

ACTIVE TECTONICS, 2018
Laurea Magistrale in Scienze Geologiche Applicate
Università degli studi di Pavia

**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

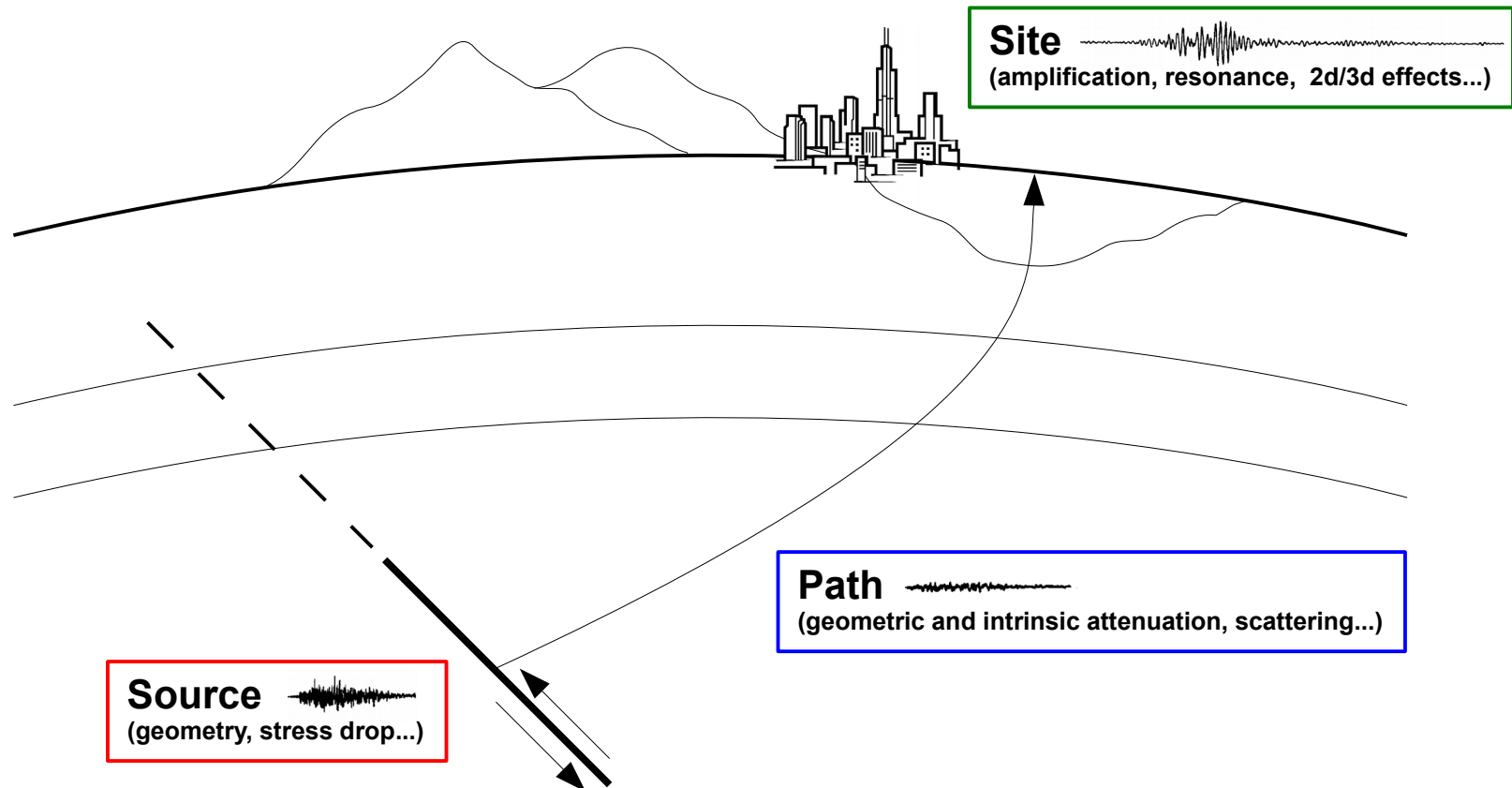


L'Aquila Earthquake 2009,
Magnitude Mw 6.3

Introduction

Factors controlling Ground Motion

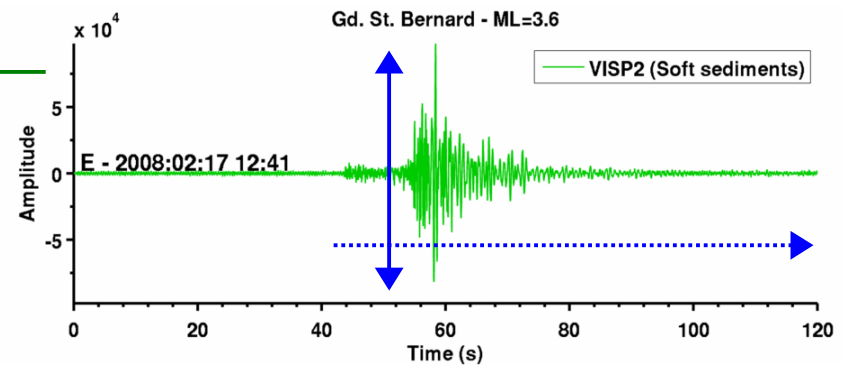
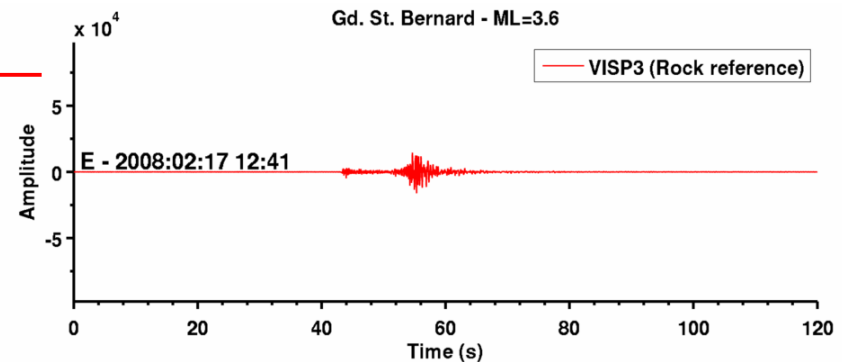
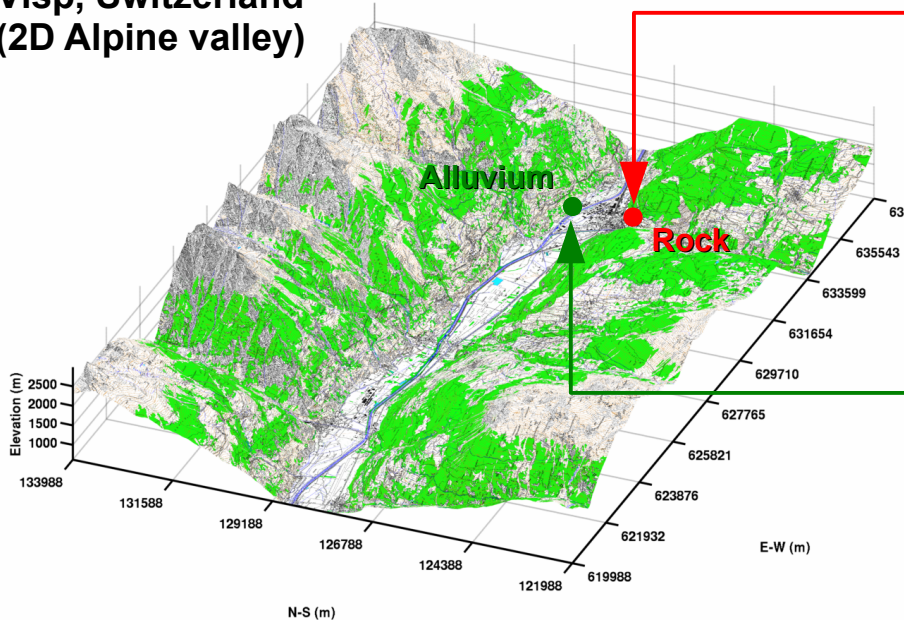
- Earthquake signals can be strongly altered during their propagation from the **source** to the **observation point**
- Significant contribution comes from the uppermost **few hundred meters of the earth structure**, where the larger variability of the geological conditions is present
- As a result,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



Effect on Ground Motion: Local Seismic Response

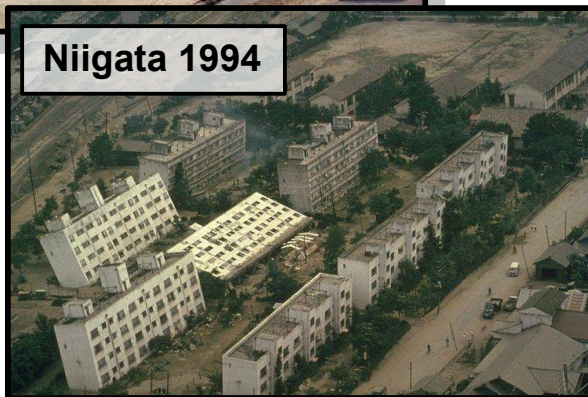
- For a particular site, the **amplitude** and **duration** of the ground motion during an earthquake can significantly be modified by the effect of the *local site conditions*
- On **very soft sediments** on top of a rigid bedrock, the ground motion can be **amplified** by more than a factor of 10, 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

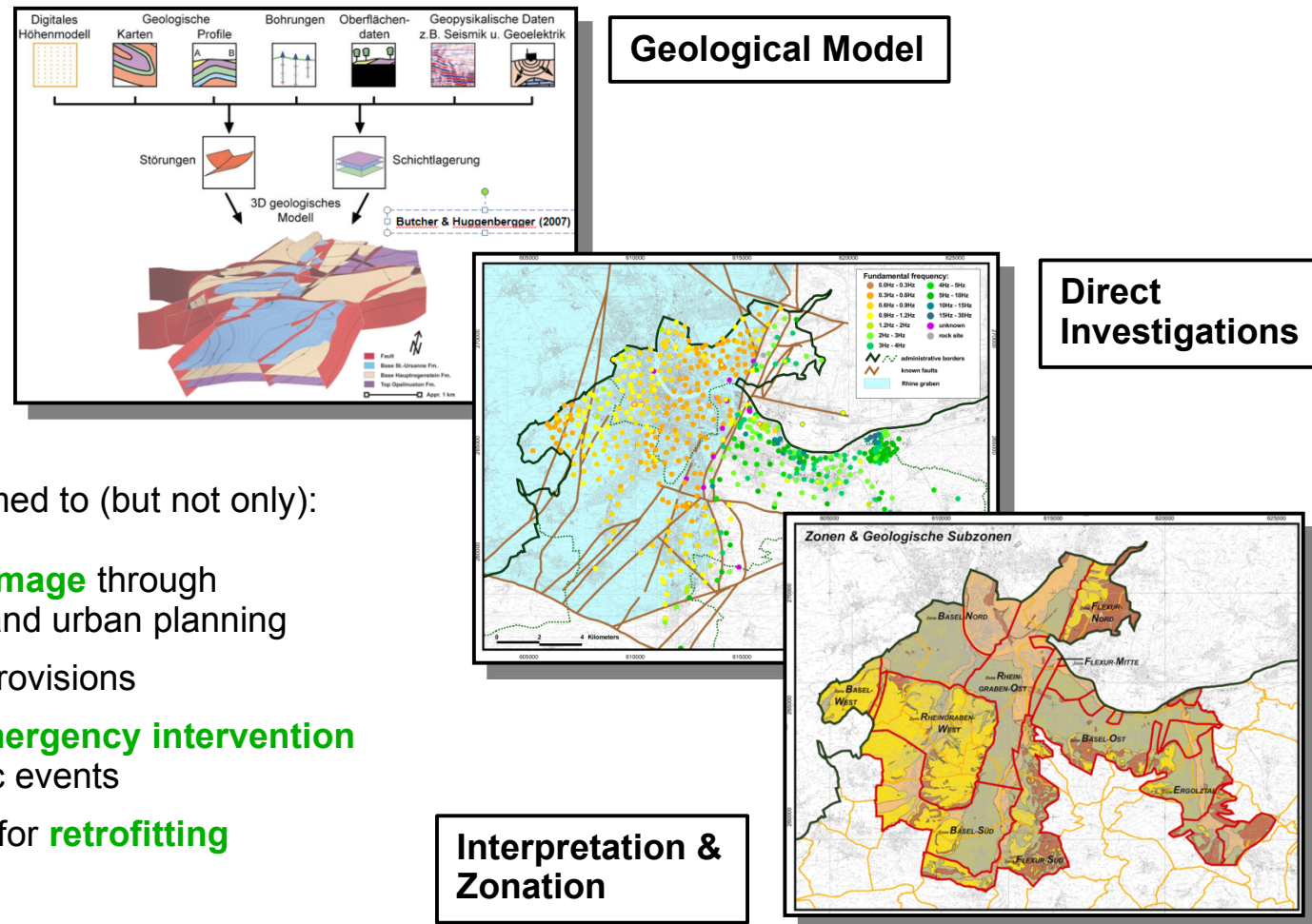
- The local environment is also vulnerable to certain shake levels, through development of **induced** or **secondary** effects, such as
 - ⇒ **Ground failures**: static displacement (offsets), subsidence, liquefaction, landslides...
 - ⇒ **Indirect or triggered effects**: flooding, tsunamis, snow avalanches..
- 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:

- ① the modification of the ground motion (amplitude, duration)
- ② earthquake induced phenomena

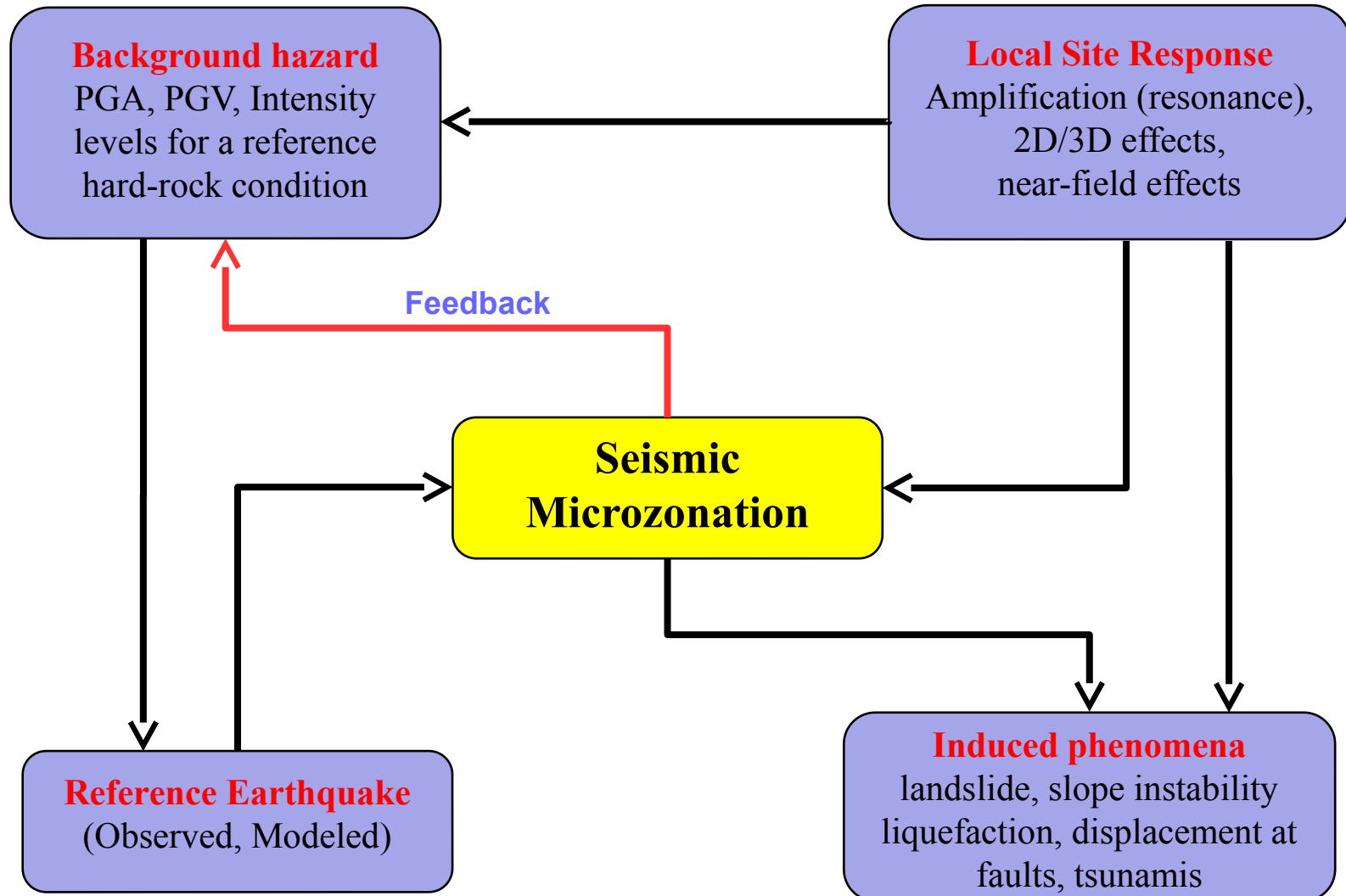


Microzonation is aimed to (but not only):

- ✓ **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)



Local Site Response

Local Effects influencing the Ground Motion

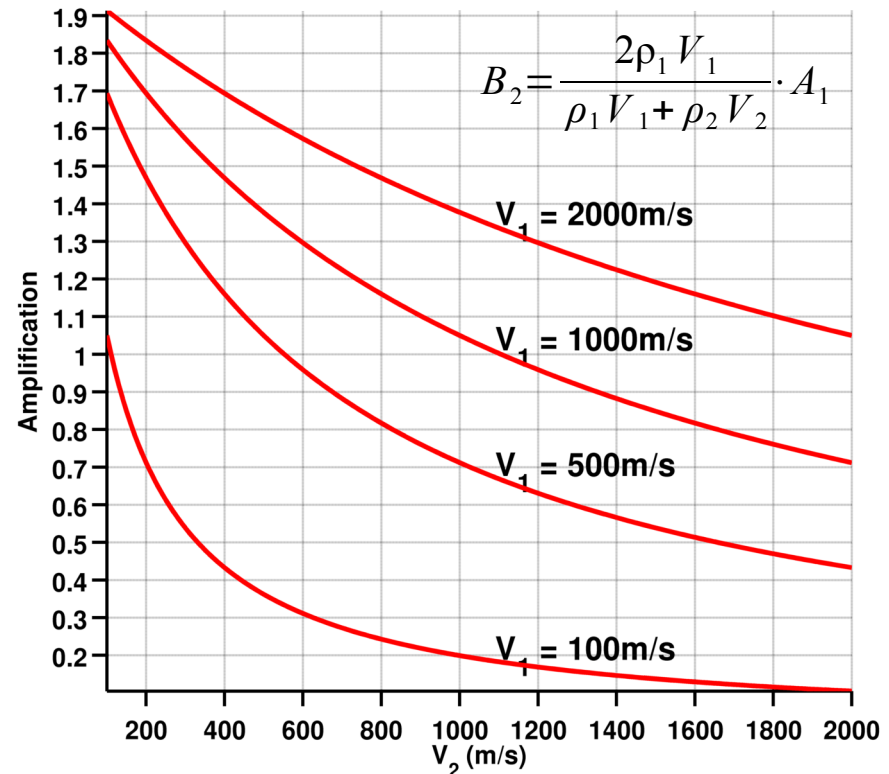
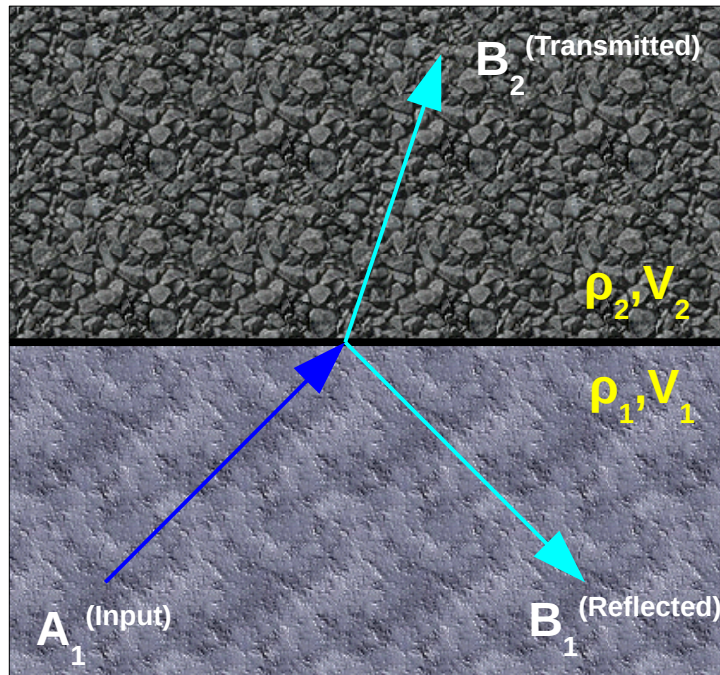
- Understanding the way local geological structures interact with the ground motion is the first step in site-response analysis
- Different phenomena can contribute to the complexity of the seismic response

- ① **Amplification phenomena** (seismic impedance contrast, resonance effect)
- ② **Geometrical effects** (2d/3d basin geometries, topography)
- ③ **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

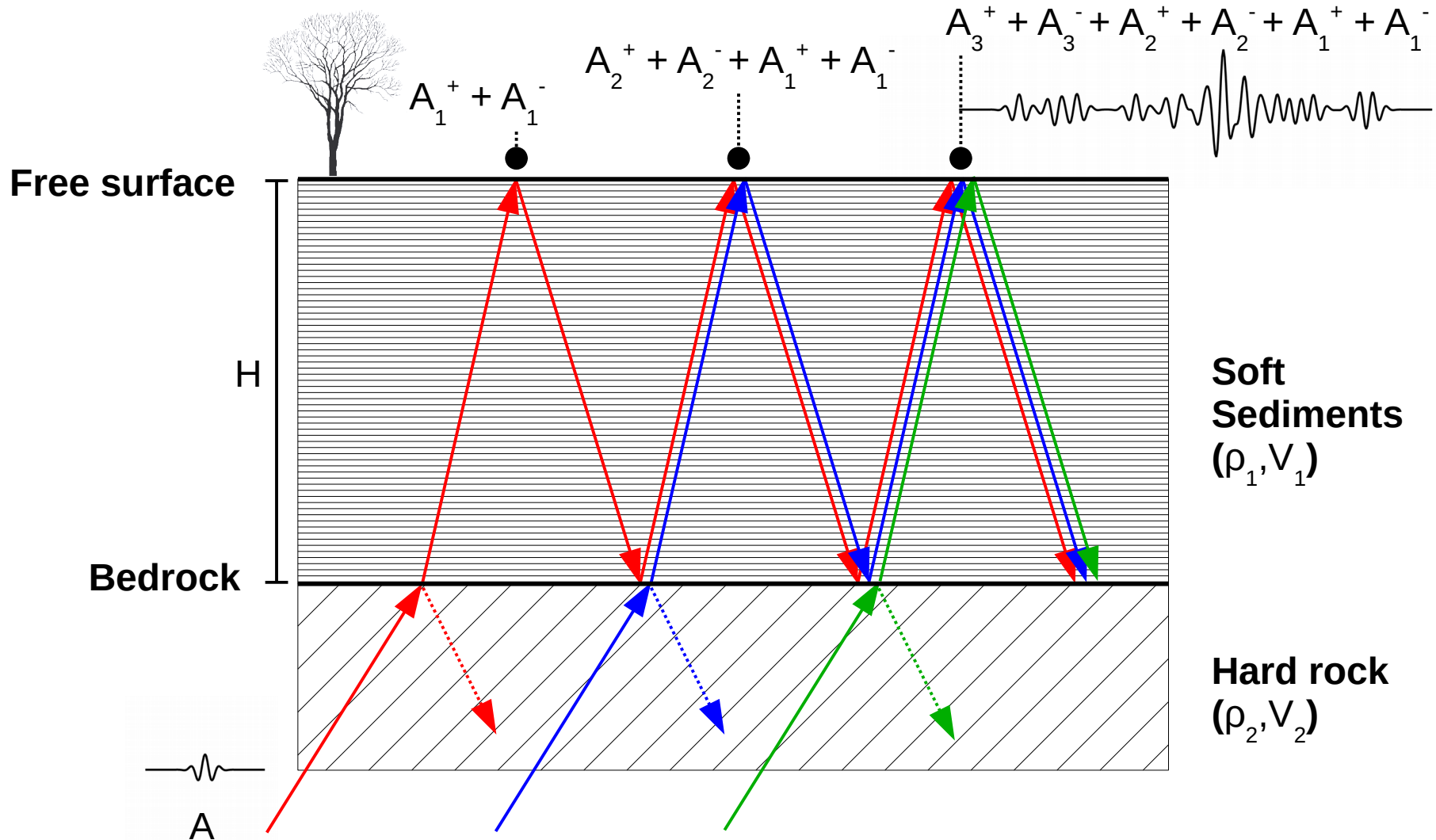
Theory of linear elasticity shows that a wave propagating across an interface between two media of different **seismic impedance** (*the product of the seismic velocity and the density*) modifies its amplitude and speed to satisfy the conservation of energy principle



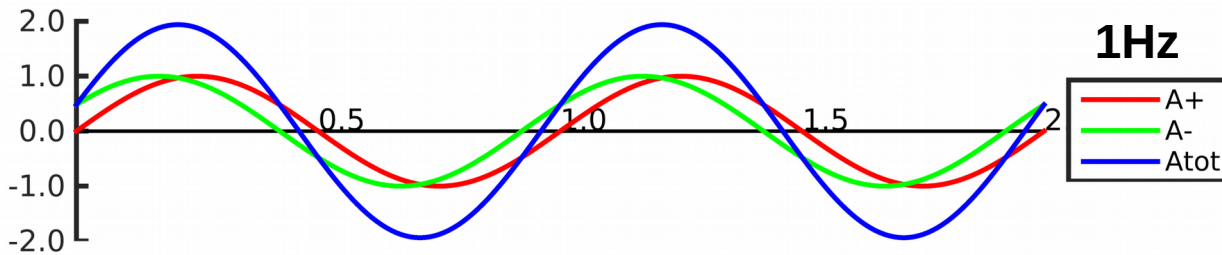
🔍 In the case of a sedimentary valley with **soft sediments** (low-velocity) on top of **rigid bedrock** (high-velocity), amplification of the ground motion has to be expected

The resonance amplification

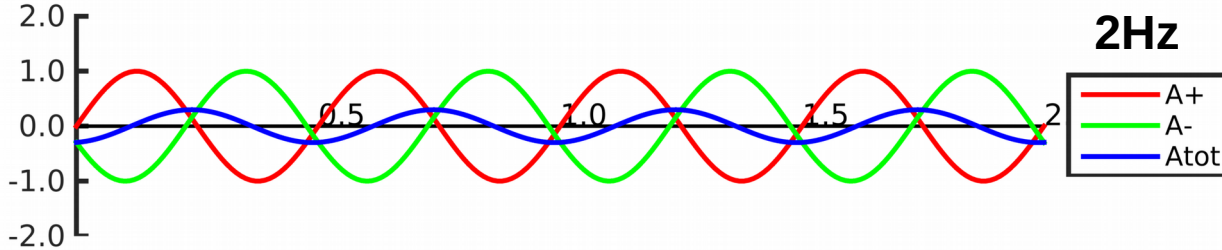
In soft sediment basins it is common a phenomenon of “*trapping*” of the wave-field, due to the multiple reflection and refraction of waves within the layers, which lead to a complex interaction called **seismic resonance**



Constructive Interference

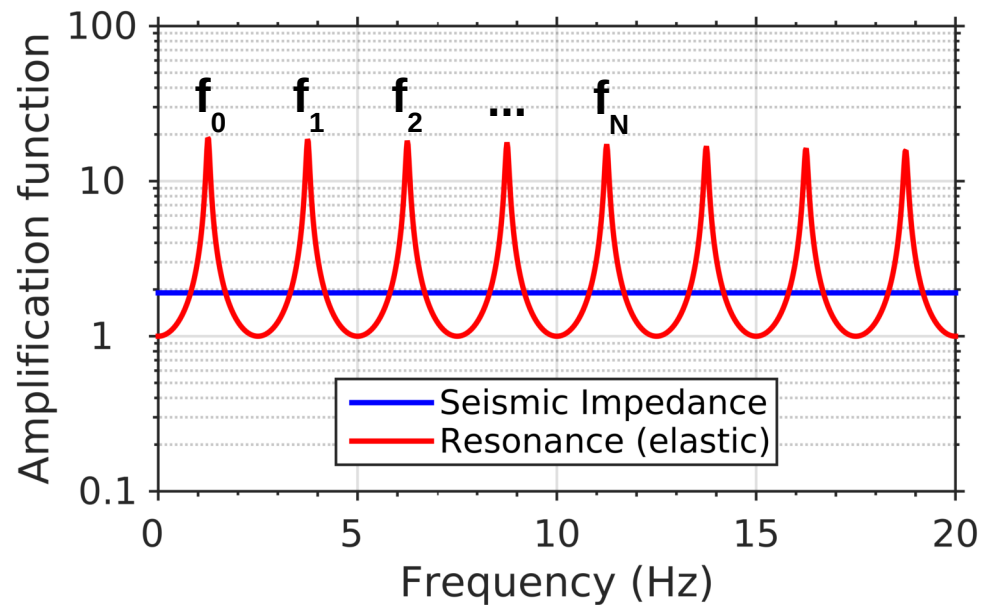


Destructive Interference



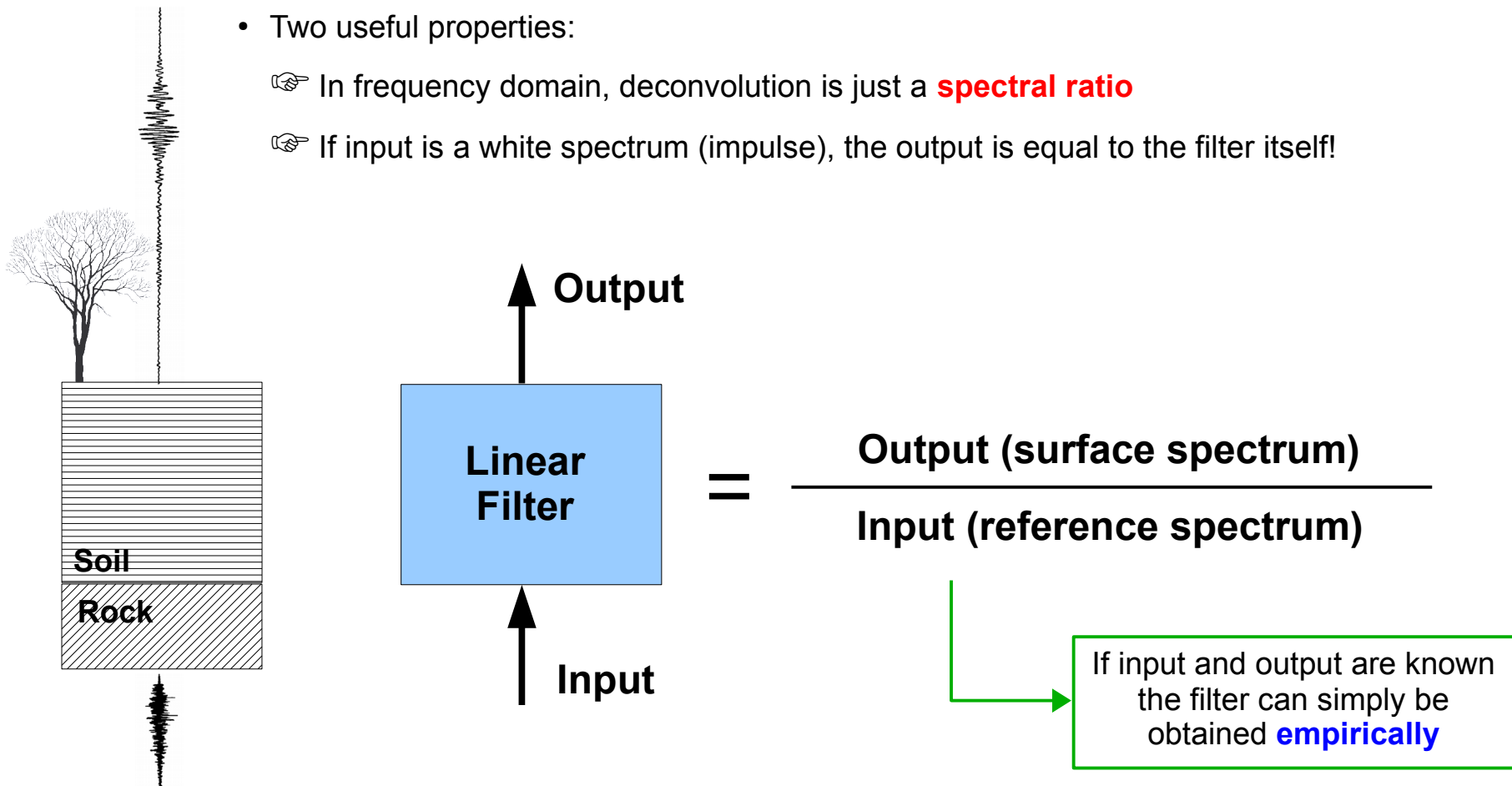
The phenomenon is **frequency dependent**, that means ground motion can either be **amplified** or **deamplified** at different frequencies....

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

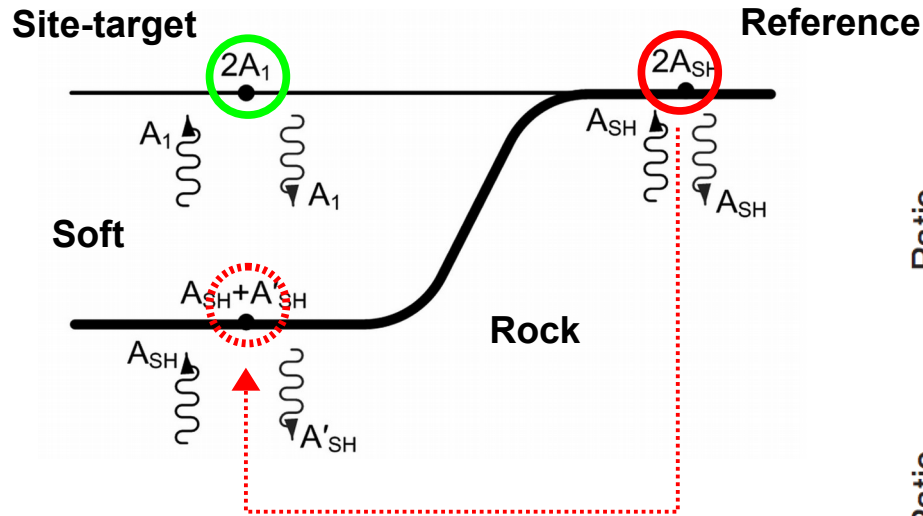


Linear Filter Equivalence

- 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!

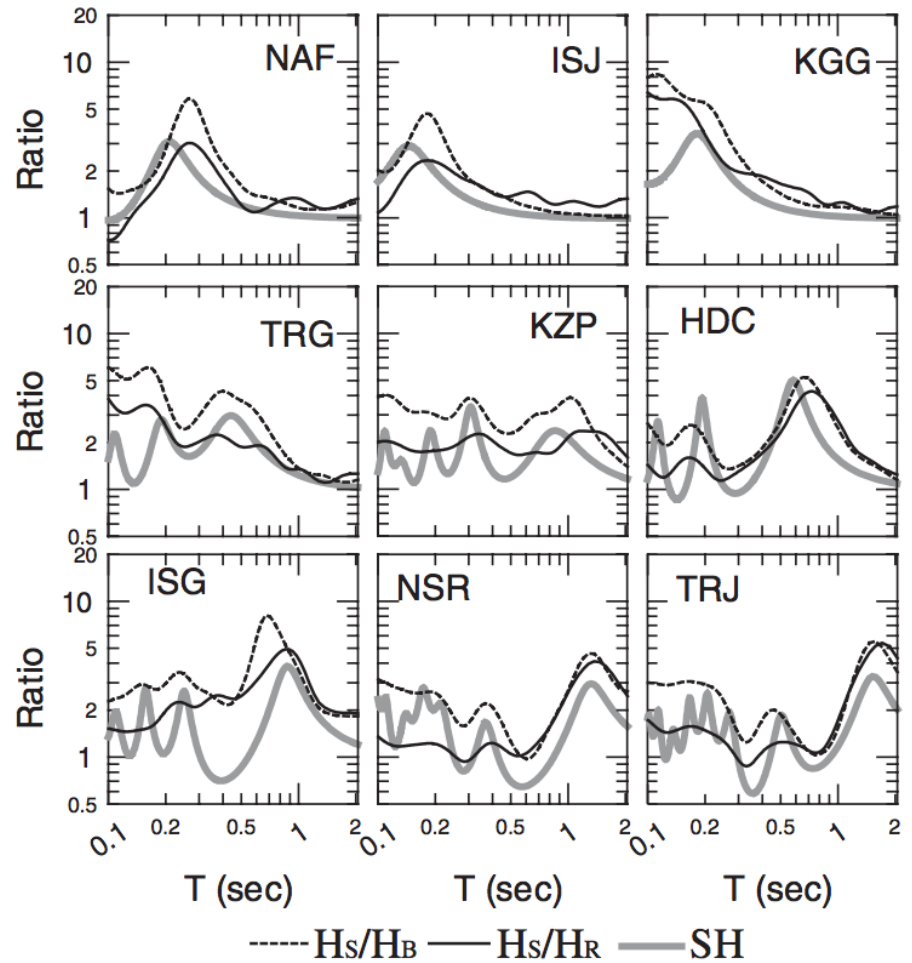


Empirical Site-to-Reference Spectral Ratios



- 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...)

SSR amplification



Rodriguez & Midorikawa (2003)

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:

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

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

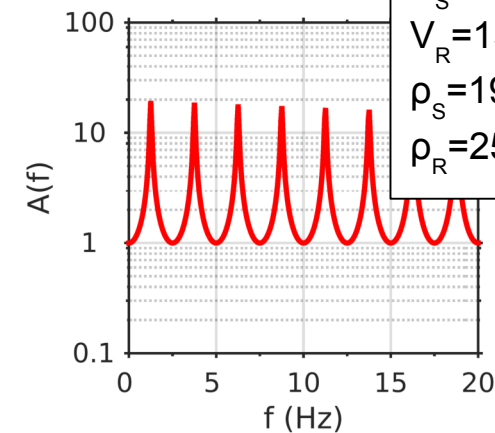
Impedance contrast

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

Fundamental

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

Overtones



$H=20\text{m}$
 $V_S=100\text{m/s}$
 $V_R=1500\text{m/s}$
 $\rho_S=1900\text{Kg/m}^3$
 $\rho_R=2500\text{Kg/m}^3$

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

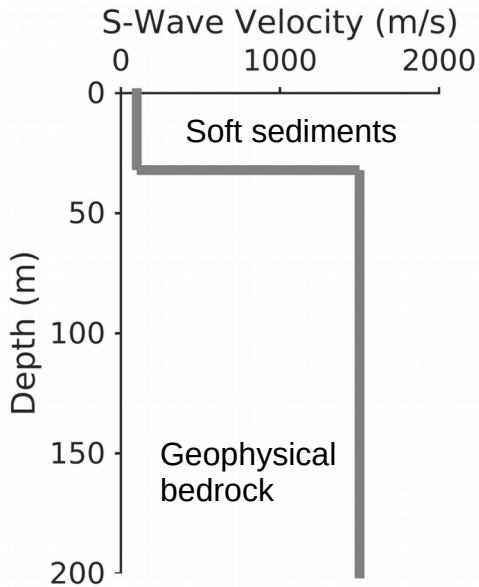
oversimplification often leads to increase in uncertainty of the solution, the so called **epistemic uncertainty**

...

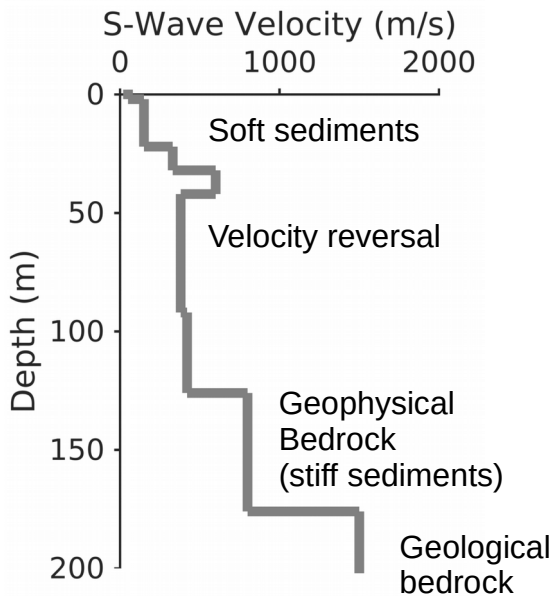
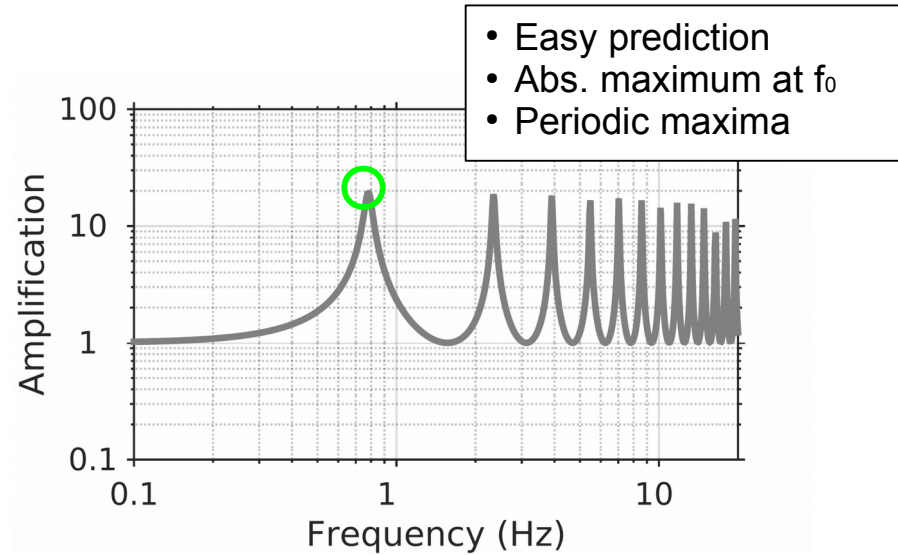
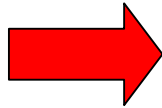
Obviously, things are getting more and more complicated when dealing with **real geological structures** and **realistic velocity profiles**

Let's see few examples....

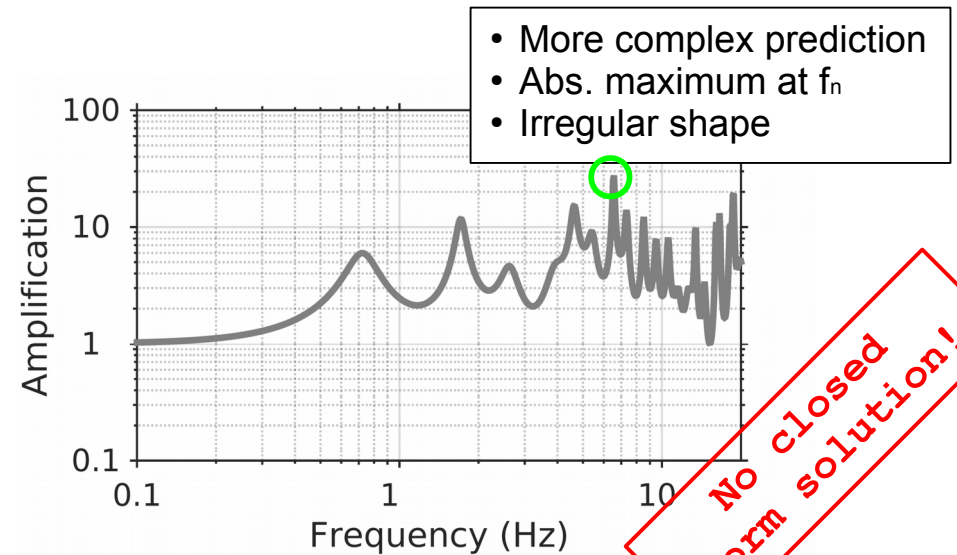
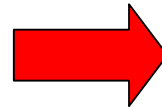
Using realistic velocity profiles



Simple case....



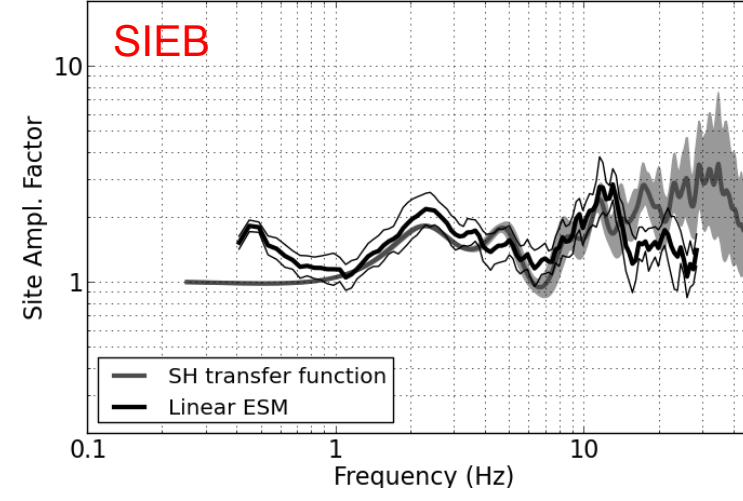
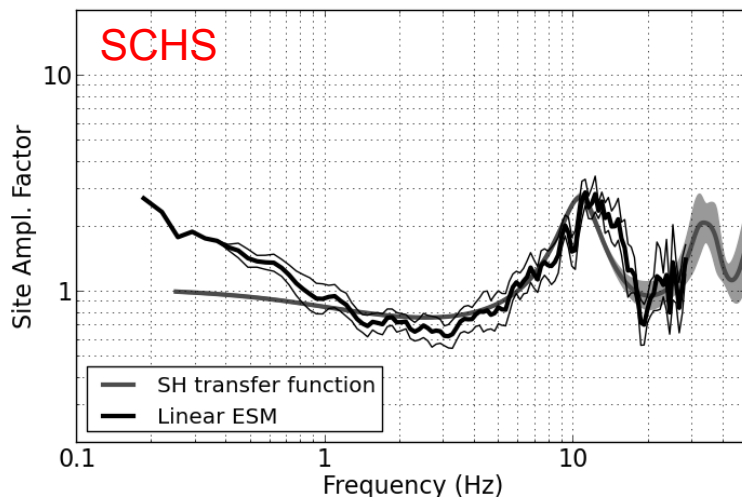
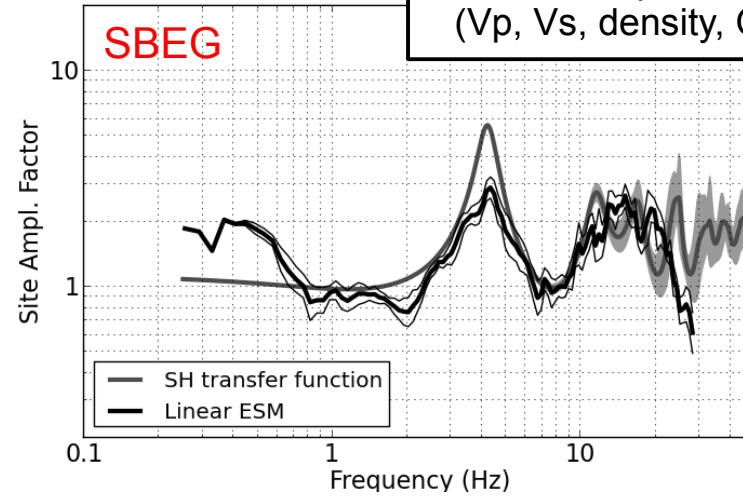
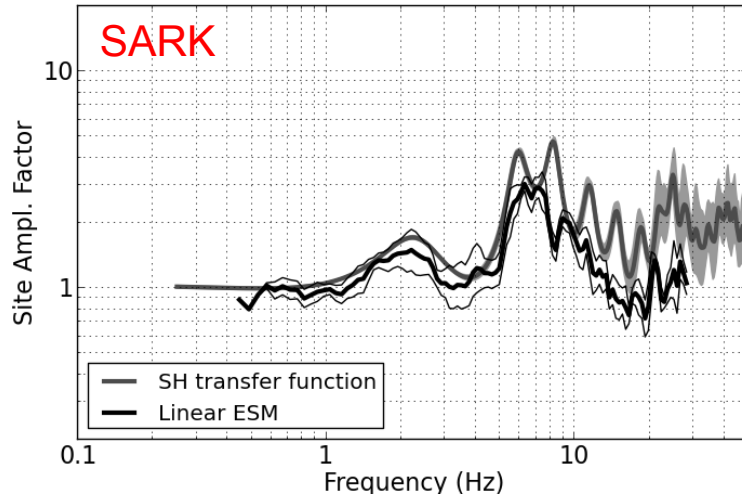
...reality

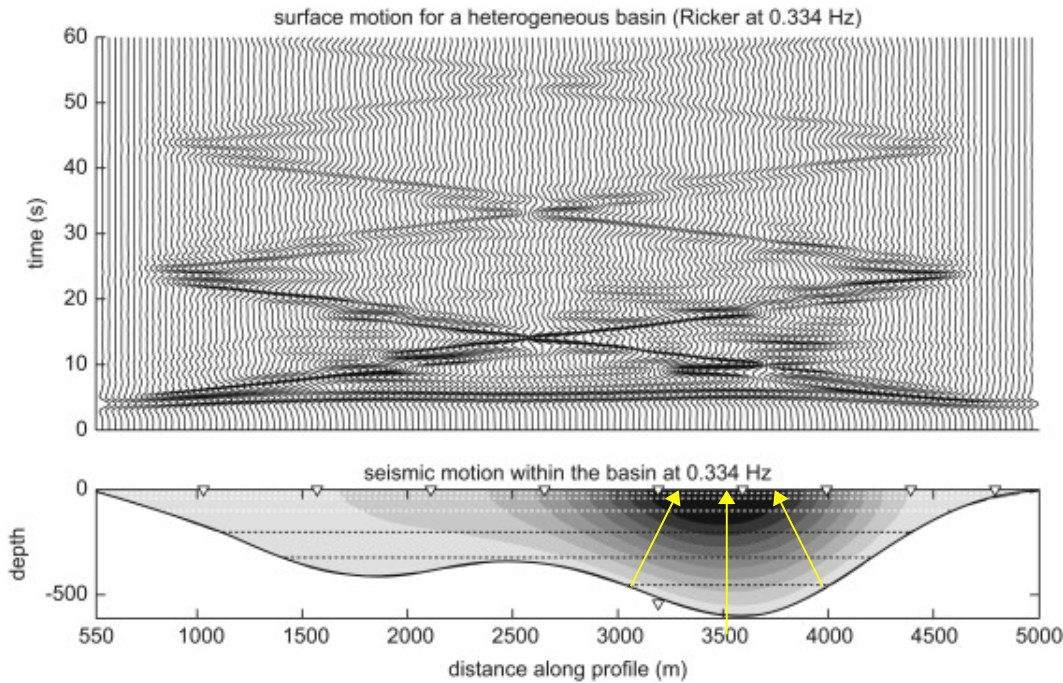


No closed form solution!

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

Require accurate knowledge of soil parameters (V_p , V_s , density, Q_p , Q_s ...)





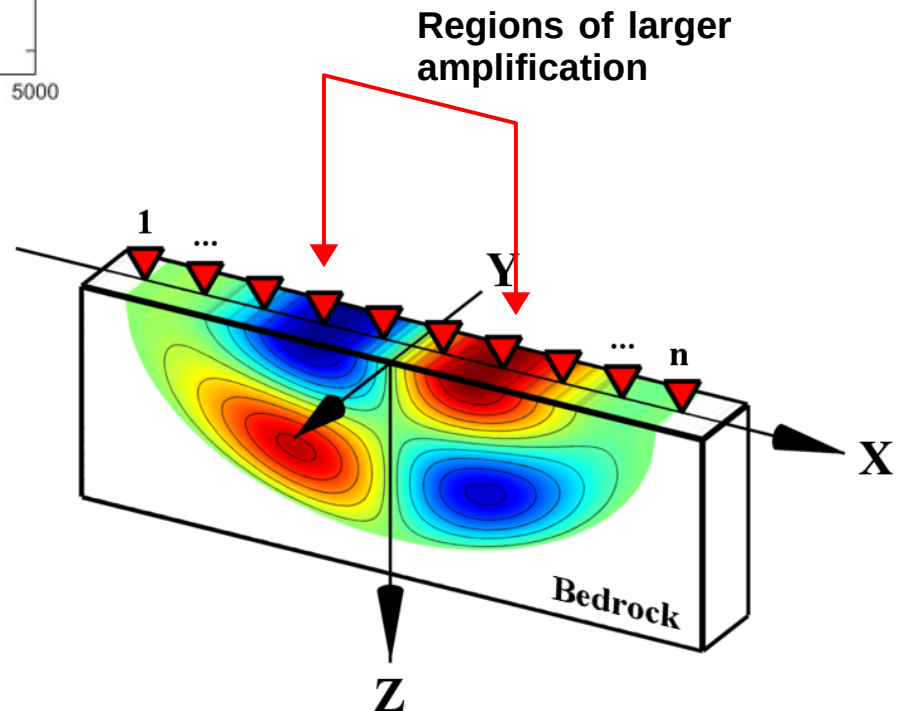
Delépine and Semblat., SDEE, 2012

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

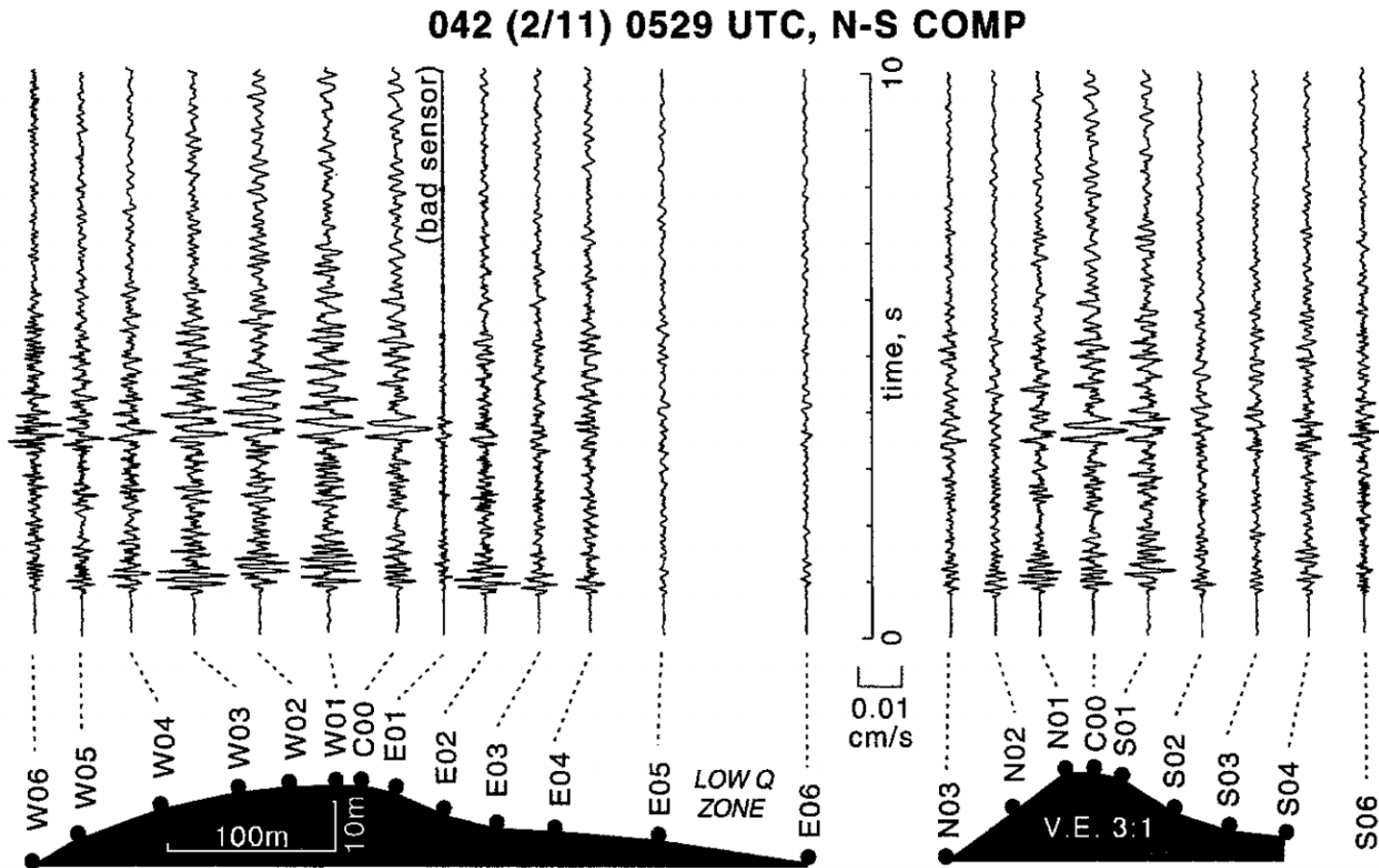
Site effects affecting the ground motion:

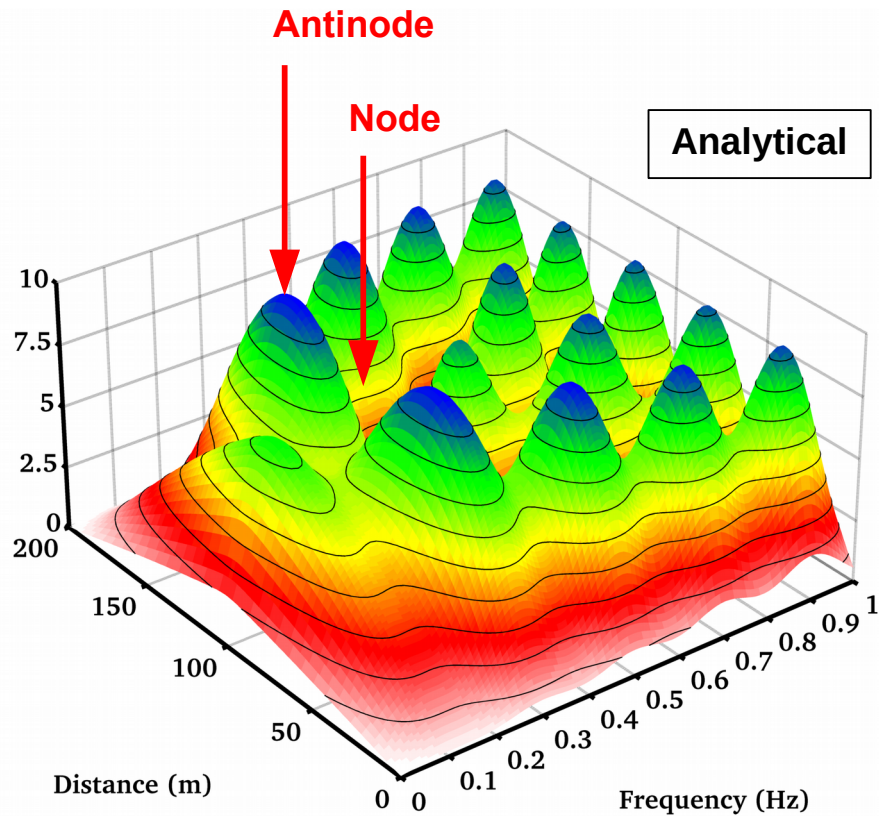
- Wave focusing and defocusing
- Wave diffraction and scattering
- **2D/3D resonance amplification**



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**).





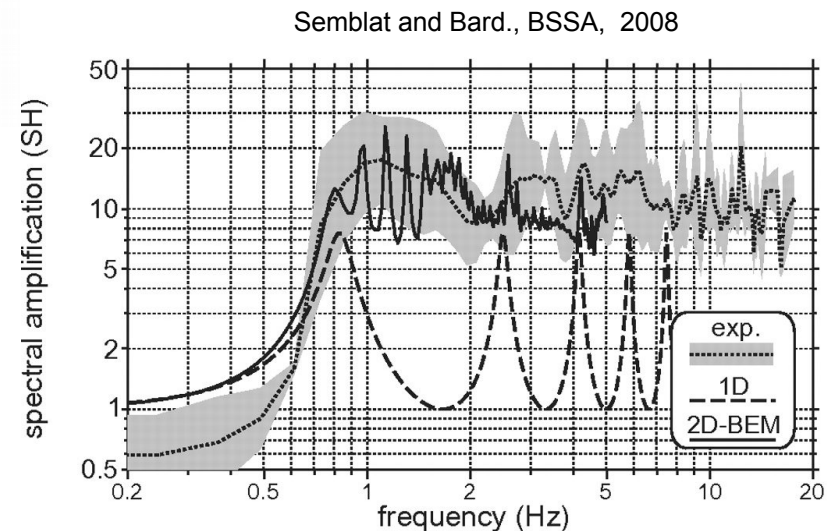
Quantifying resonance amplification is not easy:

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

2D/3D resonance amplification

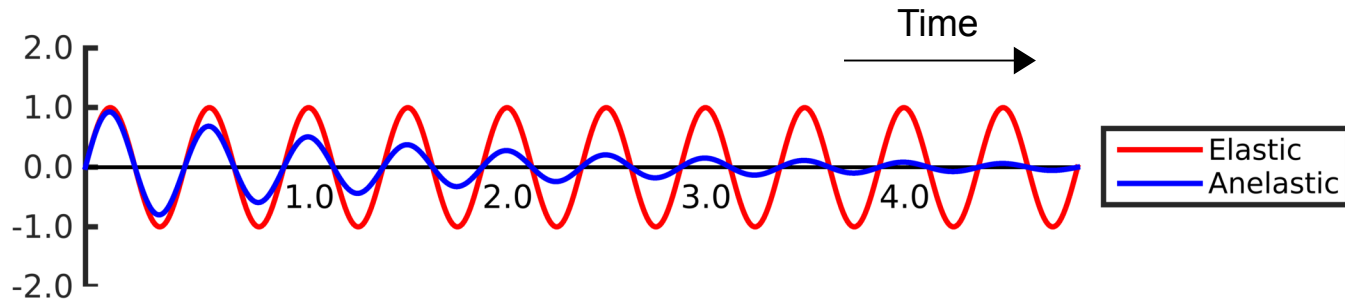
In the 2D/3D case, the resonance effect on the ground motion can be severe, but **well localized in delimited areas of the basin**

Empirical



Anelastic attenuation

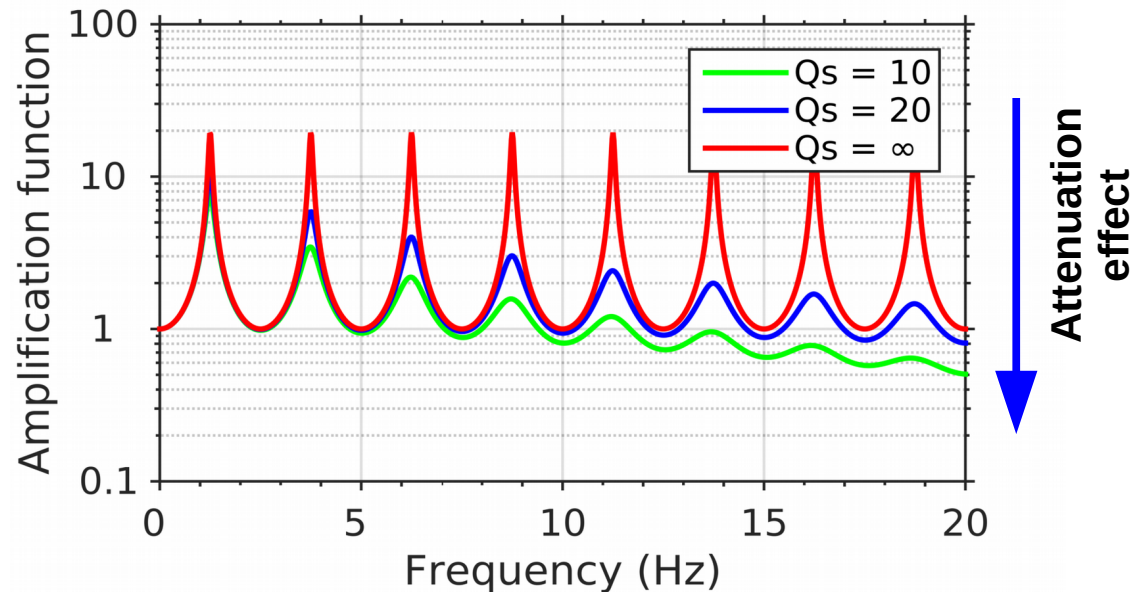
Anelastic (or intrinsic) attenuation is a property of the **visco-elastic materials**, where the energy of the propagating wave is dissipated by the effect of friction of the constituting elements (minerals, sedimentary grains, etc.)



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

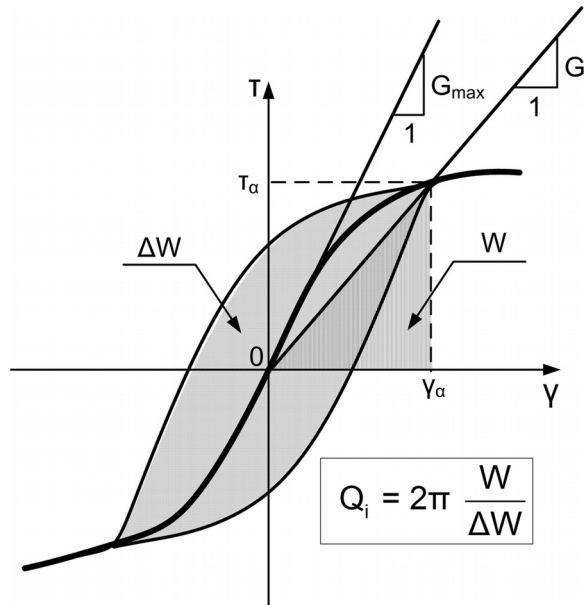
Anelastic attenuation has basically the effect of a **low pass filter**

**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)

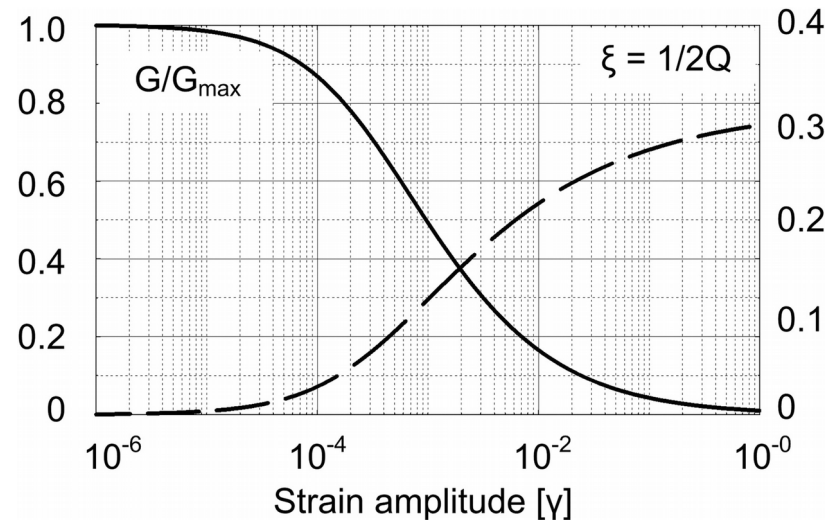
As a result, the signal amplitude is simultaneously:

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

→

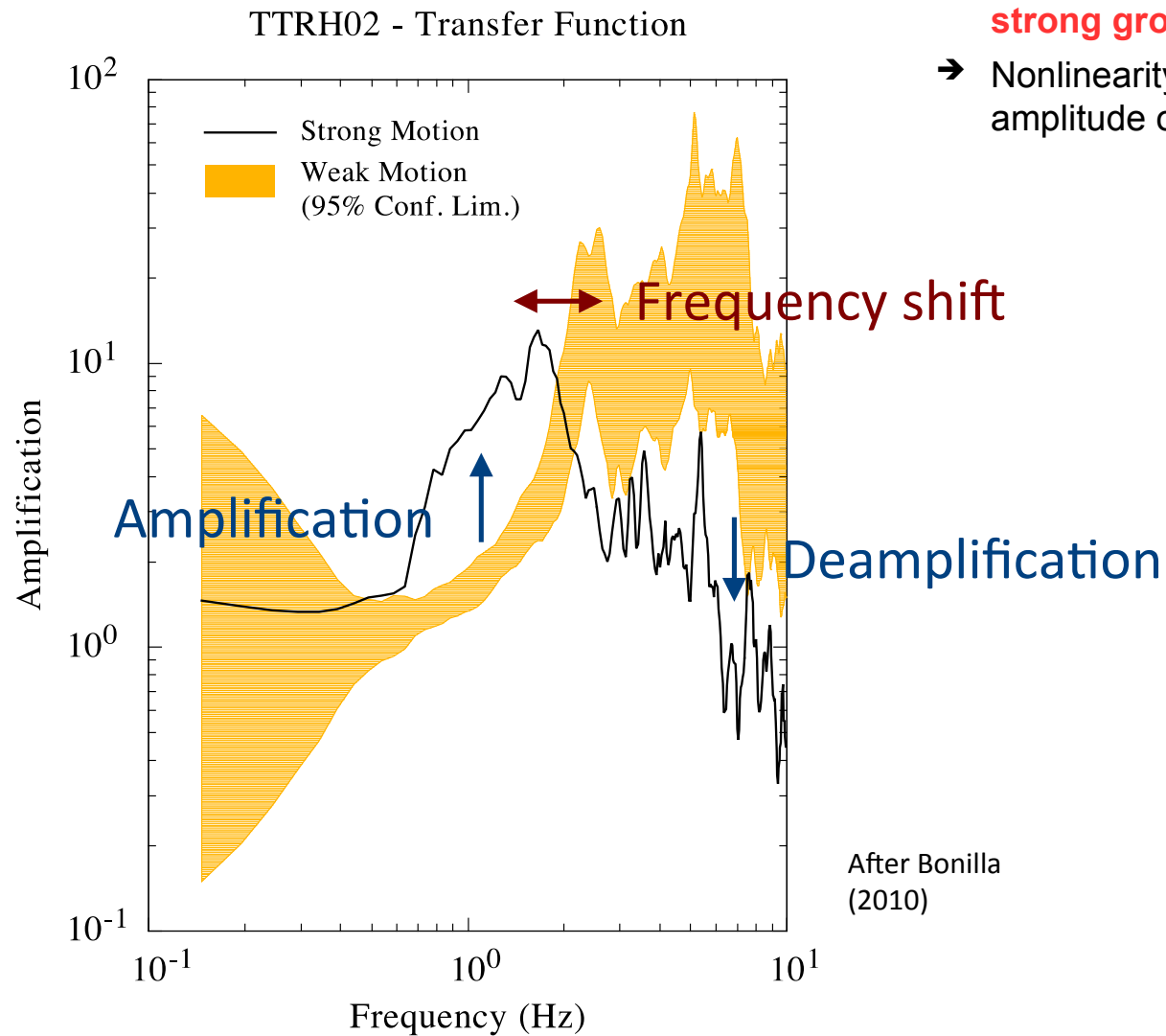
Result depends on the intensity of the shaking, the signal duration...

Assimaki et al., BSSA, 2008



The problem of soil non-linearity

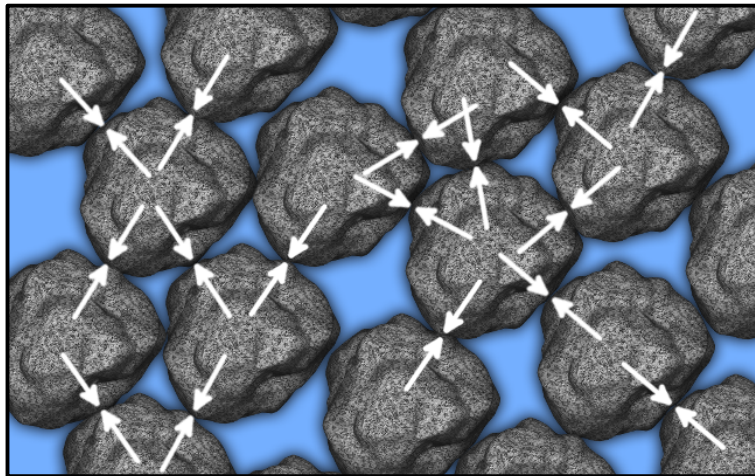
- Soil can develop a nonlinear behaviour under **strong ground motions**
- Nonlinearity changes the shape and amplitude of the **soil transfer function**



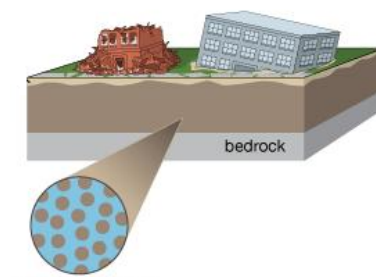
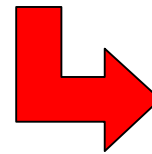
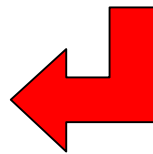
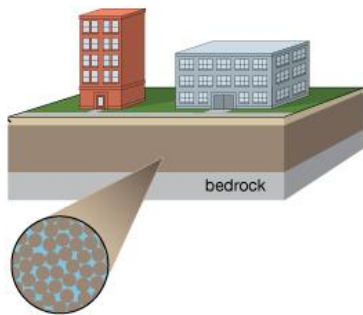
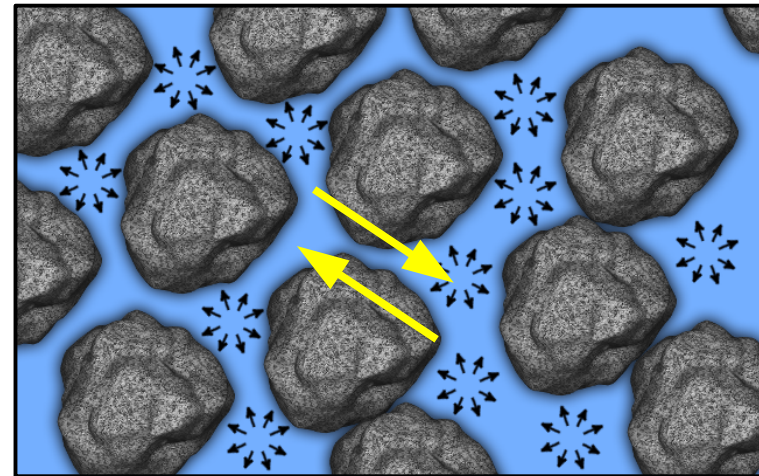
Soil Liquefaction

- 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 !





Soil Liquefaction

Some example of the effects at local scale....



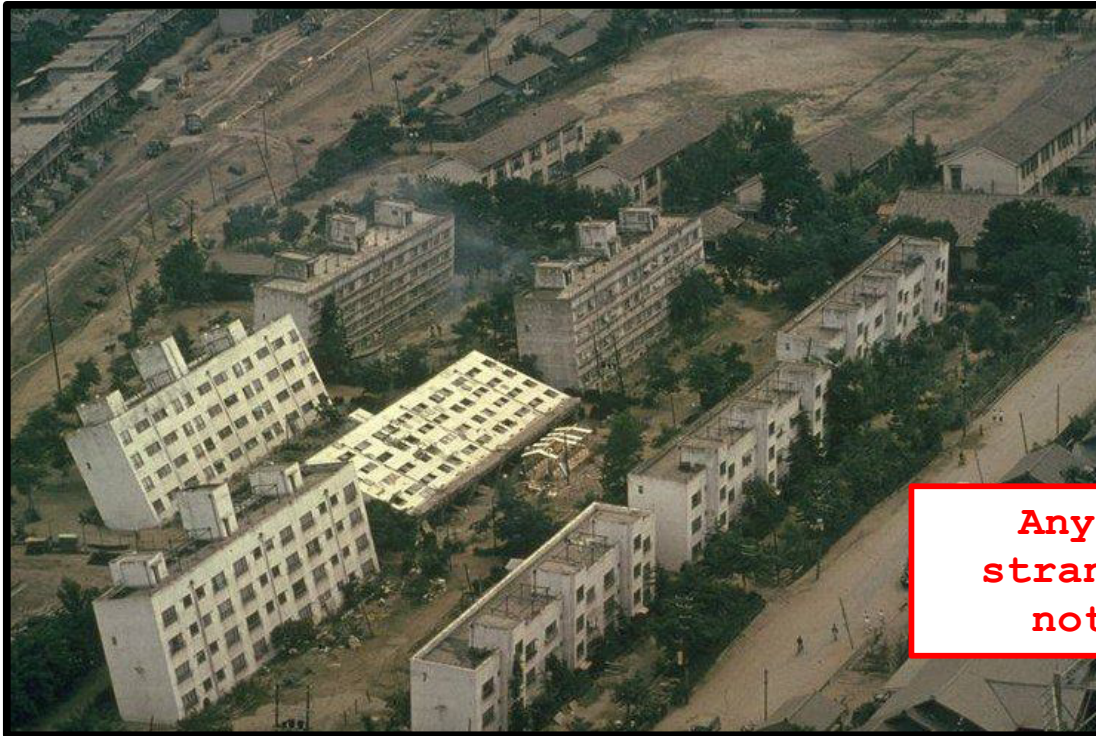
Emilia, Italy
2012
Mw 6.1



Christchurch, New Zealand 2010
Mw 7.1

Niigata, Japan 1964

Mw 7.5~7.6



Anything
strange you
notice?

Izmit, Turkey 1999

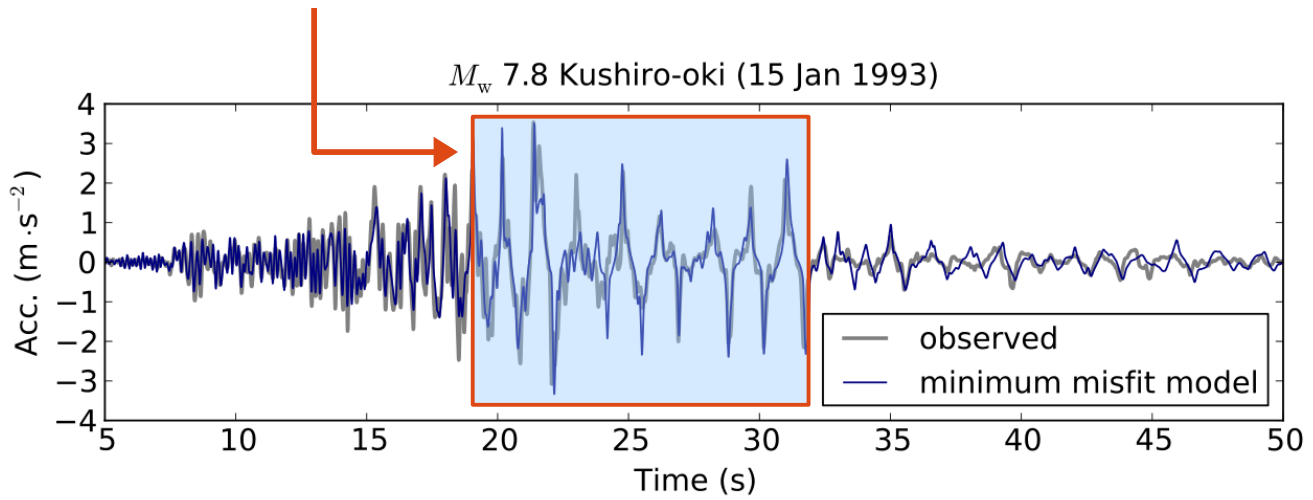
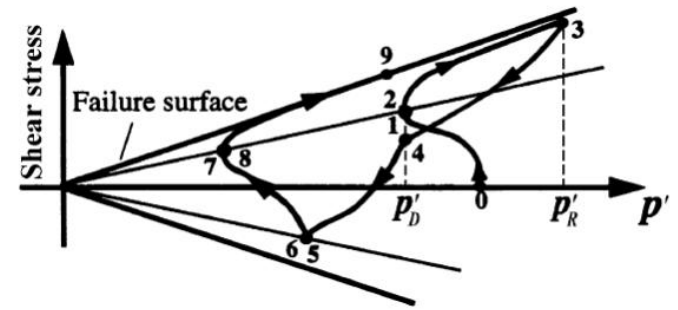
Mw 7.6



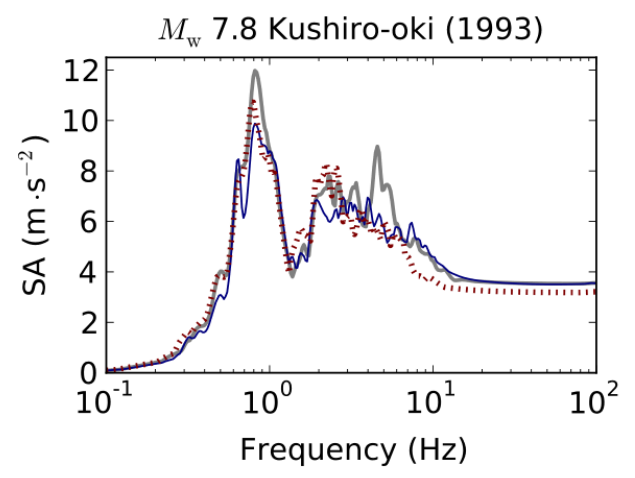
Cyclic Mobility

- 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!



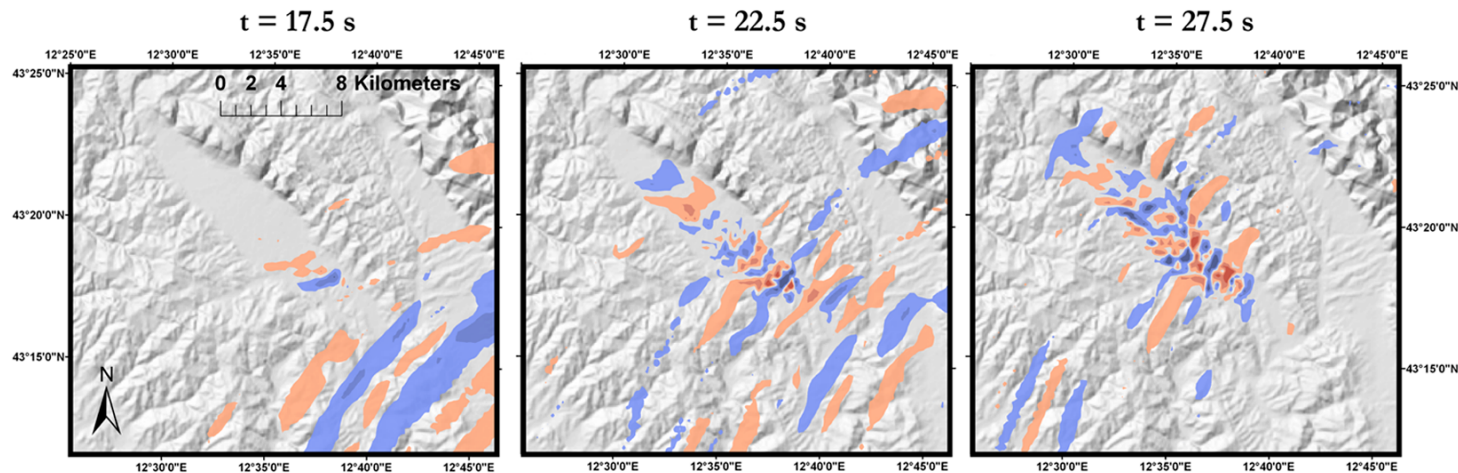
Very difficult to model! →

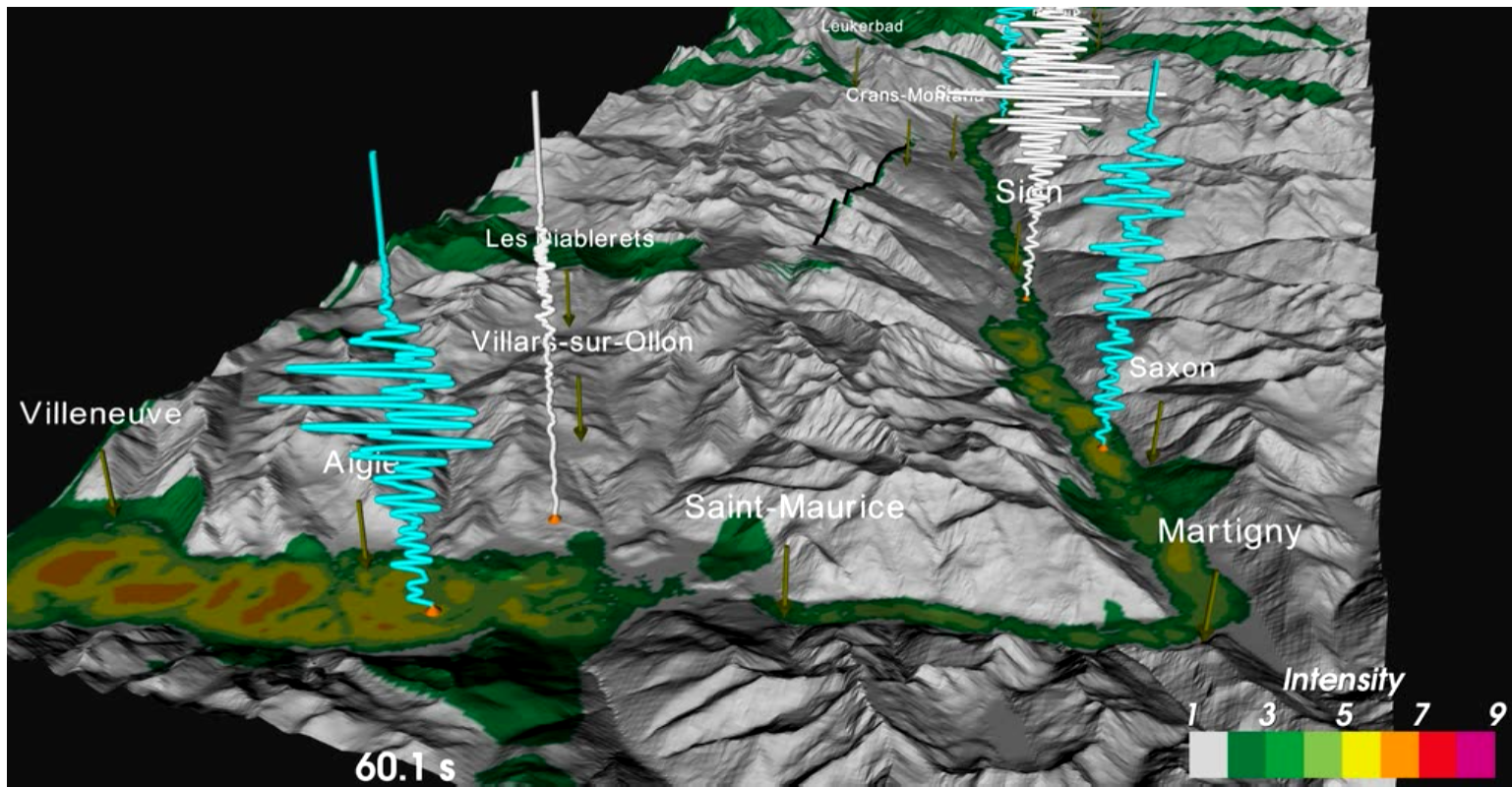


Indirect modeling methods

- 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)

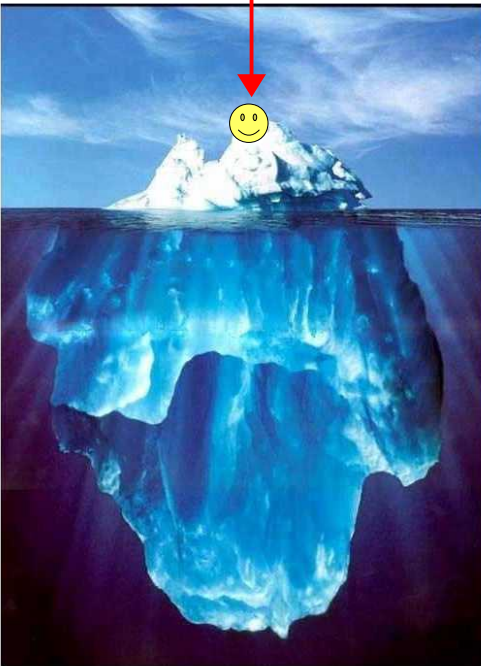
Gubbio basin (M=6)





Time to watch a movie...

YOU ARE
HERE



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.....