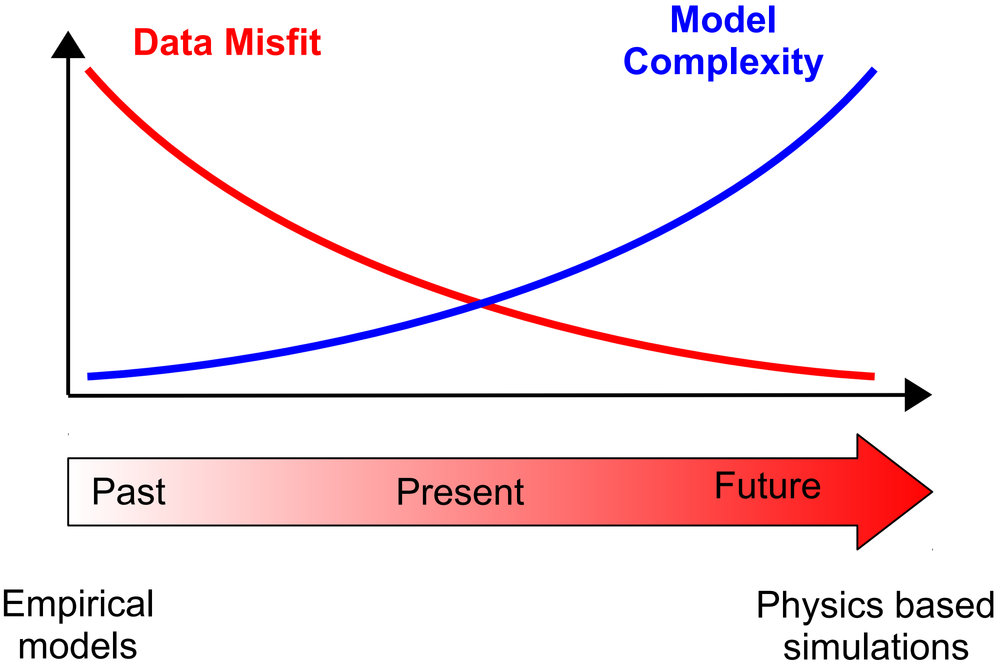
- California
- Utah
- Central U.S.
- Taiwan
- Italy
- Australia



...and the question is finally:

Is Vs_{30} really so adequate as proxy for site amplification?

Vs_{30} is probably not sufficient for future engineering products, as it introduces too large uncertainties



Epistemic uncertainty can be reduced at the expenses of increasing model complexity, by introducing **physics-based concepts**

Modeling Site-Response Into GMPEs

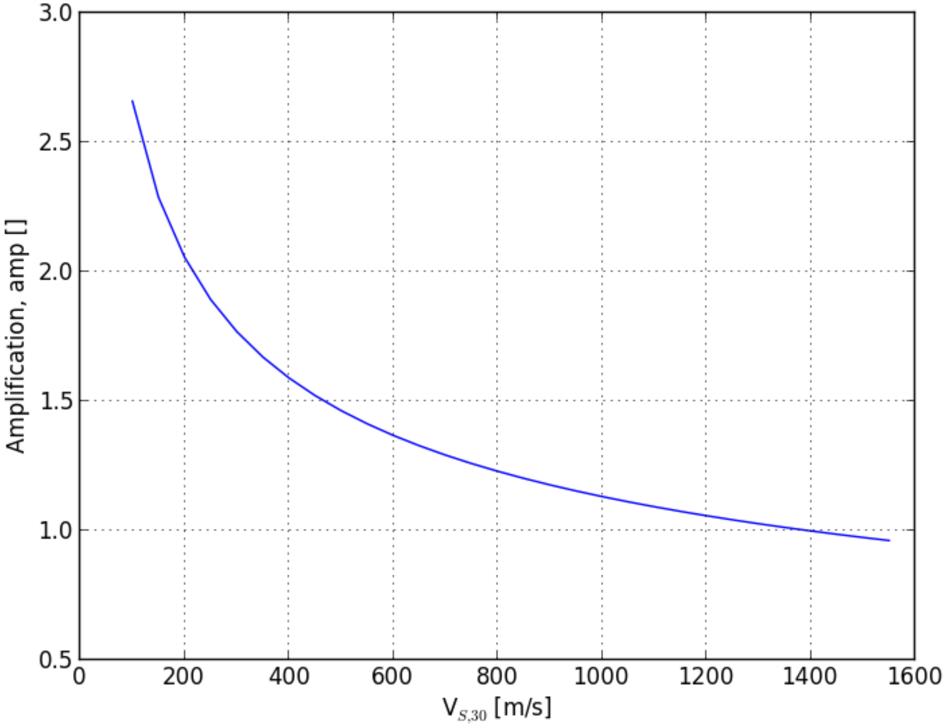
Boore et al. (1997)

Assuming a linear amplification of motion Boore et al. (1997) proposed the following formula to model site amplification using a site-specific $V_{S,30}$ value:

$$\ln(Amp) = a \ln\left(\frac{V_{S,30}}{V_{\mathrm{Ref}}}\right)$$

For PGA the coefficients are:

- $a = -0.371$
- $V_{ref} = 1396$ [m/s]



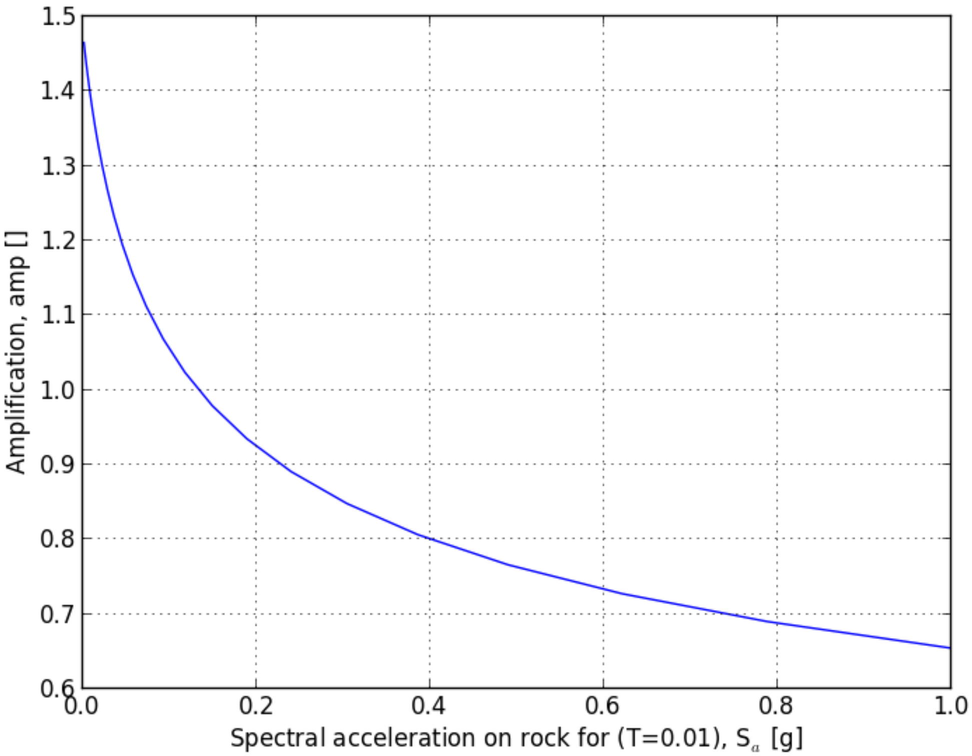
Ambrahamson and Silva (1997)

Ambrahamson and Silva (1997) using a generalized soil category developed a model for site response accounting for the non-linear behaviour of materials

$$\ln(Amp) = a + b\ln\left(P\hat{G}A_{rock} + c\right)$$

For PGA the coefficients are:

- a = - 0.417
- b = -0.230
- c = 0.03



Choi and Stewart (2005)

Choi and Stewart (2005) proposed and empirical model for assessing the nonlinear amplification factor for spectral acceleration as a function of $V_{S,30}$. The results can be used as *Vs-30-based* site factors with attenuation relationships

$$\ln(F_{ij}) = c\,\ln\left(\frac{V_{s\text{-}30_{ij}}}{V_{ref}}\right) + b\,\ln\left(\frac{PHA_{r_{ij}}}{0.1}\right) + \eta_i + \varepsilon_{ij}\,,$$

where:

- PHA_r peak horizontal acceleration for reference [rock] site condition [g]
- V_{ref} and c are regression parameters
- h_i is a random effect term for earthquake event i (should have zero median across all events, standard deviation is denoted as t); and e_{ij} represents the intra-event model residual for motion j in event i (should have median near zero for well-recorded events, standard deviation is denoted s).