Engineering Seismology and Seismic Hazard – 2019

Lecture 19

Site Effects and Microzonation

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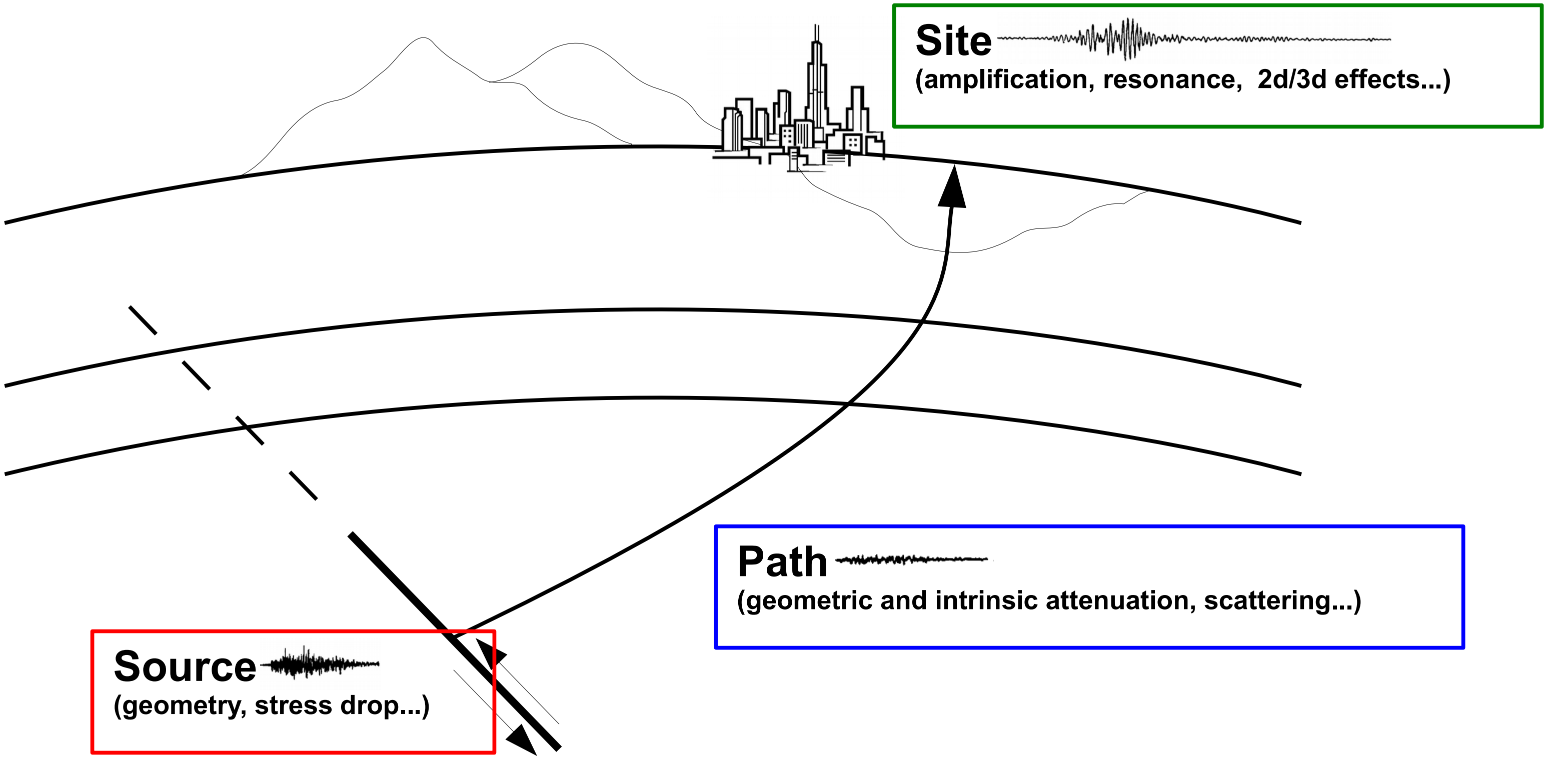
Factors controlling GM

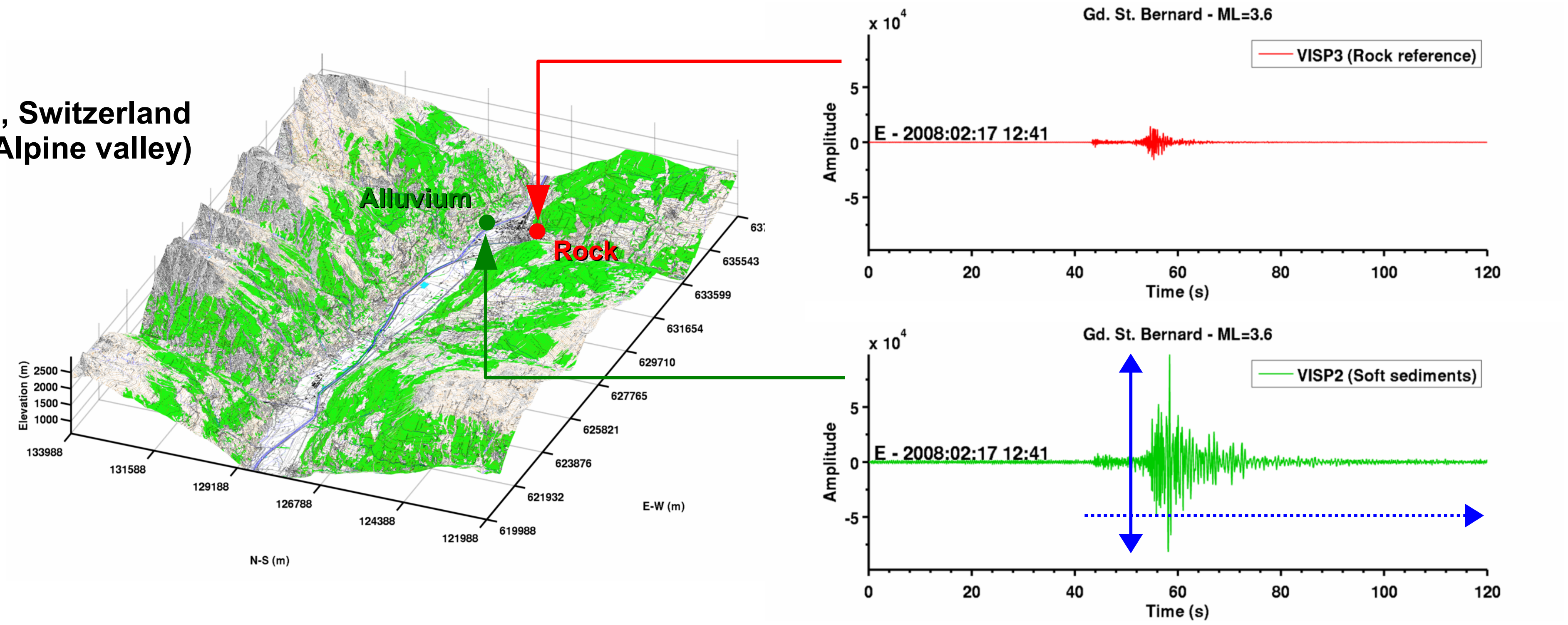
- Earthquake signals can be strongly altered during their propagation from the source to the observation point
- Significant contribution comes from the uppermost few hundred meters of the earth structure, where the larger variability of the geological conditions is present
- As a result, the waveform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



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)



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..

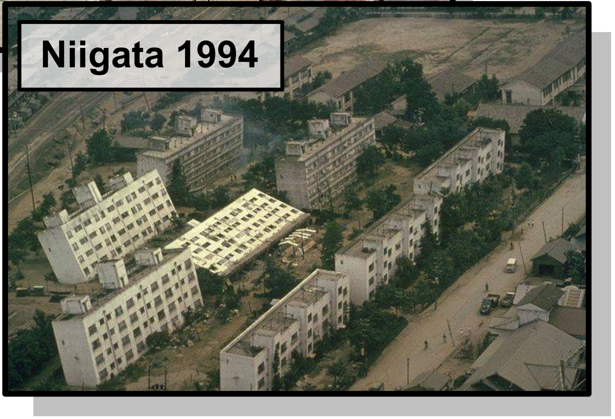
All these phenomena concur to the increase in seismic hazard at local scale


Christchurch 2010


Landers 1992


Kobe 1995


Tohoku 2011


Niigata 1994

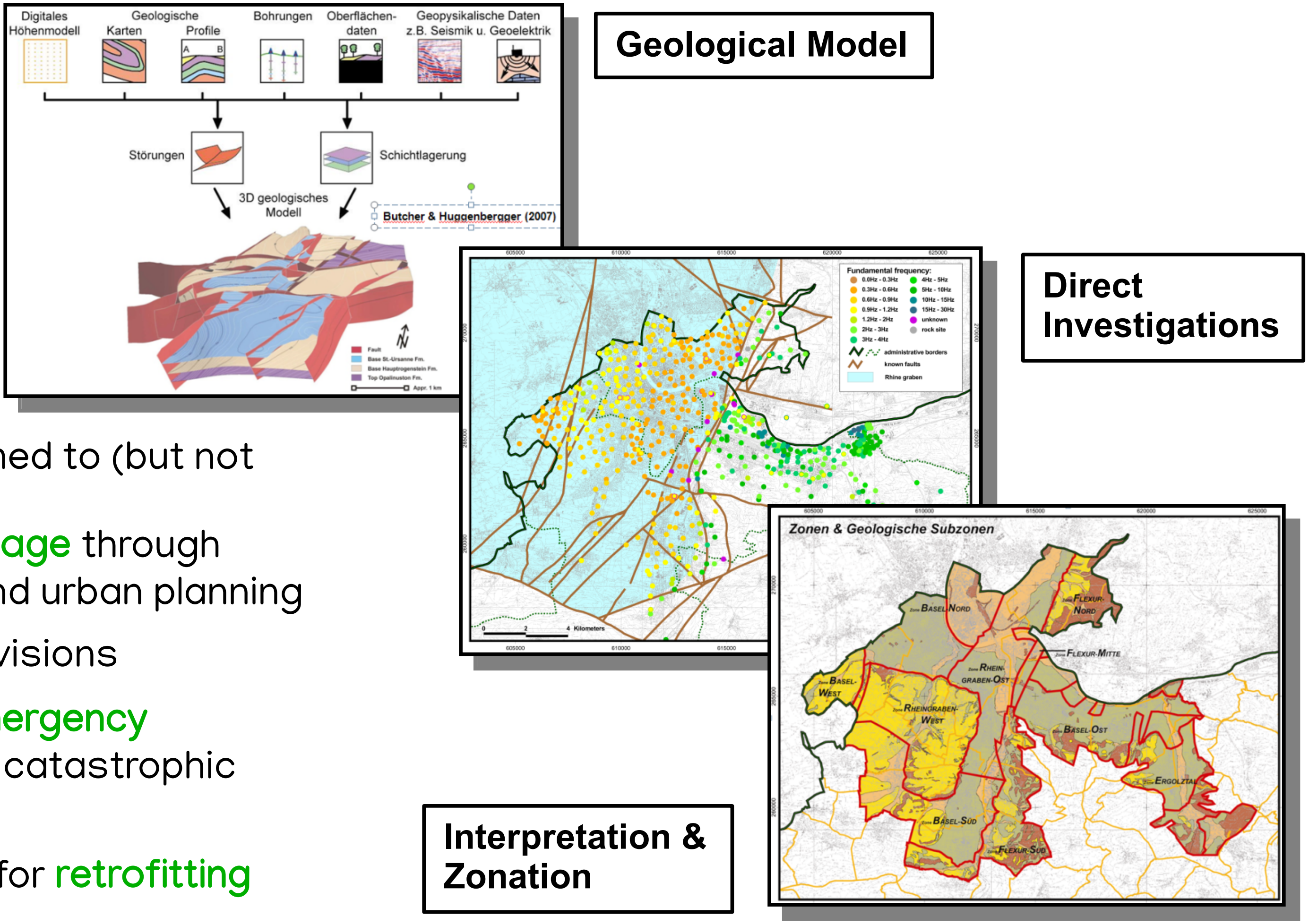

Wenchuan 2008

Seismic Microzonation

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

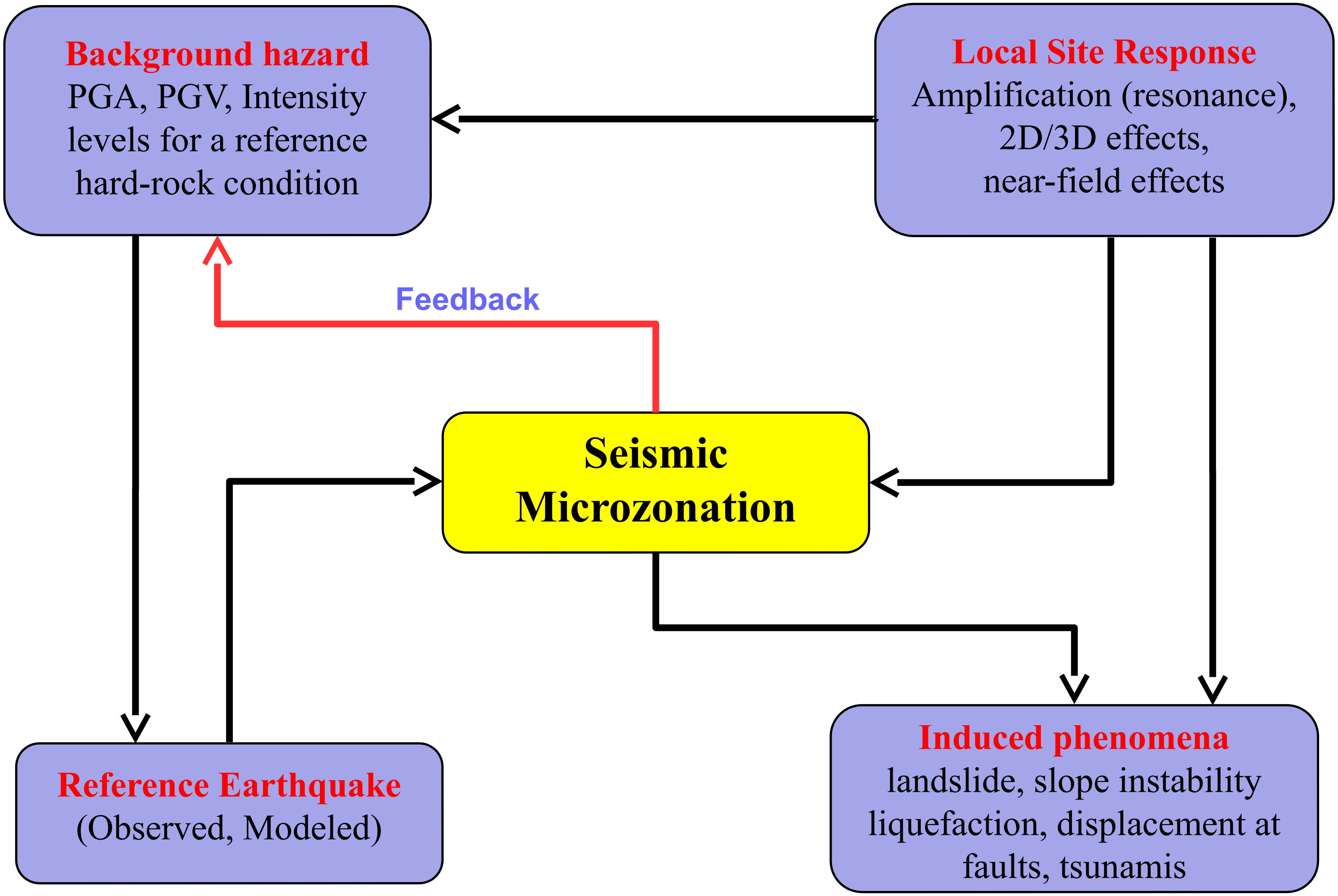
Interpretation & Zonation

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

Effects on 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:

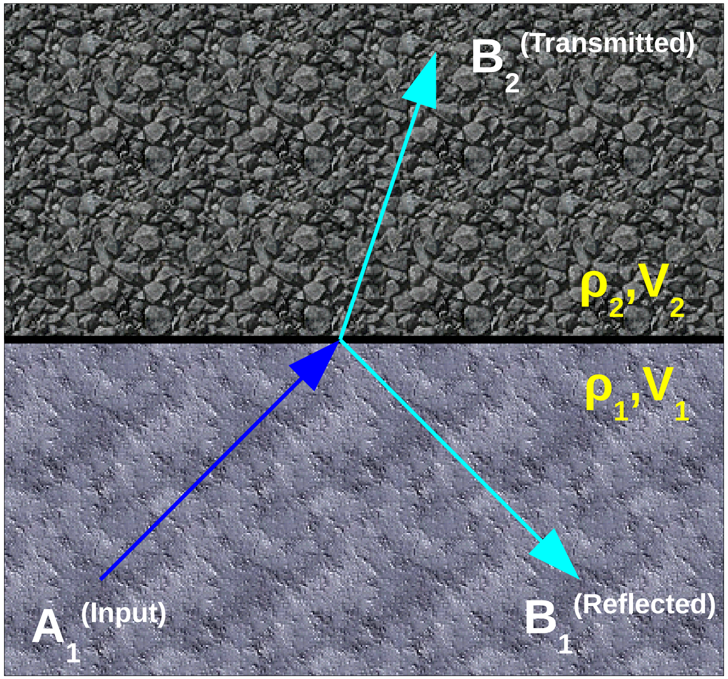
❶ Amplification phenomena (seismic impedance contrast, resonance effect)
❷ Geometrical effects (2d/3d basin geometries, topography)
❸ Soil non-elastic behavior (anelasticity, scattering, non-linear response)

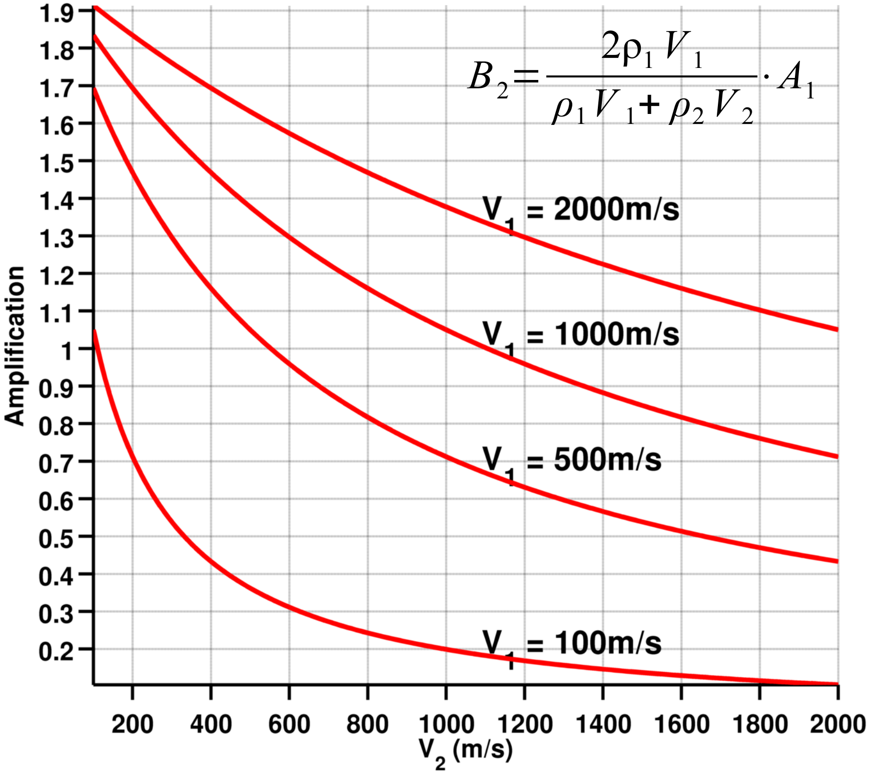
Boundaries between these phenomena are overlapping; often one site-effect is controlled by the occurrence of others (e.g. 3d anelastic resonance....)

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

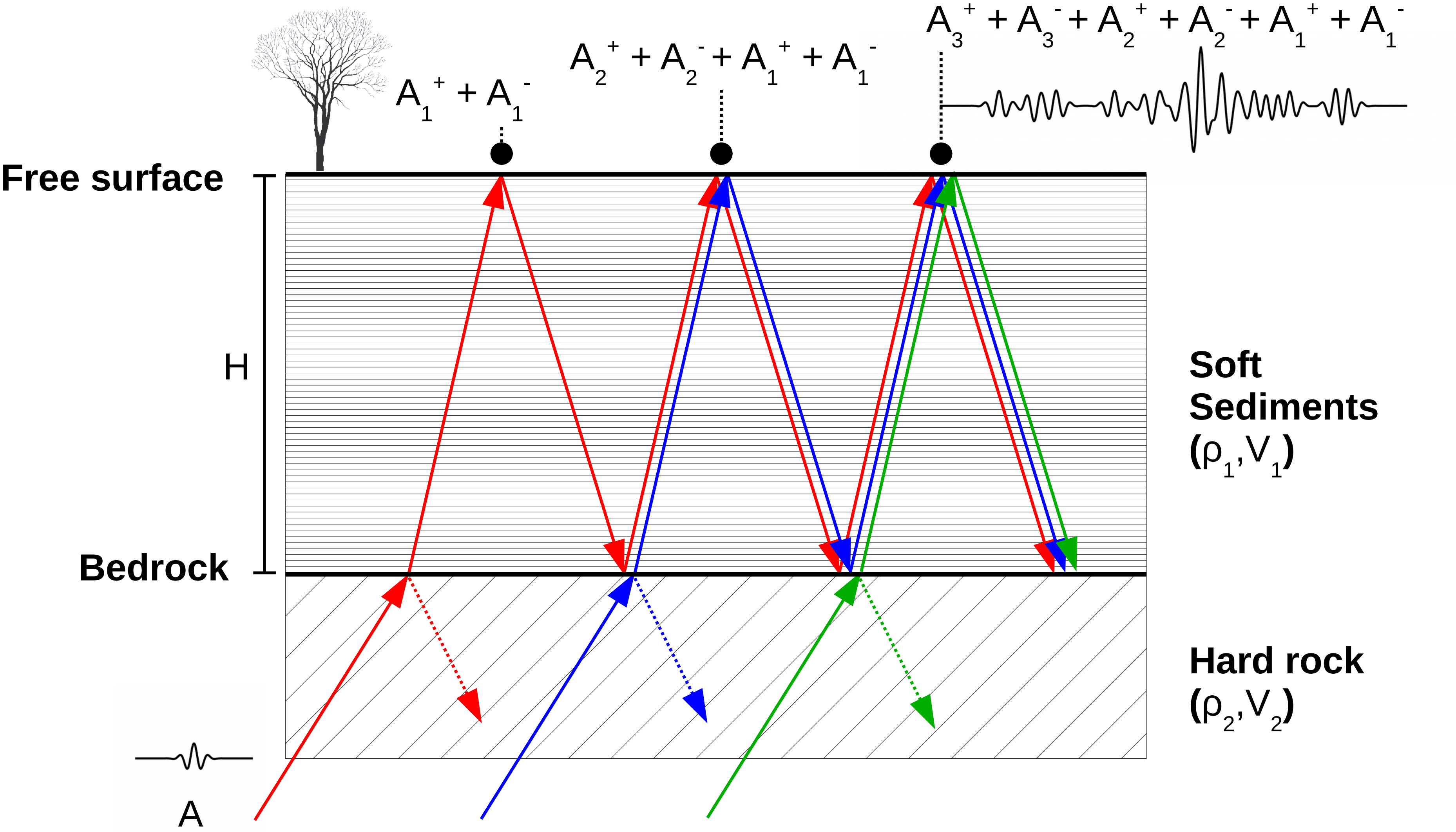




✎ In the case of a sedimentary valley with **soft sediments** (low-velocity) on top of **rigid bedrock** (high-velocity), amplification of the ground motion has to be expected

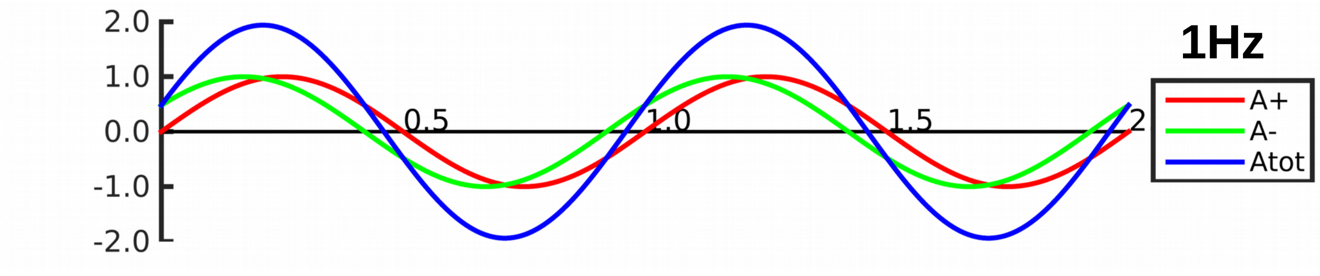
Seismic Resonance

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

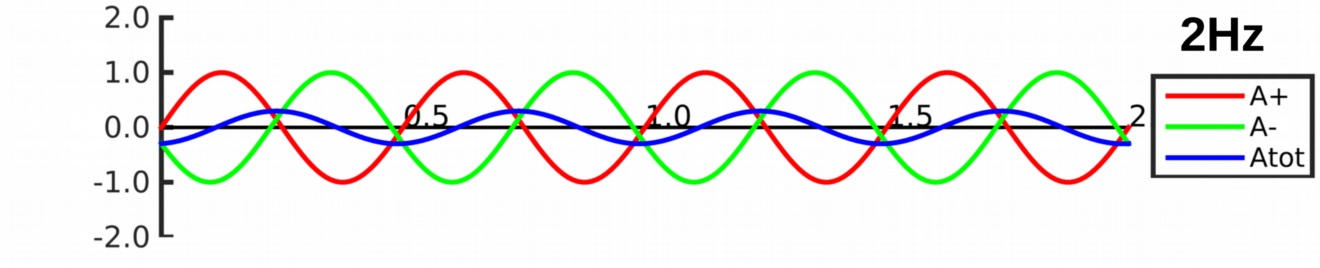


Seismic Resonance

Constructive Interference

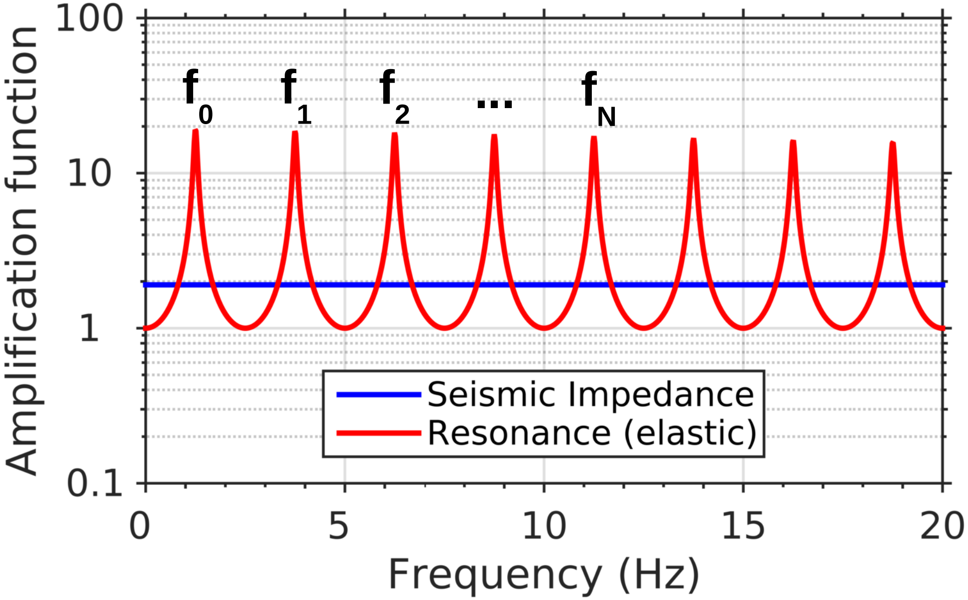


Destructive Interference



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 (f0, f1, … fn), controlled by the geometrical and mechanical properties of the soil

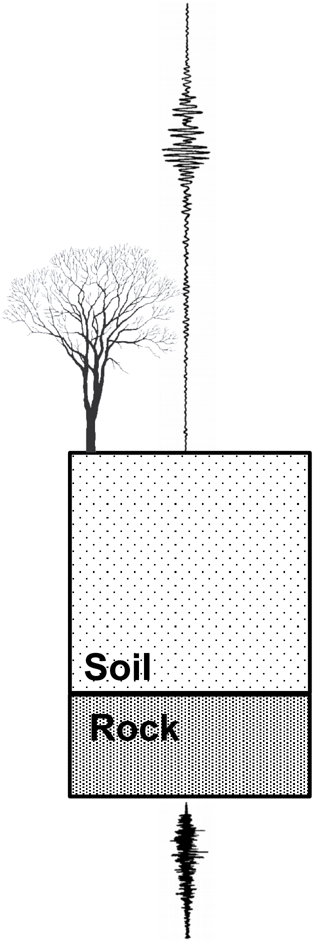


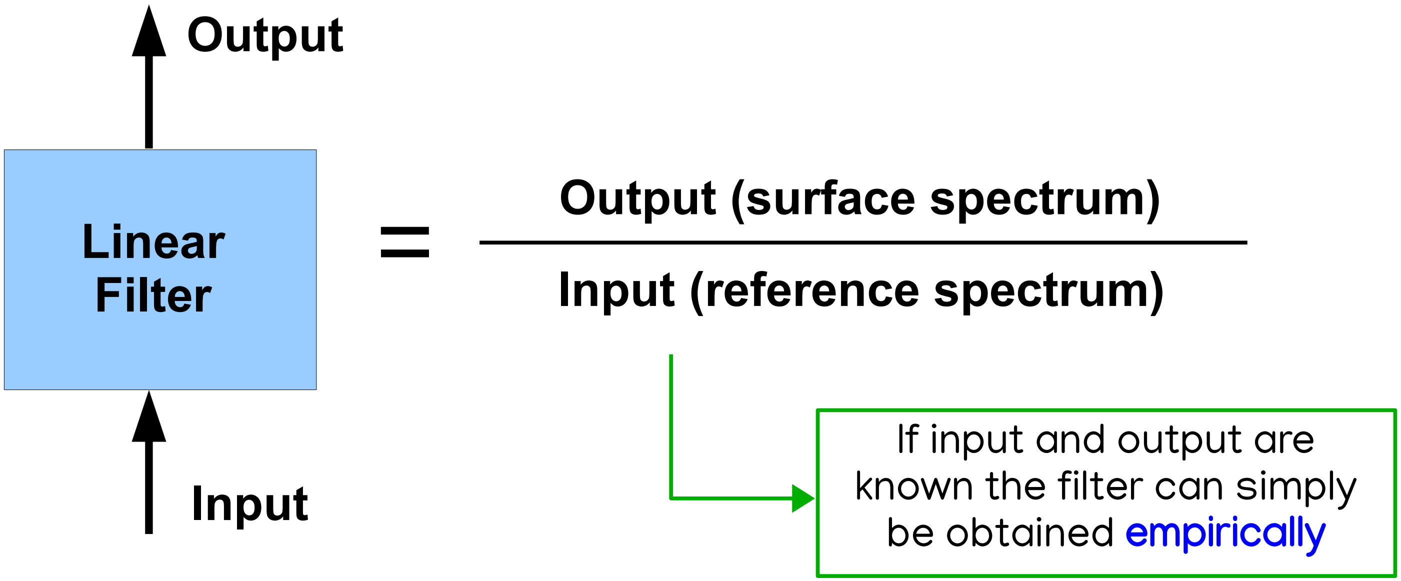
Linear Filter Equivalence

- 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!

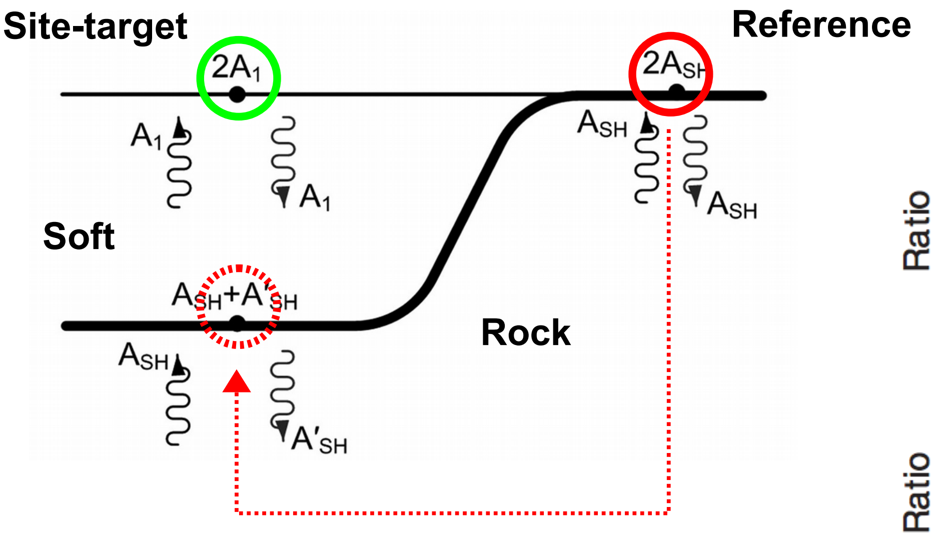


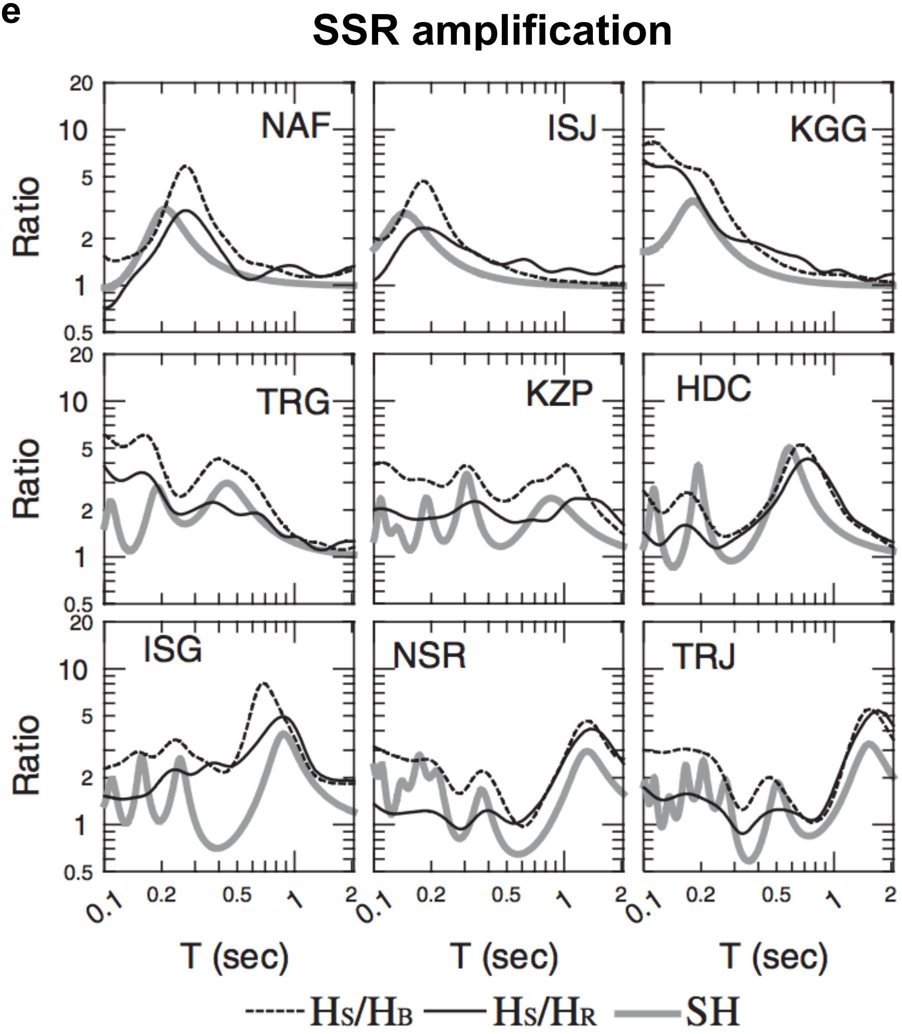


$$\text{Linear Filter} = \frac{\text{Output (surface spectrum)}}{\text{Input (reference spectrum)}}$$

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

Site-to-Reference Spectral Ratios





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...)

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:

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

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

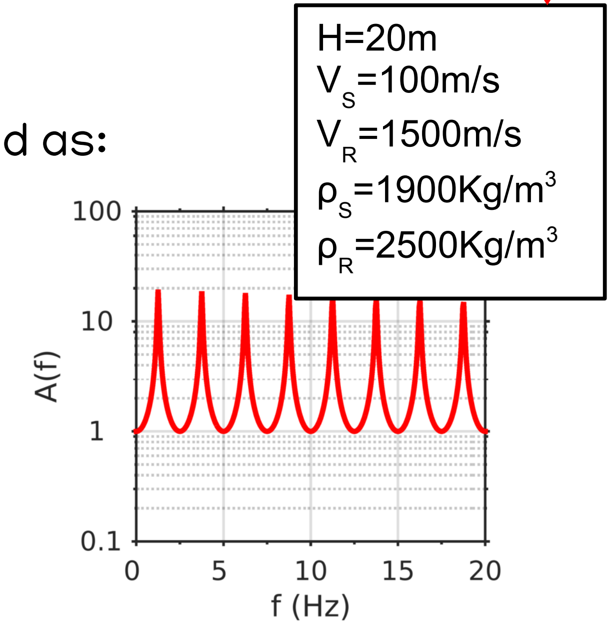
Impedance contrast

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

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

Issues

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

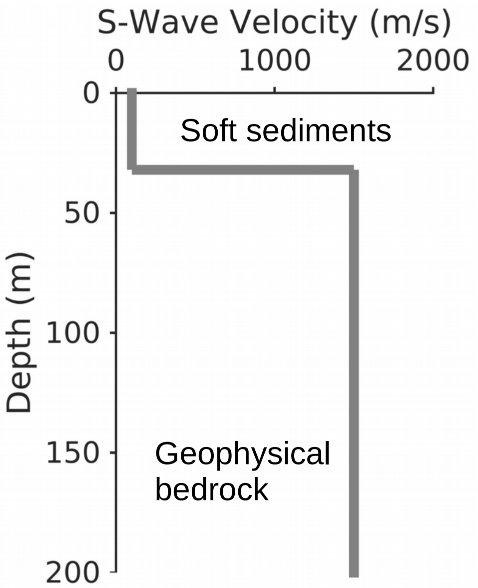
oversimplification often leads to increase in uncertainty of the solution, the so called epistemic uncertainty

...

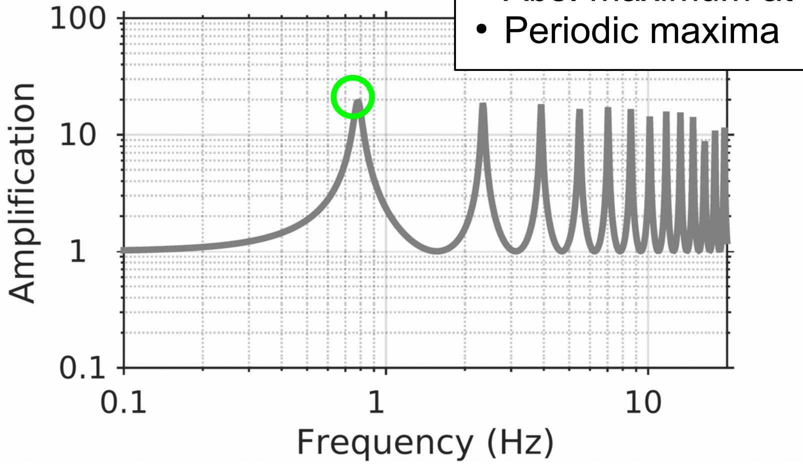
Obviously, things are getting more and more complicated when dealing with real geological structures and realistic velocity profiles

Let's see few examples....

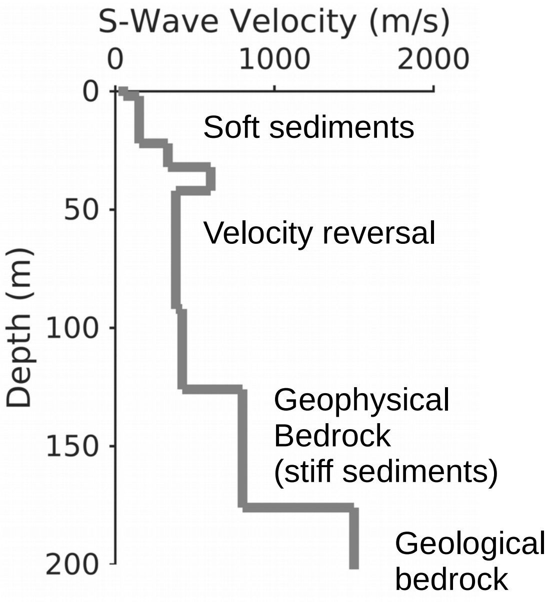
Using realistic velocity profiles



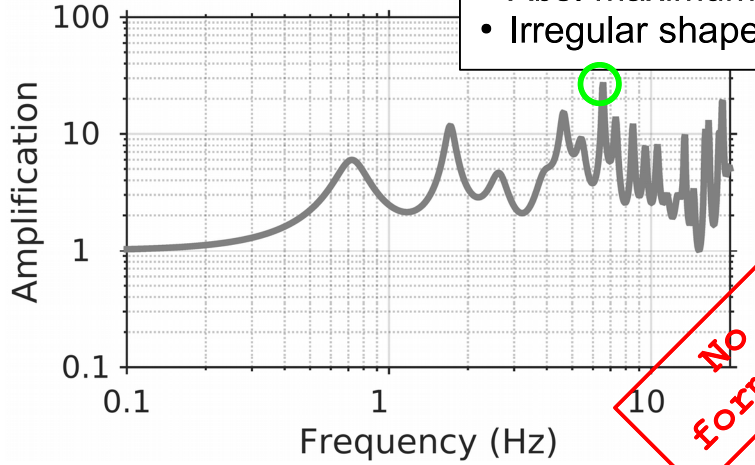
Simple case....



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



...reality



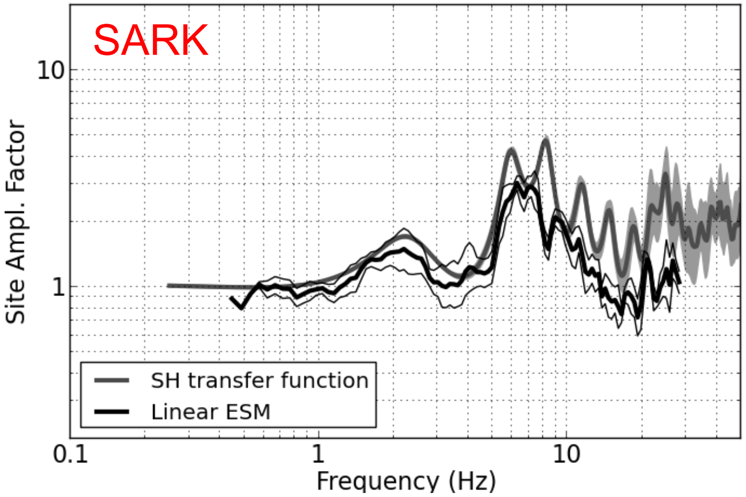
- More complex prediction
- Abs. maximum at f_n
- Irregular shape

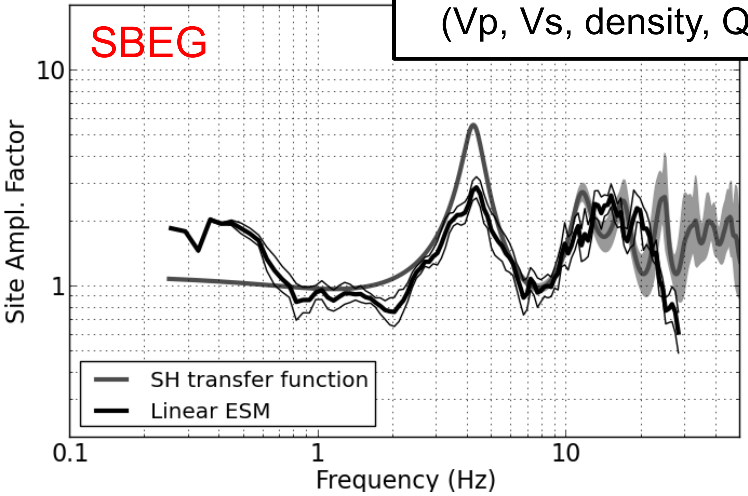
No closed form solution!

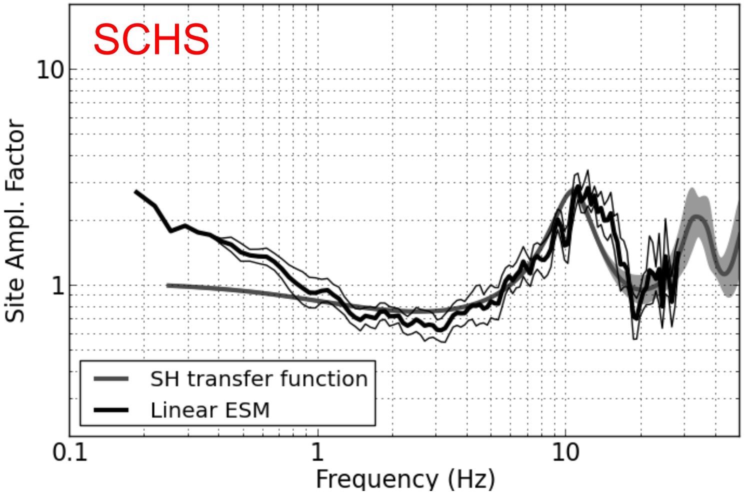
1D Cases

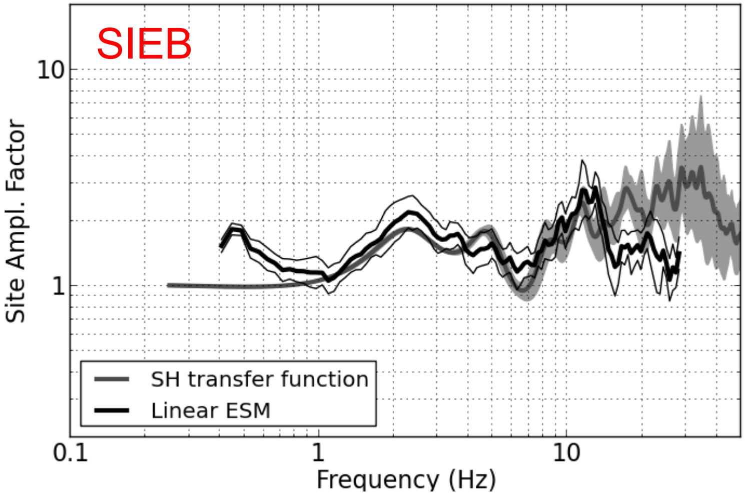
...nonetheless, good results can still be obtained with 1D modeling

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

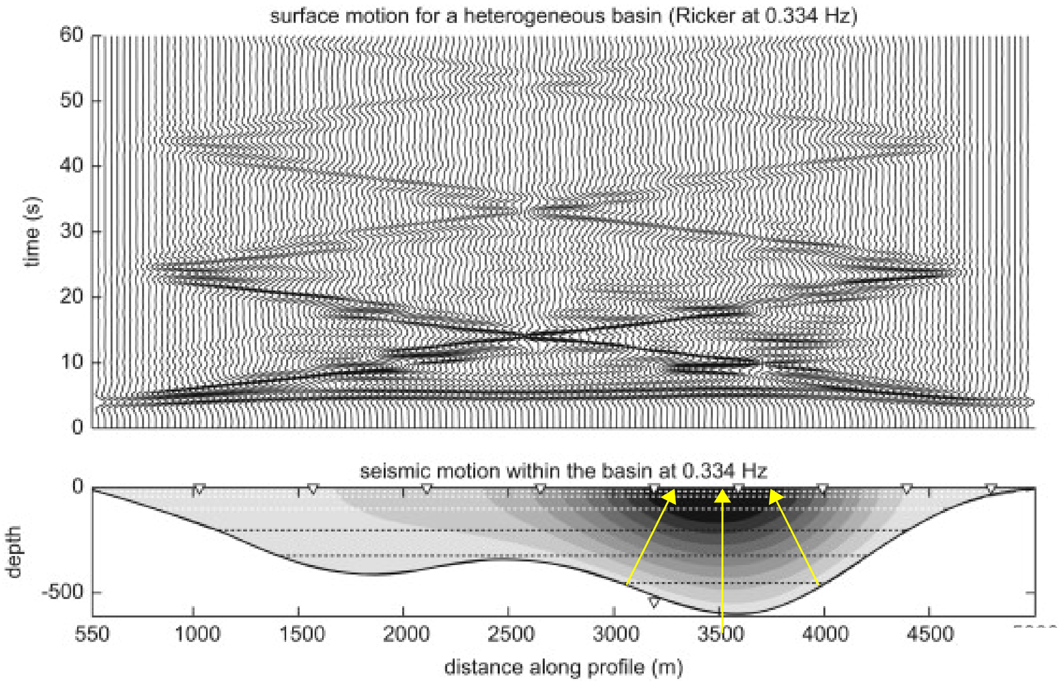








2D/3D basin effects

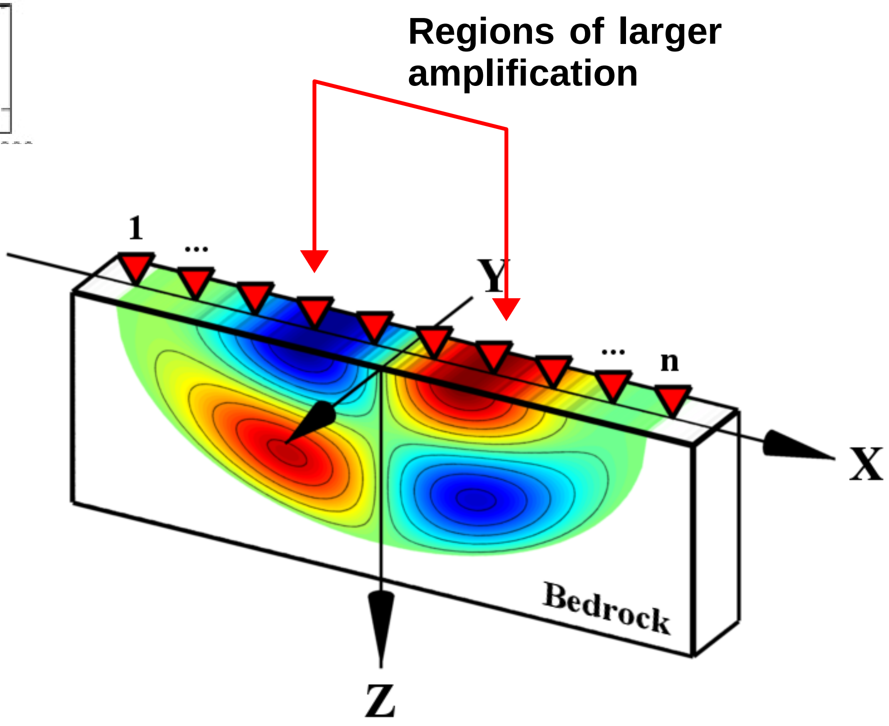


surface motion for a heterogeneous basin (Ricker at 0.334 Hz)

seismic motion within the basin at 0.334 Hz

Delépinea and Semblat., SDEE, 2012

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



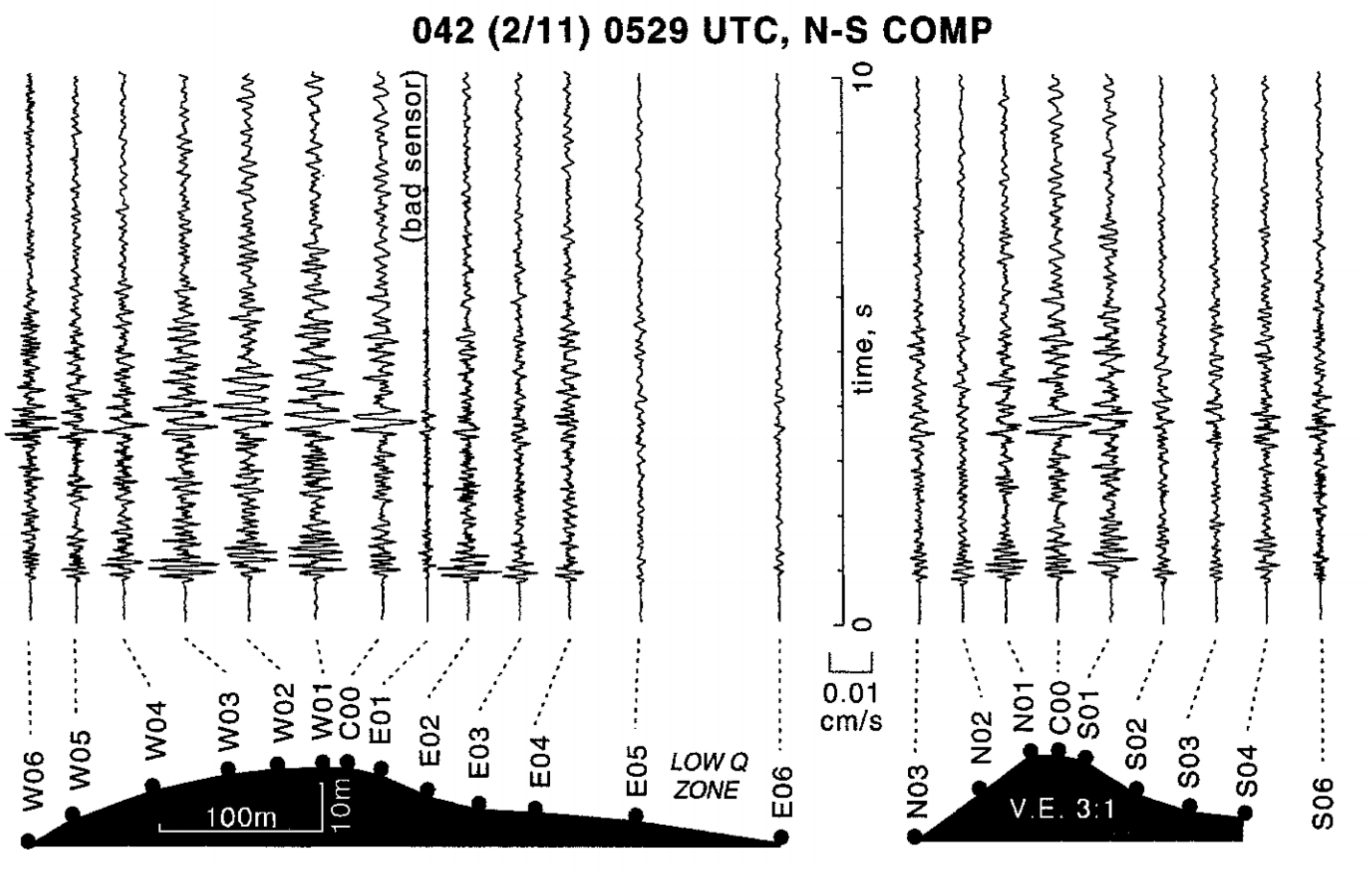
Regions of larger amplification

Site effects affecting the ground motion:

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

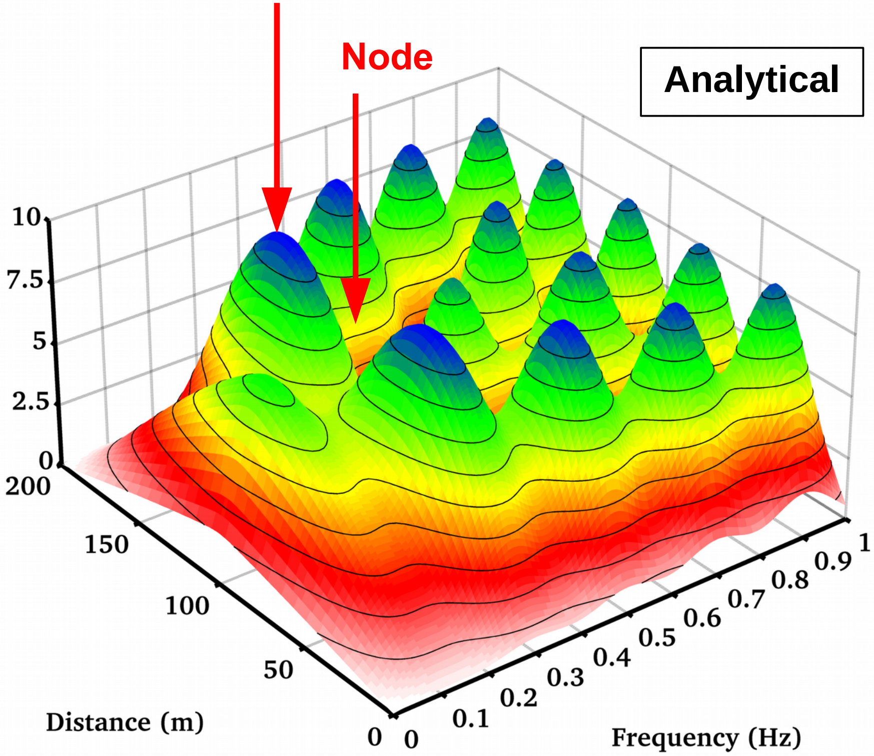
2D/3D Topographic Effects

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



Antinode

Node

Analytical

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

Quantifying resonance amplification is not easy:

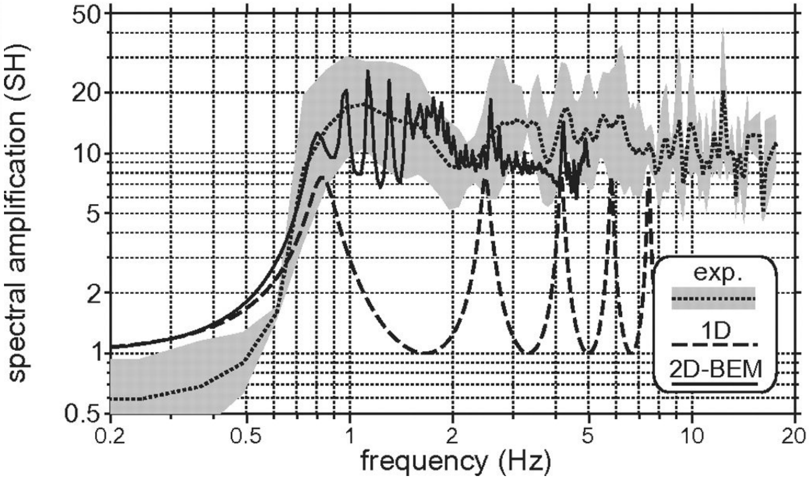
⇨ Analytical solutions (nearly) impossible

⇨ Numerical analysis very complex

⇨ Empirical estimation problematic....

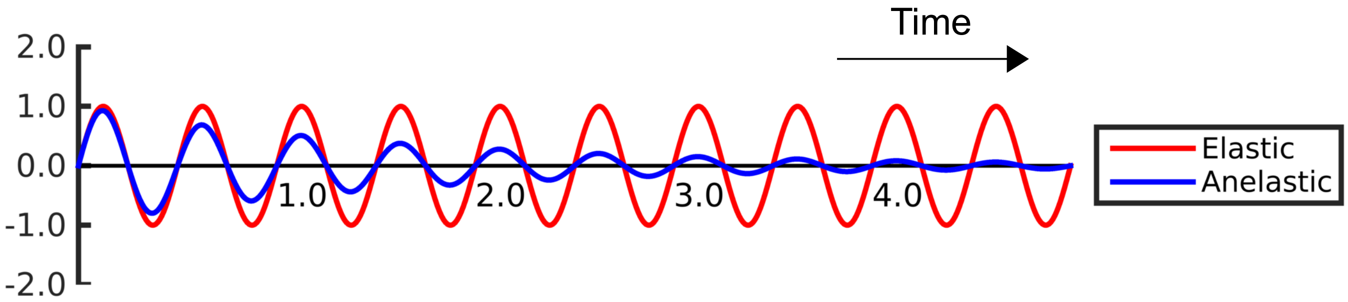
Empirical

Semblat and Bard., BSSA, 2008



Anelastic Attenuation

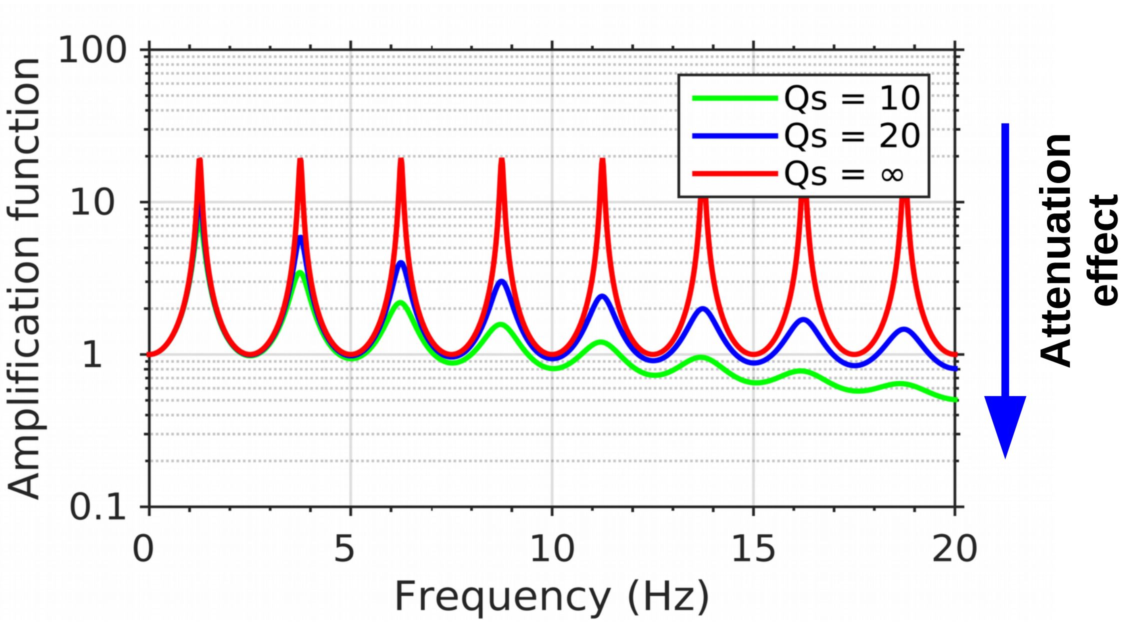
Anelastic (or intrinsic) attenuation is a property of the visco-elastic materials, where the energy of the propagating wave is dissipated by the effect of friction of the constituting elements (minerals, sedimentary grains, etc.)



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

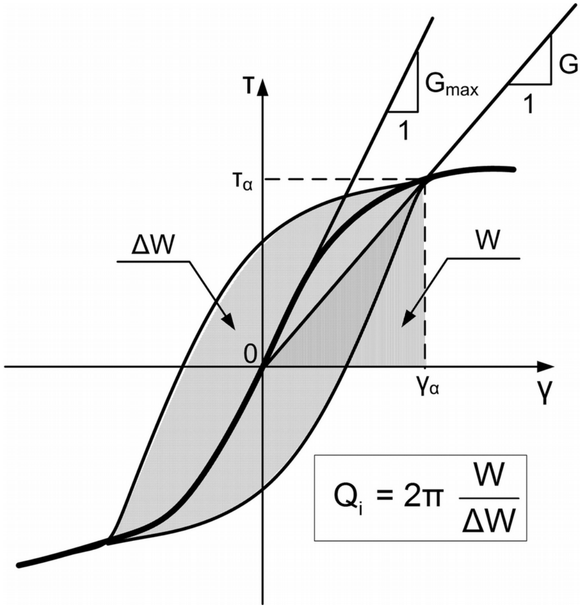
Anelastic attenuation has basically the effect of a low pass filter

Qs calibration not easy!



Non-linear Soil Behavior

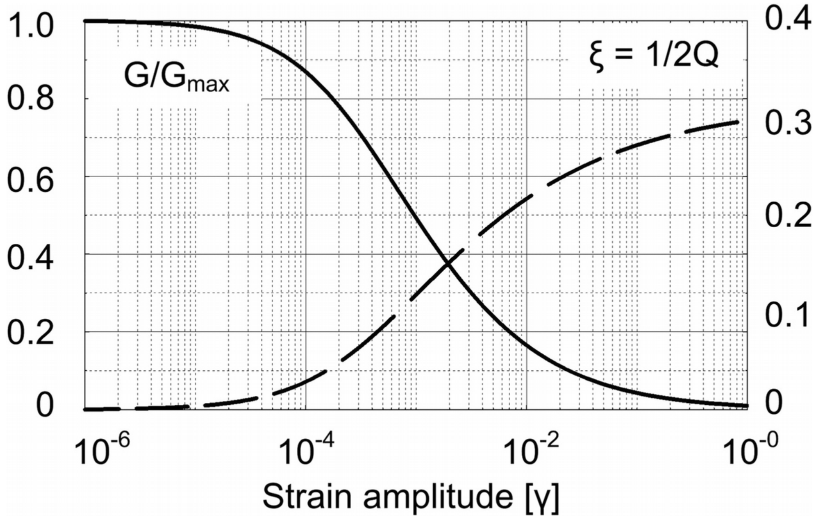
As the excitation level increases during strong earthquakes, some loose soils start behaving following a **non-linear stress-strain relation**



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

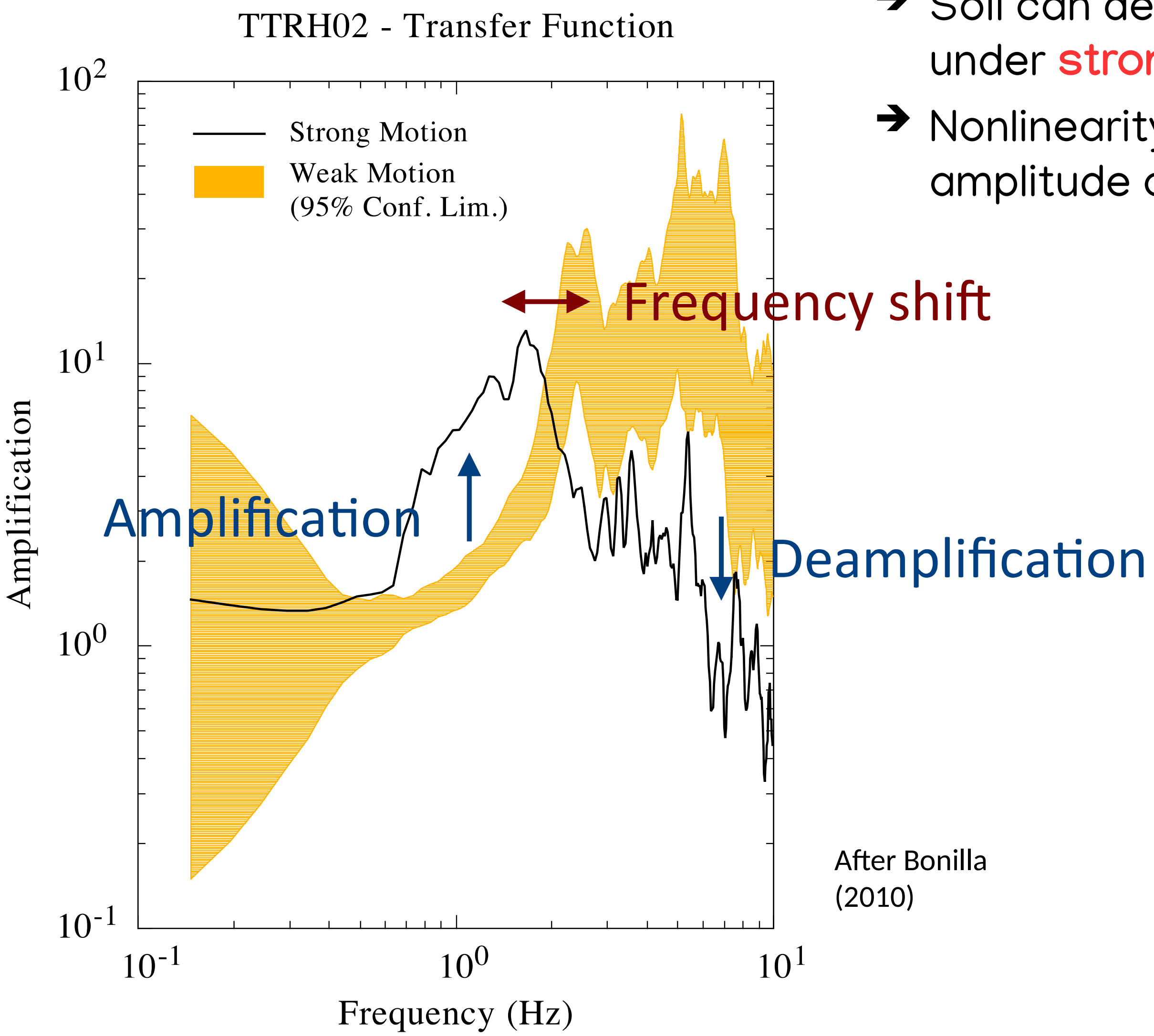


As a result, the signal amplitude is simultaneously:

- ❶ **decreased** by attenuation
- ❷ **increased** by increase in velocity

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

Non-linear Soil Behavior



After Bonilla (2010)

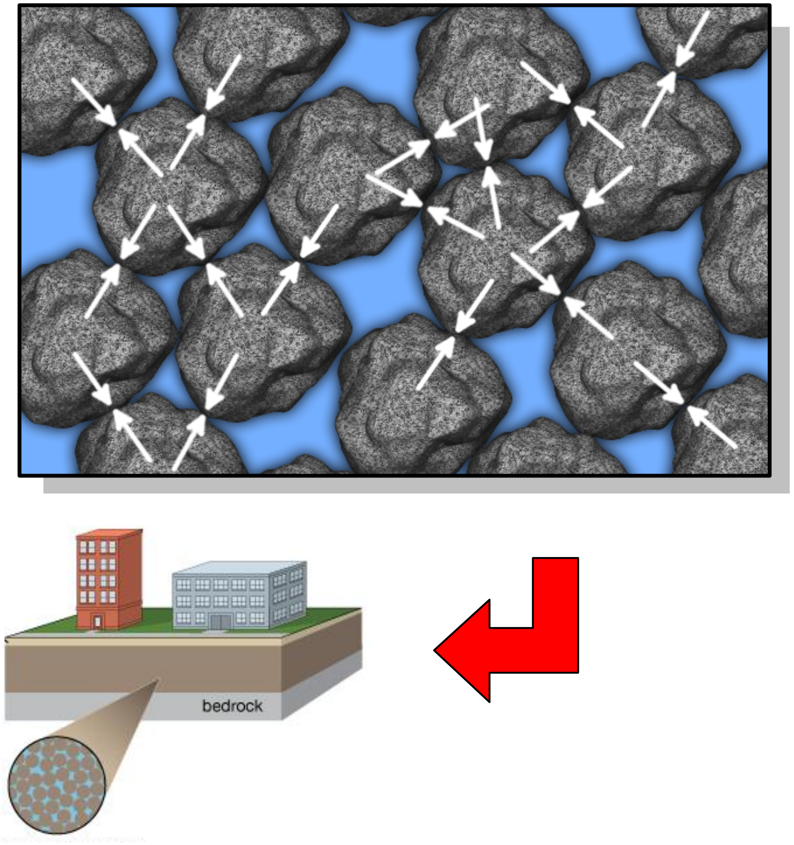
The problem of soil non-linearity:

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

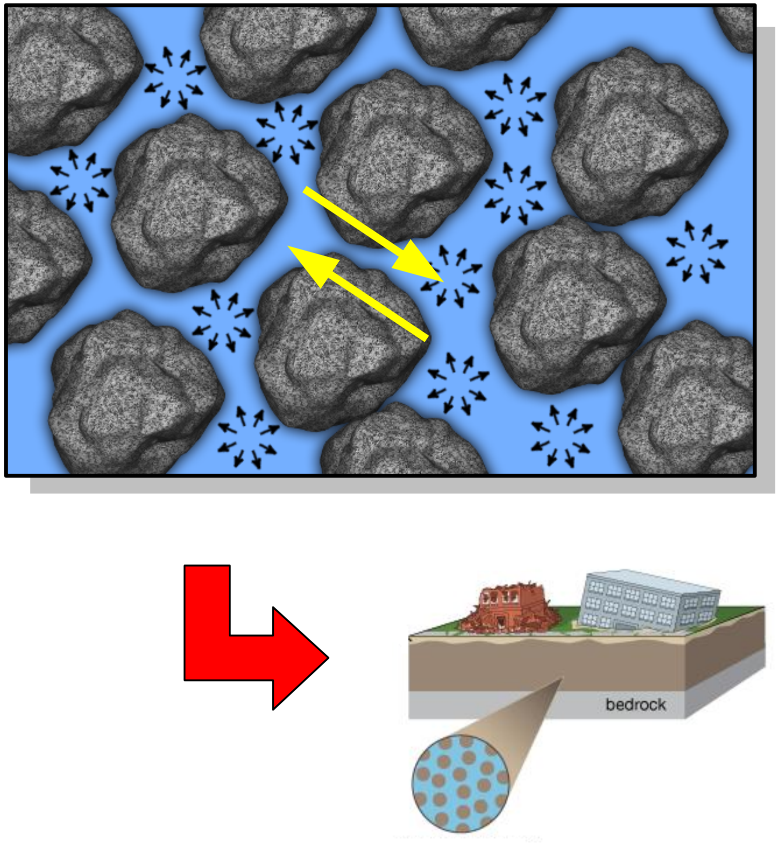
Soil Liquefaction

- 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 !



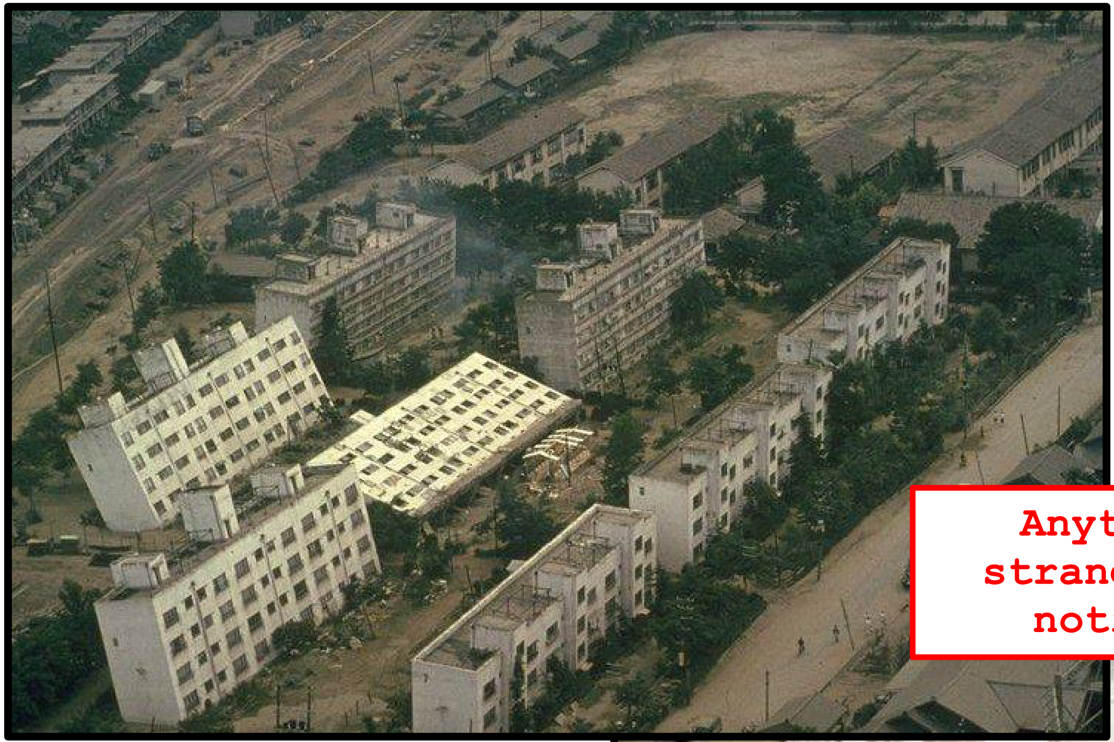
Liquefaction Examples

Kobe, Japan 1995
Mw 6.9

Emilia, Italy 2012
Mw 6.1

Christchurch, New Zealand 2010
Mw 7.1

Liquefaction Examples



Niigata, Japan 1964

Mw 7.5~7.6

Anything strange you notice?

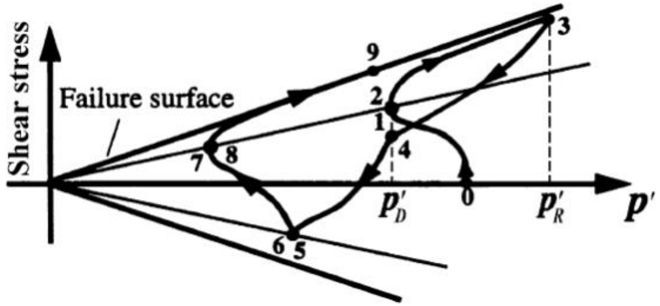
Izmit, Turkey 1999

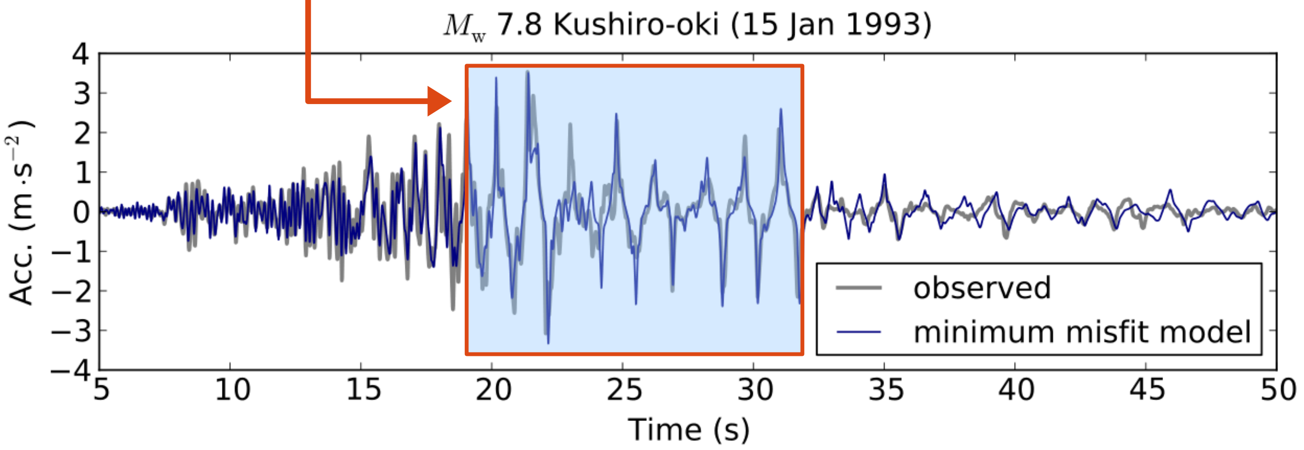
Mw 7.6

Cyclic Mobility

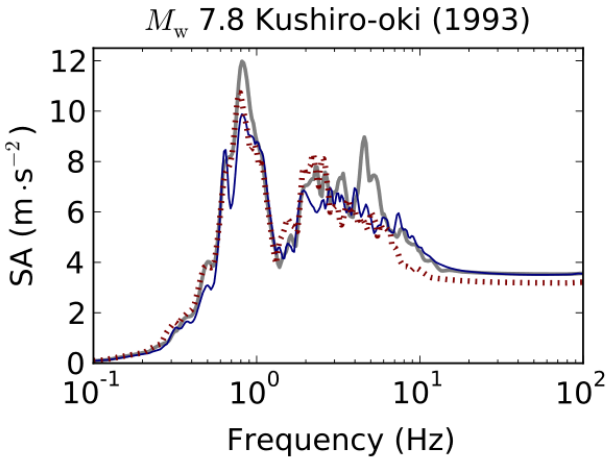
- It occurs in dense, cohesionless saturated soils when cyclic loading-unloading is applied
- The material experiences several cycles of softening (decrease in shear resistance) and stiffening
- Soil failure may occur after several cycles of loading
- Earthquake signal can heavily be altered by development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

Complex stress path!





Very difficult to model!



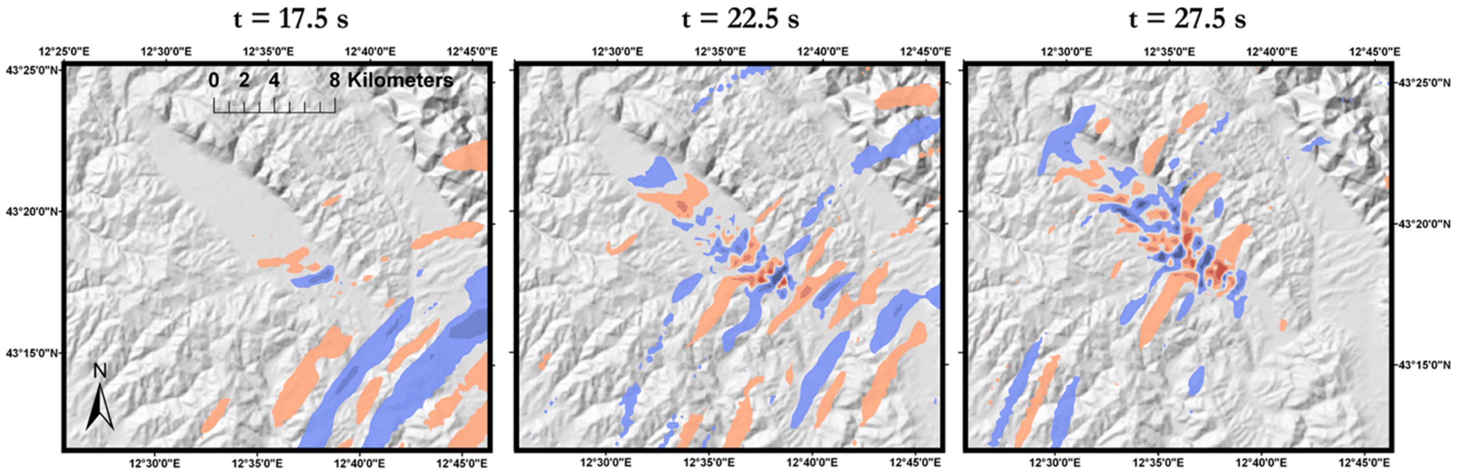
Indirect Modeling Mothods

- 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)

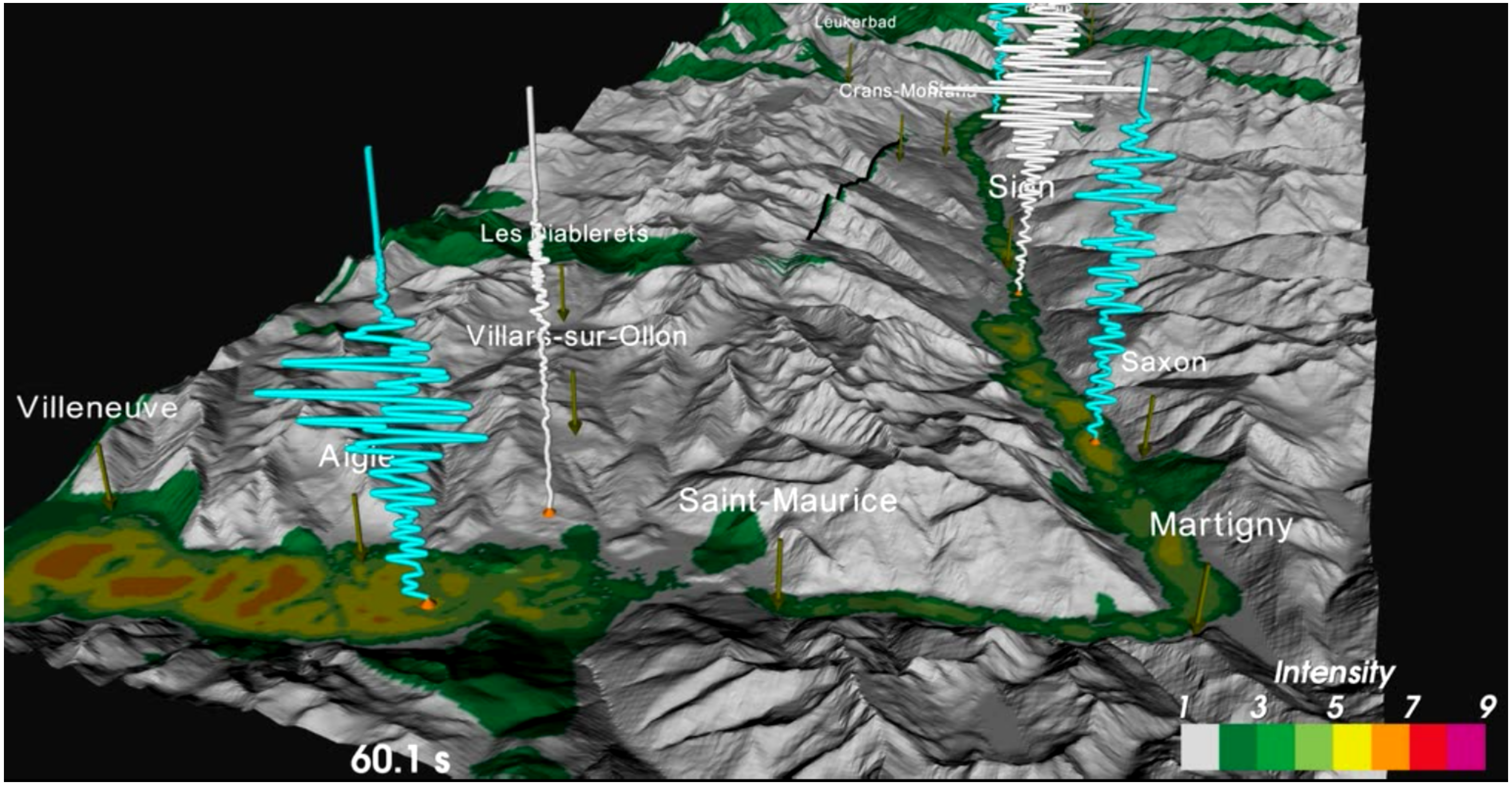
t = 17.5 s

t = 22.5 s

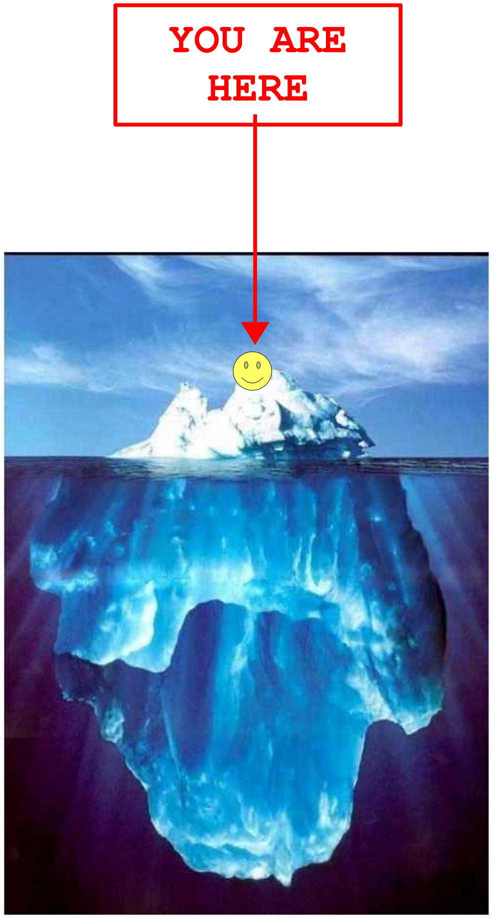
t = 27.5 s

Paolucci & Smerzini, esg4, 2012

Time to Watch a Movie…



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......

Title