ESC 2010
European Seismological Commission 32nd General Assembly
September 6-10, Montpellier, France

Site effects : Impact, advances and challenges

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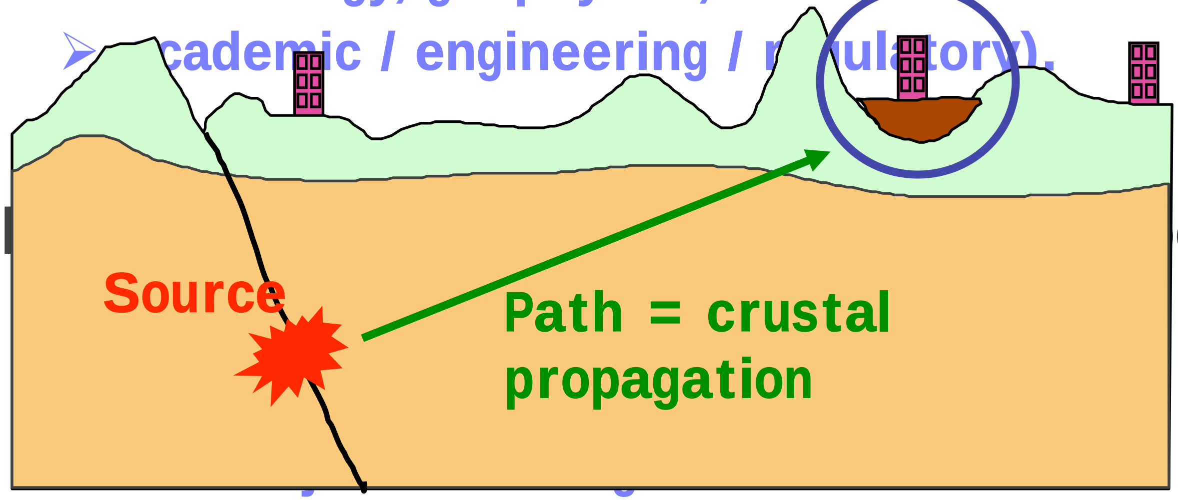
LCPC

Introduction

Interface topic

different disciplinary fields & communities :

- ➢ seismology, geophysics, soil and structural
- ➢ academic / engineering / regulatory).



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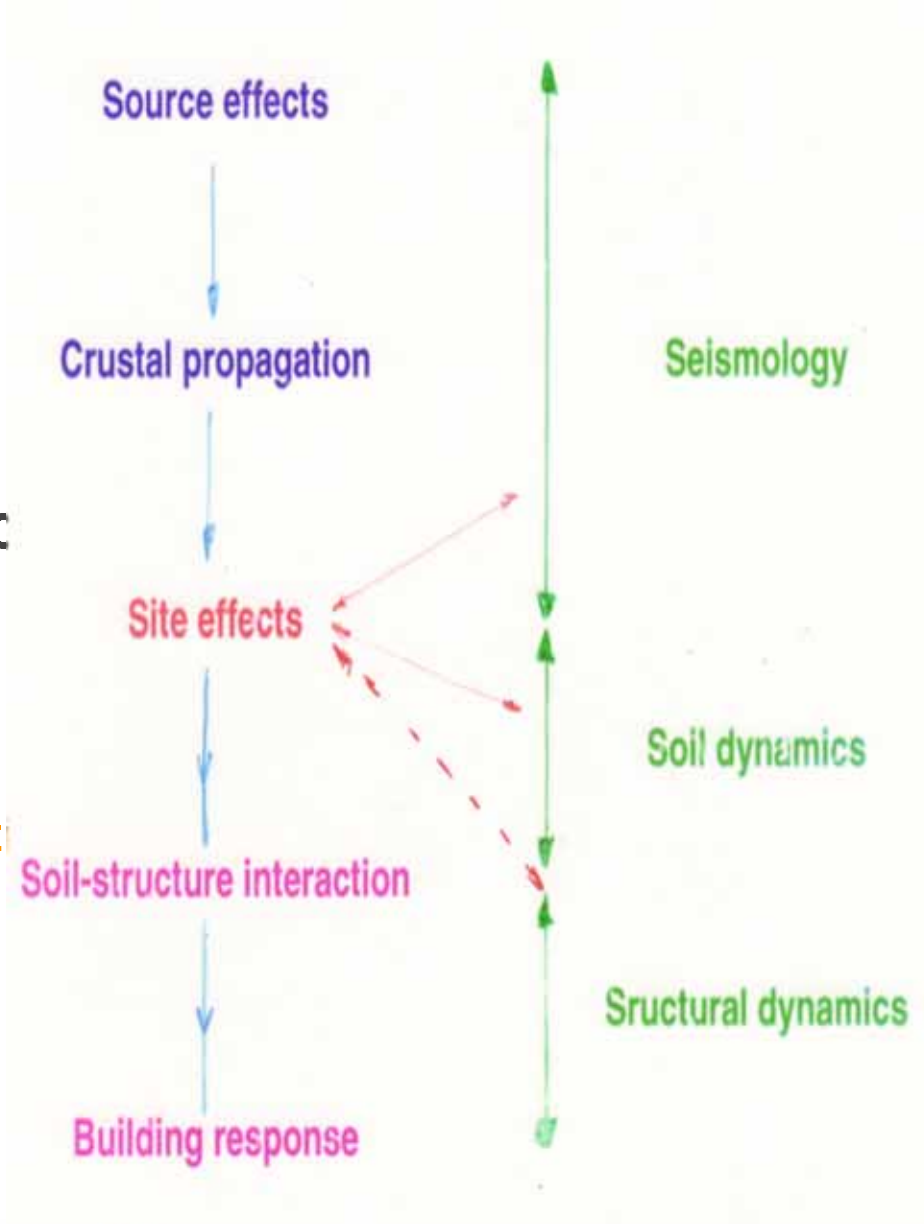
- in view of a more satisfactory account



Outline

Introduction

Basic Physics

Main tools

Practice : Engineering issues

Conclusions / Comments

Basic Physics

Two kinds of site effects

"Direct" (="ground shaking") site effects : Wave propagation effects

- resulting in **localized amplifications,** (or deamplifications), **highly variable with frequency**, possibly reaching **very high levels (> 10)**
  - Surface topography
  - "Soft" surface deposits

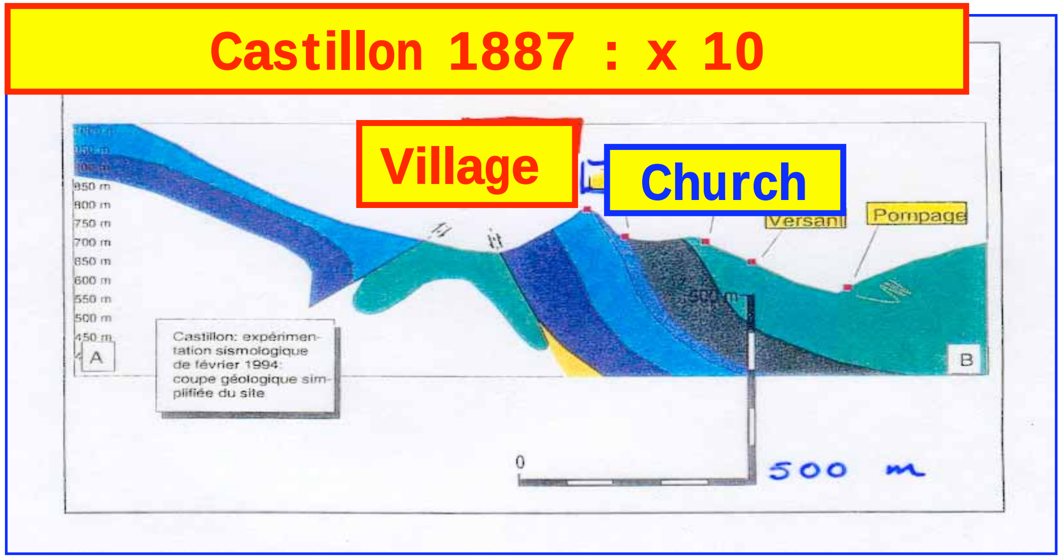
Induced site effects

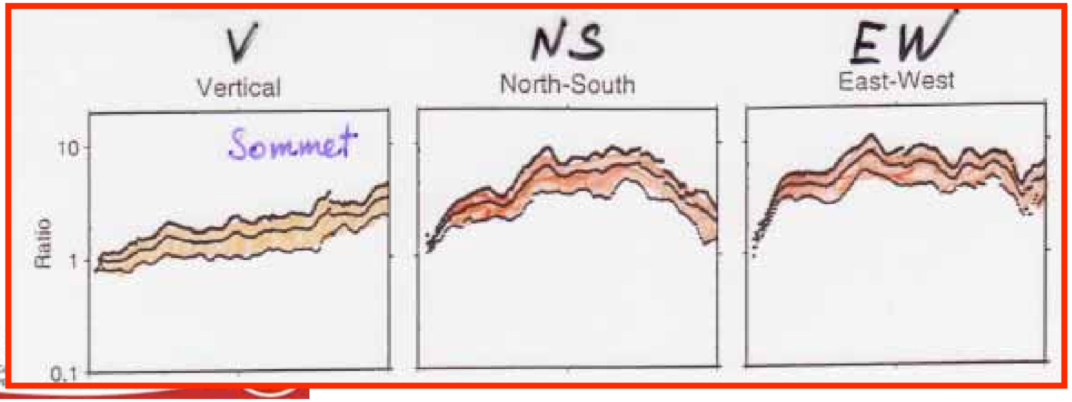
- Soil damage resulting in localized soil failures
  - Liquefaction of water saturated sandy deposits, settlements
  - Slope instabilities (slides, falls, debris flows, ...)

Effects of surface topography

Various evidence

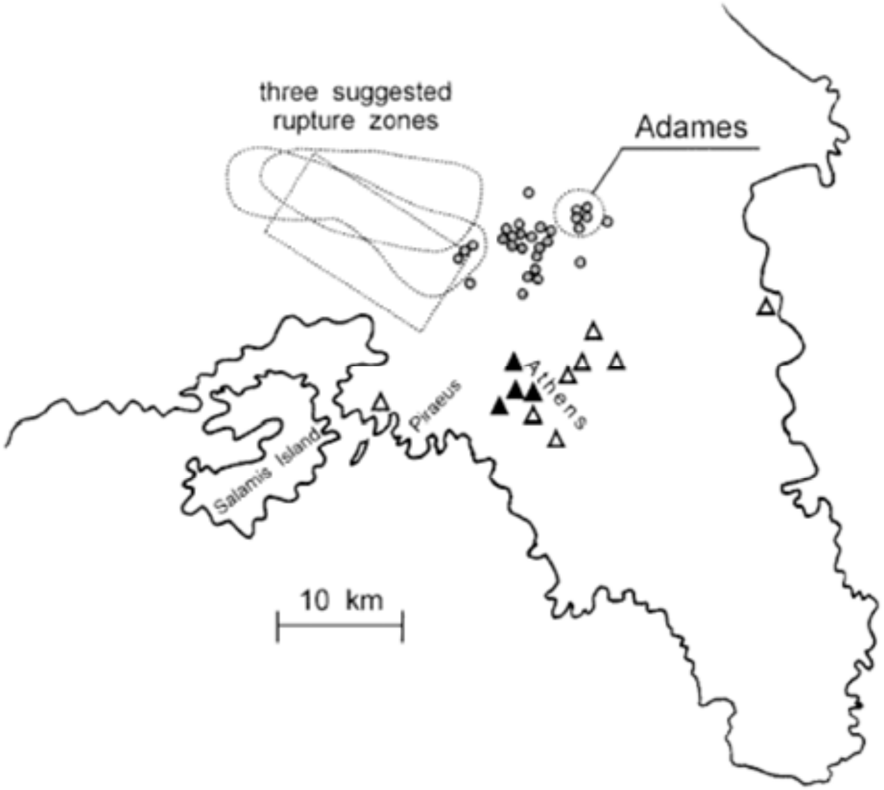
- "Classical"
  - instrumental recordings
  - observed (heavy) damage
- Remote sensing
- Spatial variability
- Insurance claims

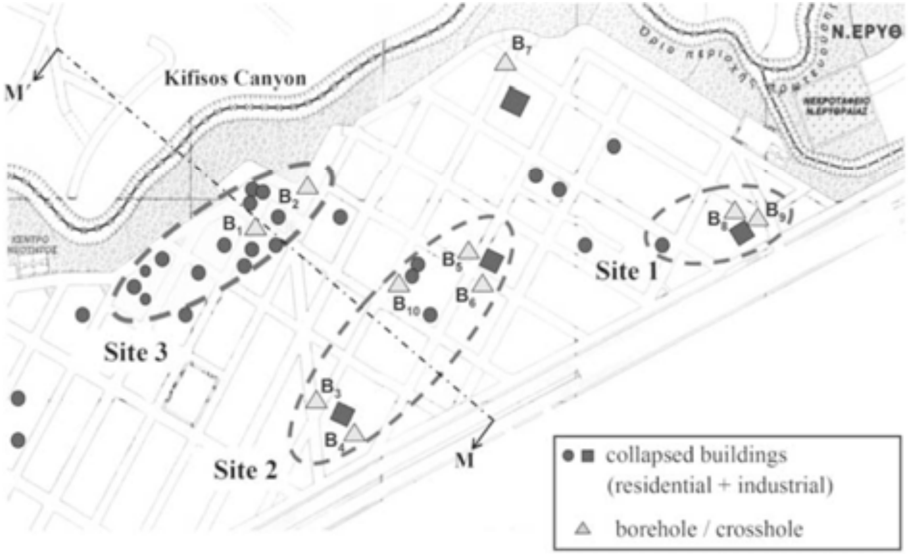


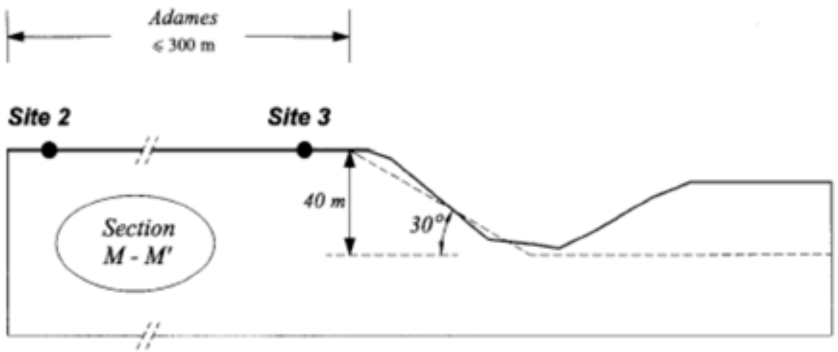


(Nechstchein et al., 1995)

Example cliff damage : the Adames area (Athens, 1999)

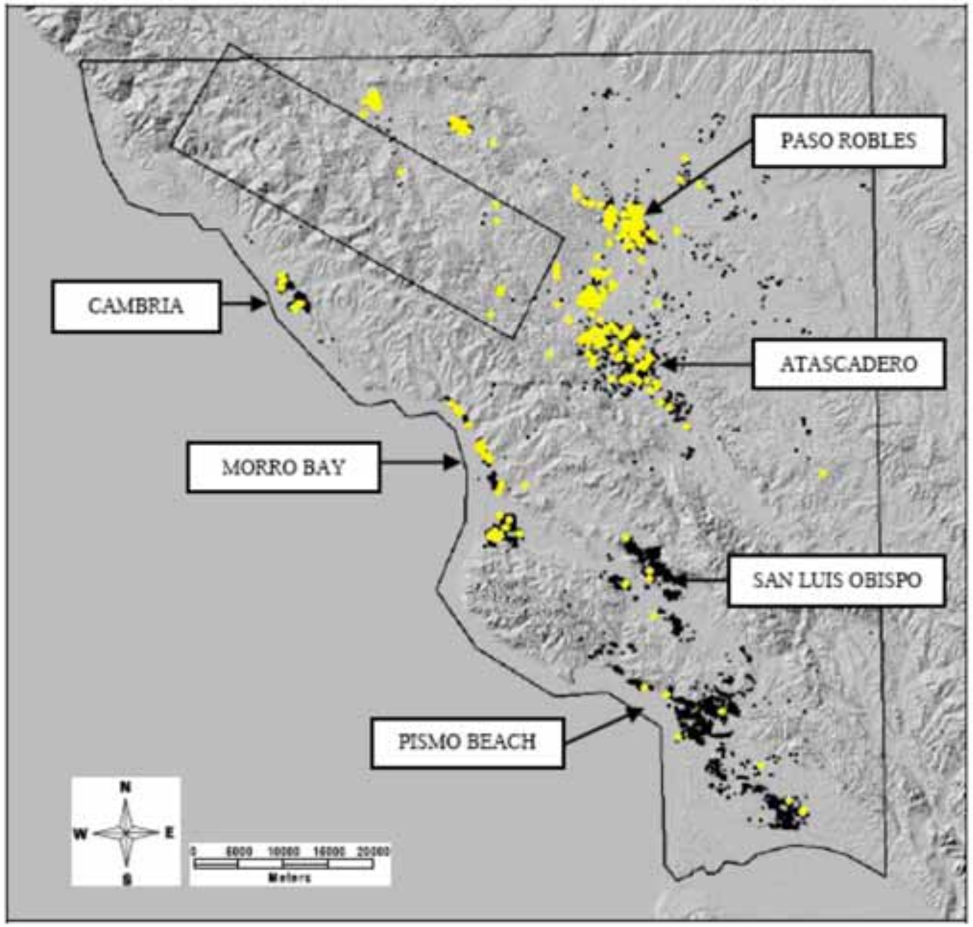


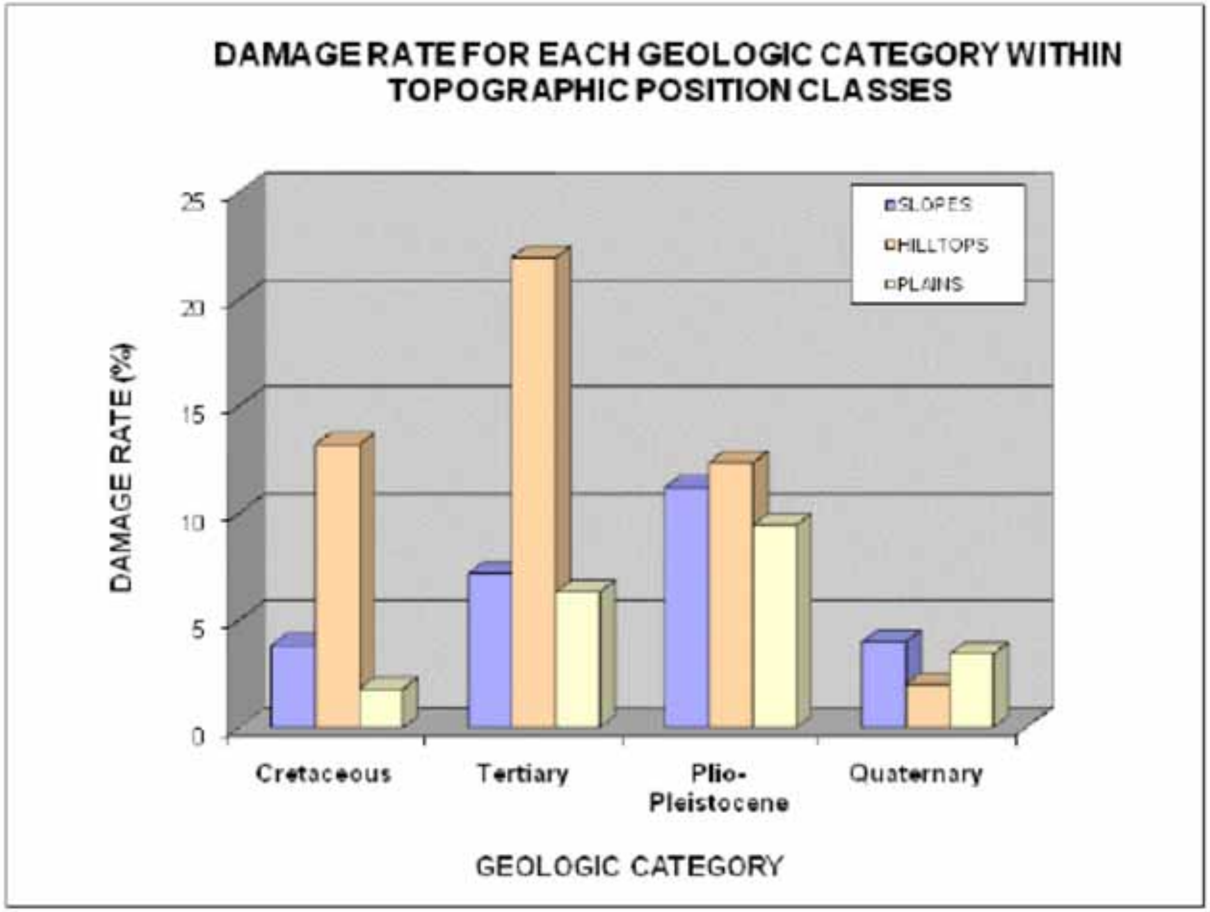




(Gazetas et al., 2002; Assimaki et al., 2005)

Evidence from insurance claims
San Simeon 2003 (see McCrink et al. 2010)





Yellow : insurance claim
Black dot : insured house

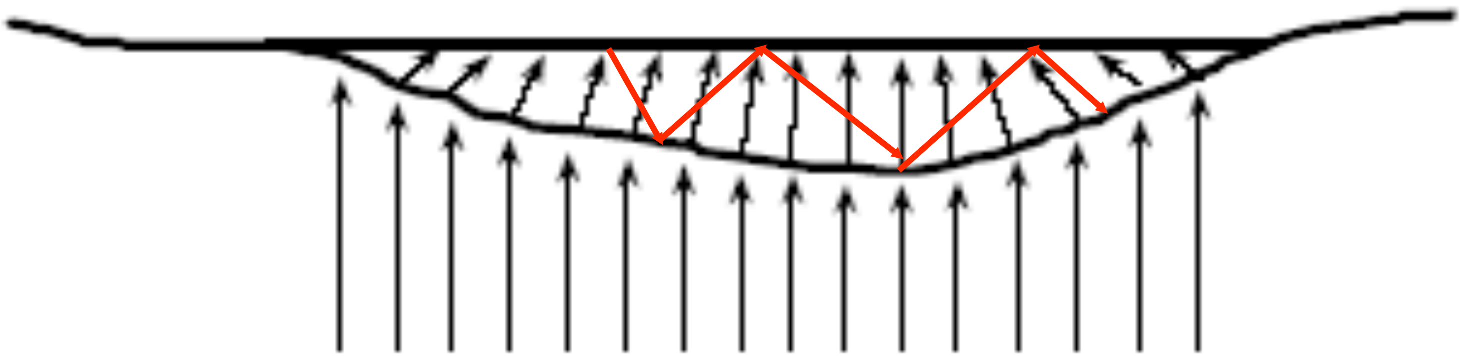
(McCrink et al., 2010; Courtesy C. Real)

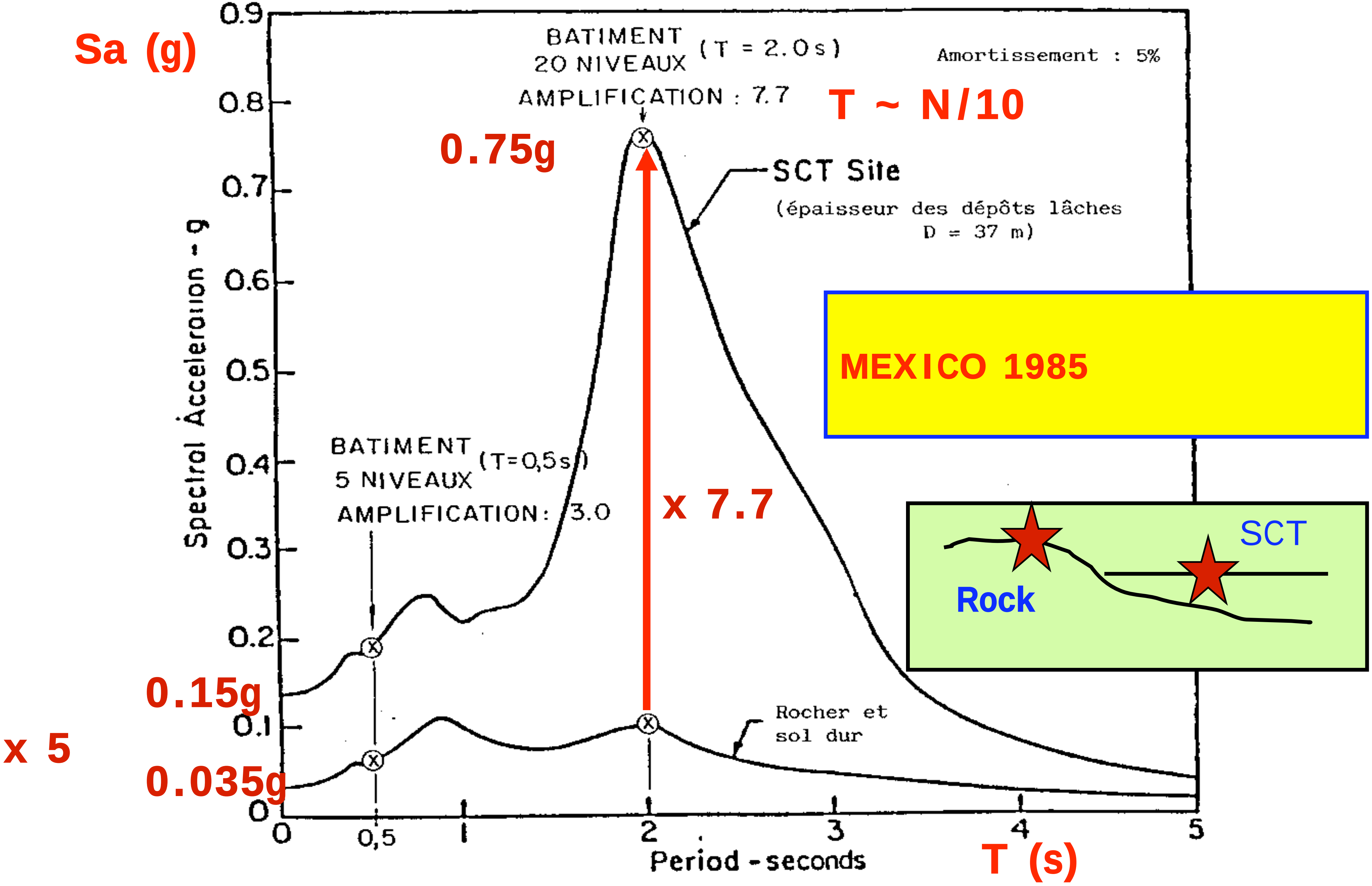
Resonance effects in sediments

- **Wave field in surface deposits**
  - Refraction, diffraction, focusing
  - Wave Trapping
    - vertical reverberations
    - lateral reverberations

! + soil non-linearities !

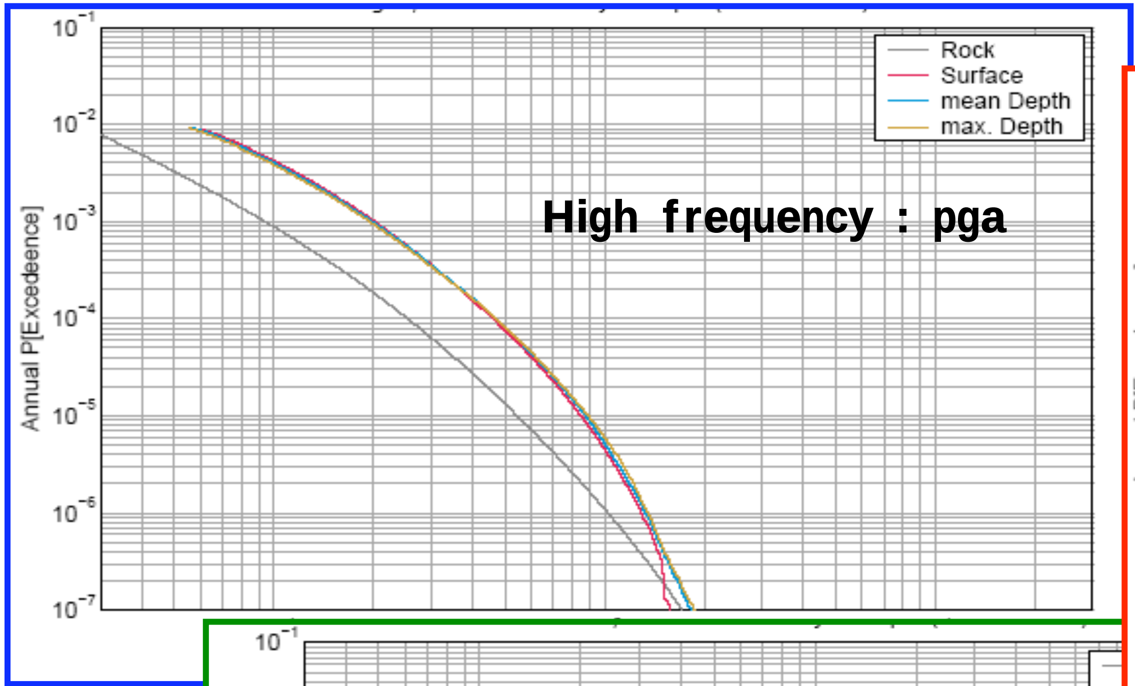
- **Consequences**
  - constructive interferences: amplification
  - trapping : prolongation
  - resonance at specific frequencies

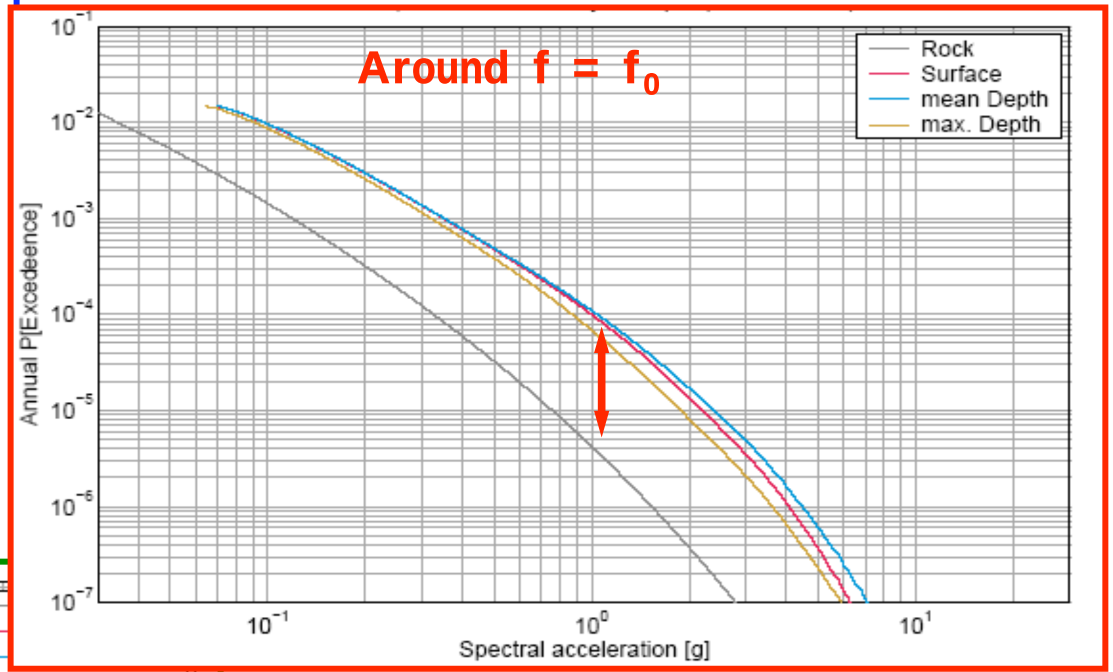


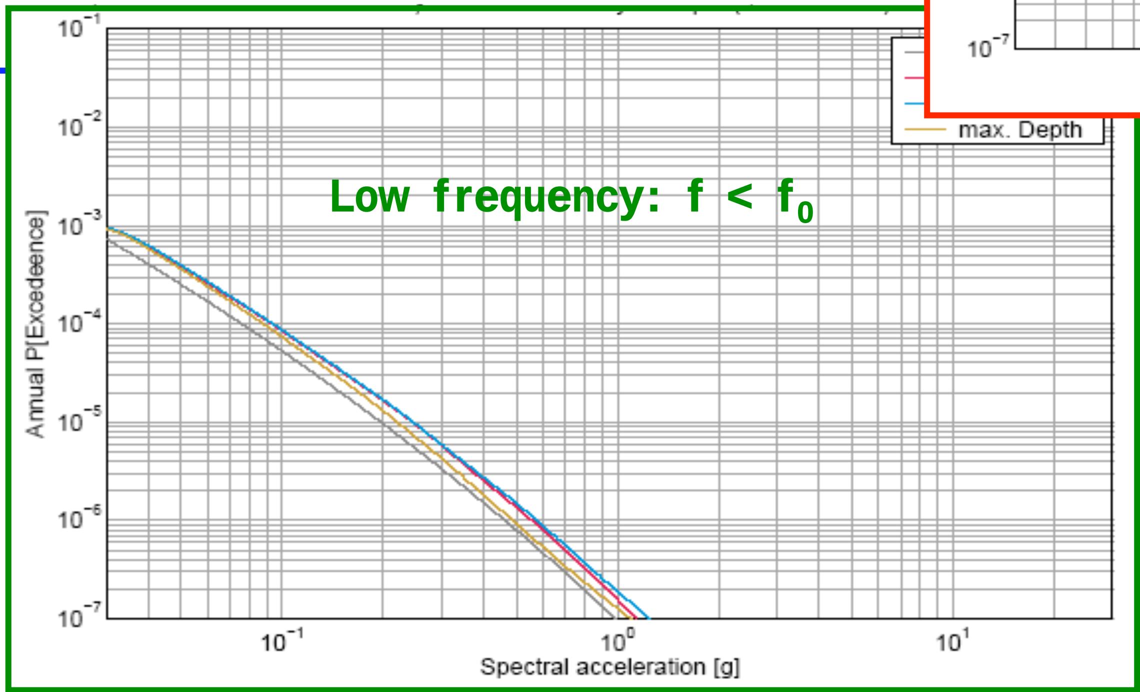


(Mouroux, 1999)

Impact of site conditions on hazard curves





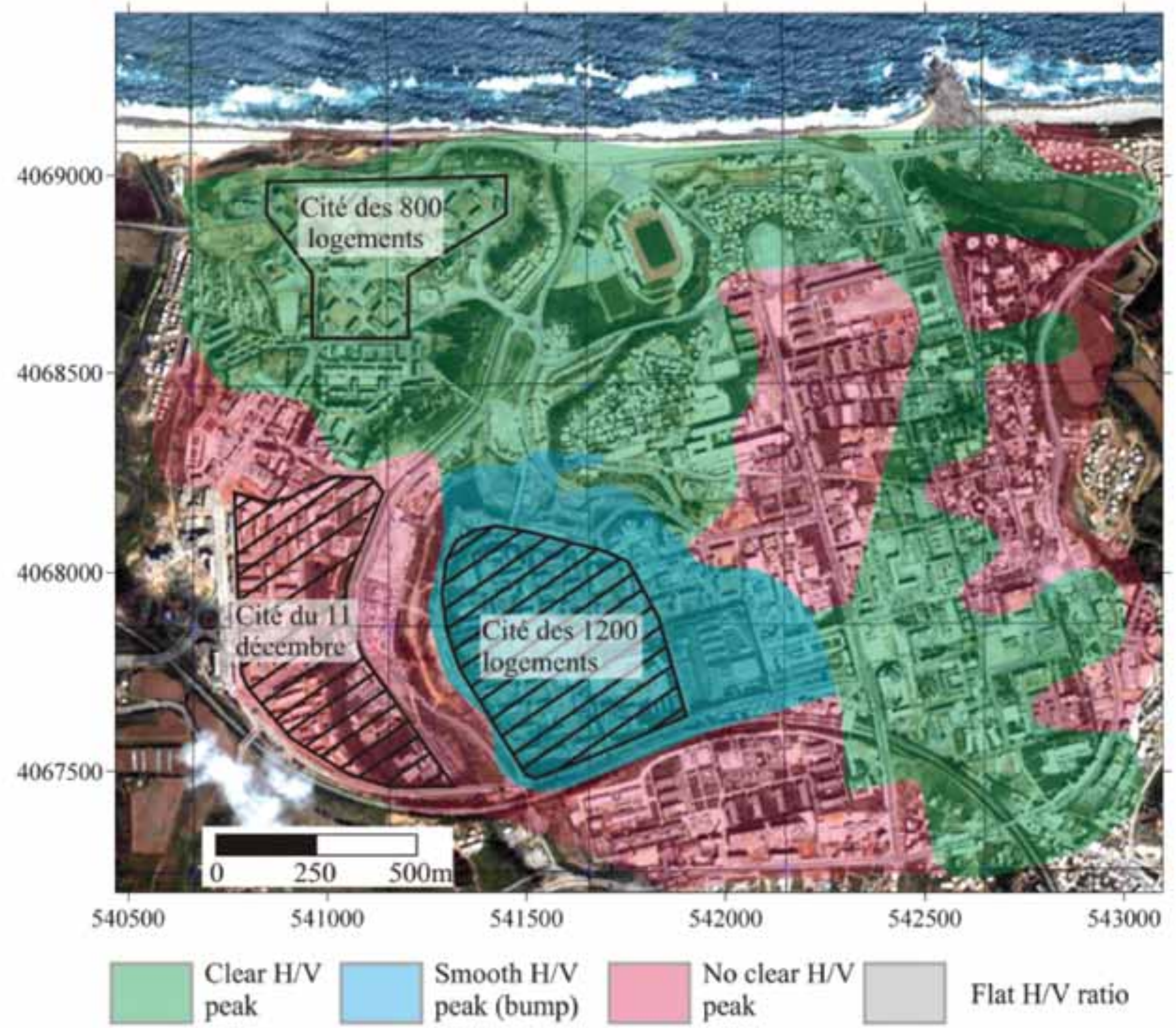


Conclusions

Up to a 2 to 3 factor for a given annual probability p_a

A factor u to 10 on p_a for a given spectral level

Site effects should not be invoked to explain all damage anomalies



▲ **Figure 5.** Map showing the location of the heaviest damages in the "Cité des 1200 logements" and the "Cité du 11 décembre" urbanizations (hatched areas), with the H/V peak distribution, over a May 2003 Quickbird satellite photography of Boumerdes city. Green areas are zones where a clear H/V peak is identified, red areas are zones where such a peak cannot be identified, and the blue area is zone 3B where a bump rather than a peak is shown of H/V curves. In the gray zone, H/V curves are flat. Note that the most damaged zones correspond to areas without a clear H/V peak, while, for example, only slight damages are observed in the "Cité des 800 logements," located in a zone where a clear H/V peak is identified.

Hellel et al. 2010

Physical understanding : main challenges

? Separation source / path / site effects : is it relevant

- ? sensitivity of site effects to incident wave-field characteristics
- near-field issues

Surface topography effects

- ? links to weathering and local heterogeneities
- can we rely on a modelling approach ?

Sediments

- effects and amount of non-linearity
  - especially at large depth
  - larger number of soil/rock pairs and/or vertical arrays,
- 2D / 3D effects : "overamplification" and duration

Wave-field composition

- complexity and origin (regional, local ? natural / anthropic ?)
- effects of soil short wavelength heterogeneities – natural or anthropic - on the spatial variability of ground motion

? Separation source / site ?

Ideally, a site response study should include

- rupture mechanism (source)
- wave propagation in the crust to bedrock top (path)
- how surface motion is influenced by soil layers located above the bedrock top
- possible coupling

  (wavefield, azimuth/incidence, shock waves, ...)

In practice

- ? Experimental evidence for such sensitivity ?
- ? Feasibility for routine analysis

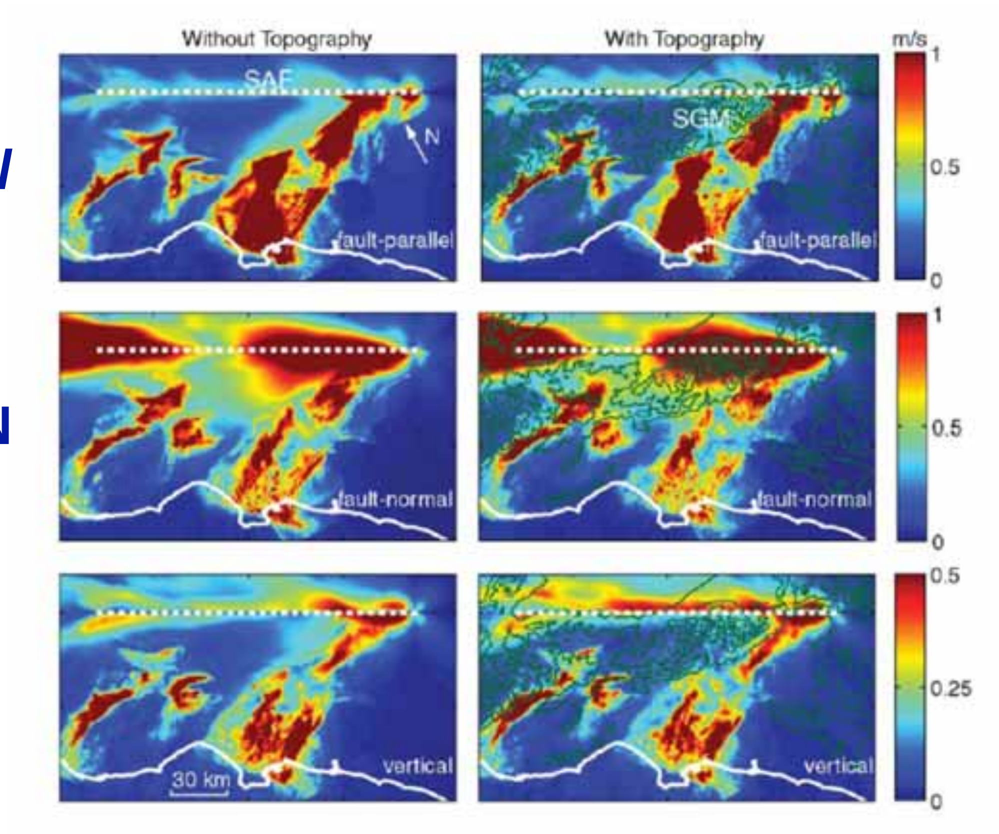
Expected sensitivity to incident wavefield

Scattering effects induced by topography (LA area)

H//

HN

V



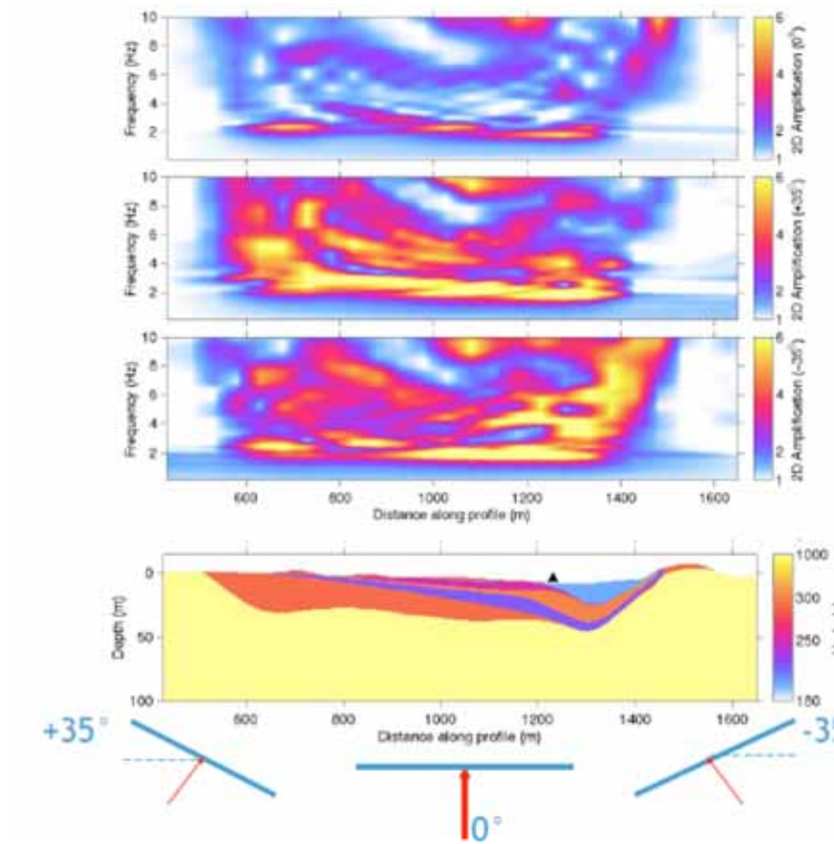
(Ma et al., 2007)

Effects of incidence angle on valley reponse (linear case)

θ=0°

θ=35°

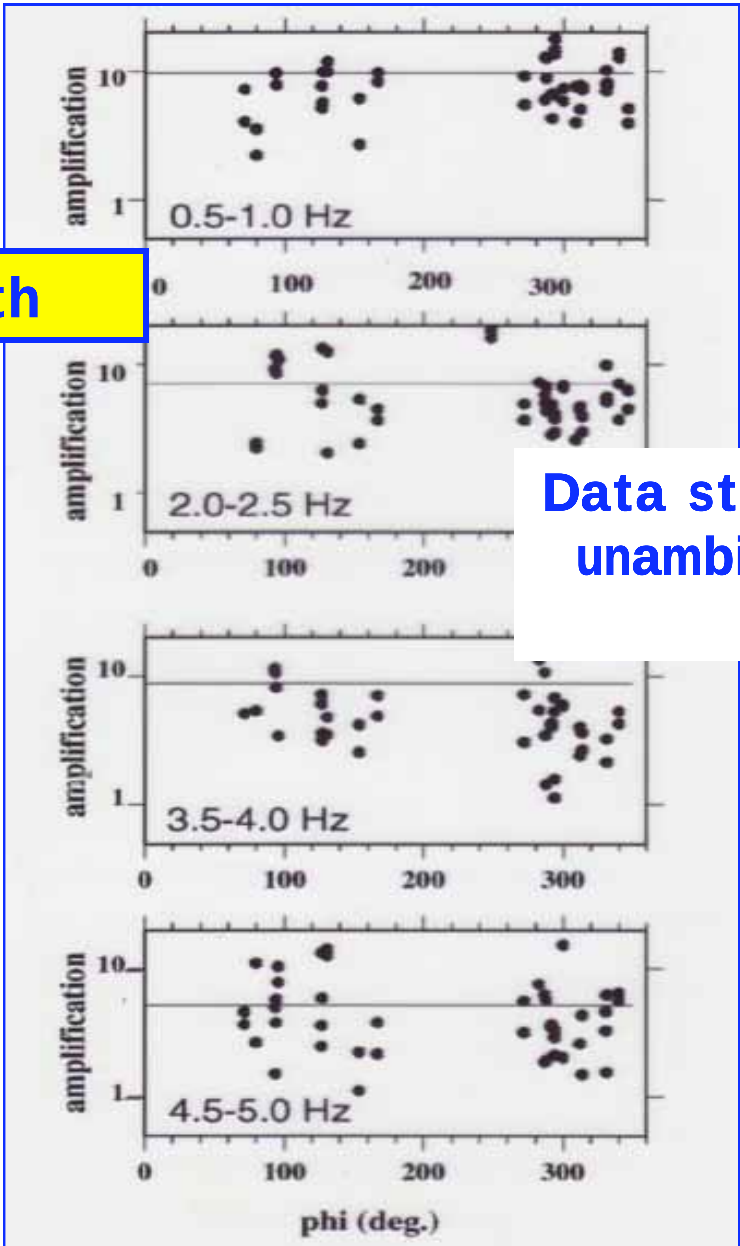
θ=-35°



(Gélis et al., 2008)

? Observed dependence on azimuth and distance ?

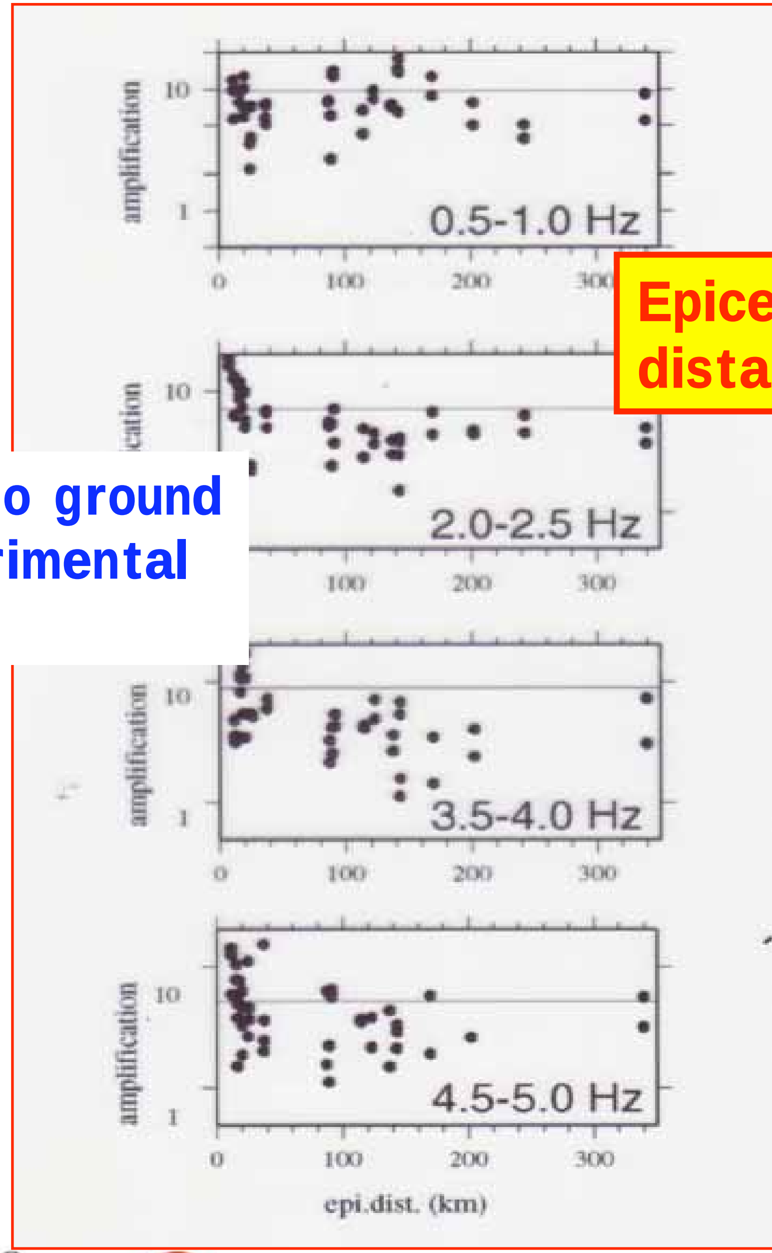
Azimuth



TST site, Volvi

Data still too few to ground unambiguous experimental evidence

Epicentral distance



(Riepl, 1997)

Recent results on surface topography effects

Additional consistent evidence of amplification

- convex parts : hill-tops and cliffs
- mixed with geological / lithological effects
  - especially at high frequencies

+ Diffraction / scattering effects

- increased variability

  ? Larger σ for GMPE in mountainous areas ?
- significant strains

  (upper bounds from displacements and Rayleigh velocity)

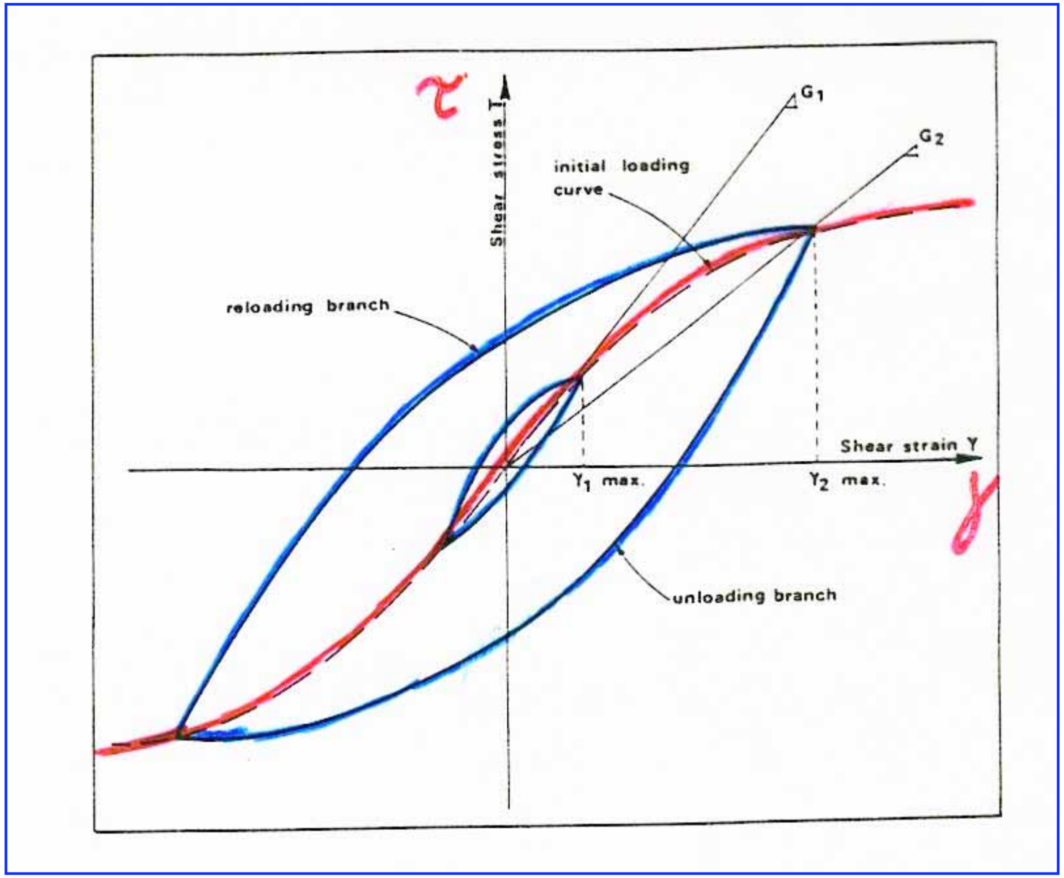
Still (most) missing and welcome

- Dense array recordings coupled with detailed geophysical surveys
- HF issue : short wavelength characterization at shallow depth
- convincing statistics for building codes
- ? effects of strains on landslide triggering

Non-linear behavior

Origin: Soil degradation under large deformation

- ➢ decrease of shear modulus
- ➢ Increase of damping



Consequences

Fundamental frequency f_0

$f_0 = \beta_1/4h,\ \beta_1 = (G_1/\rho_1)^{0.5}$

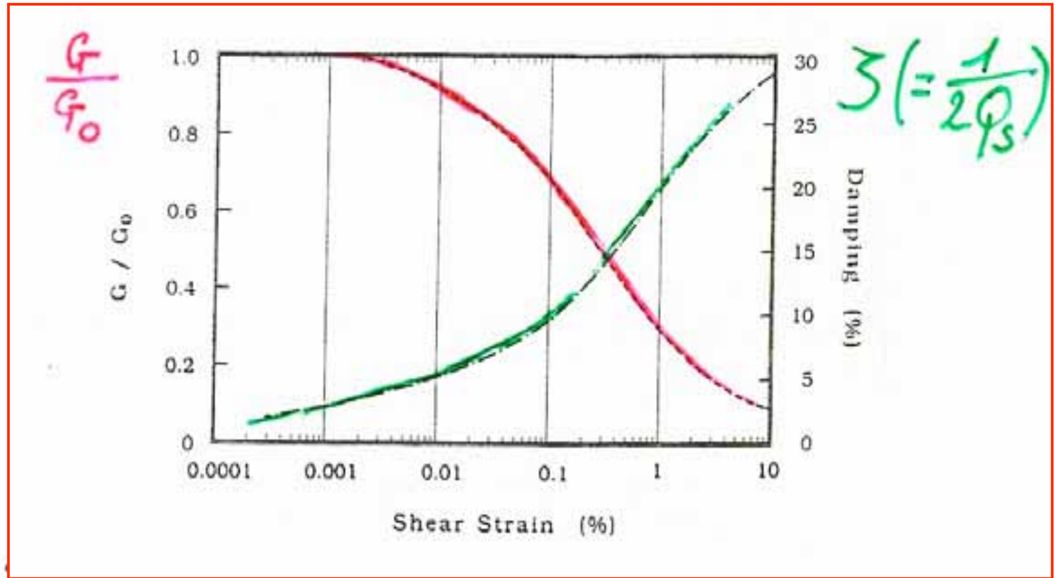
$\Rightarrow$ Decrease of f_0

Amplification A_0

$A_0 = C\ /\ (1\ + 0{,}5\ \pi\ \zeta_1\ C\ )$

$C = \rho_2.\beta_2/\rho_1.\beta_1 \nearrow\ ,\ \zeta_1 \nearrow$

$\Rightarrow$ Decrease of A_0

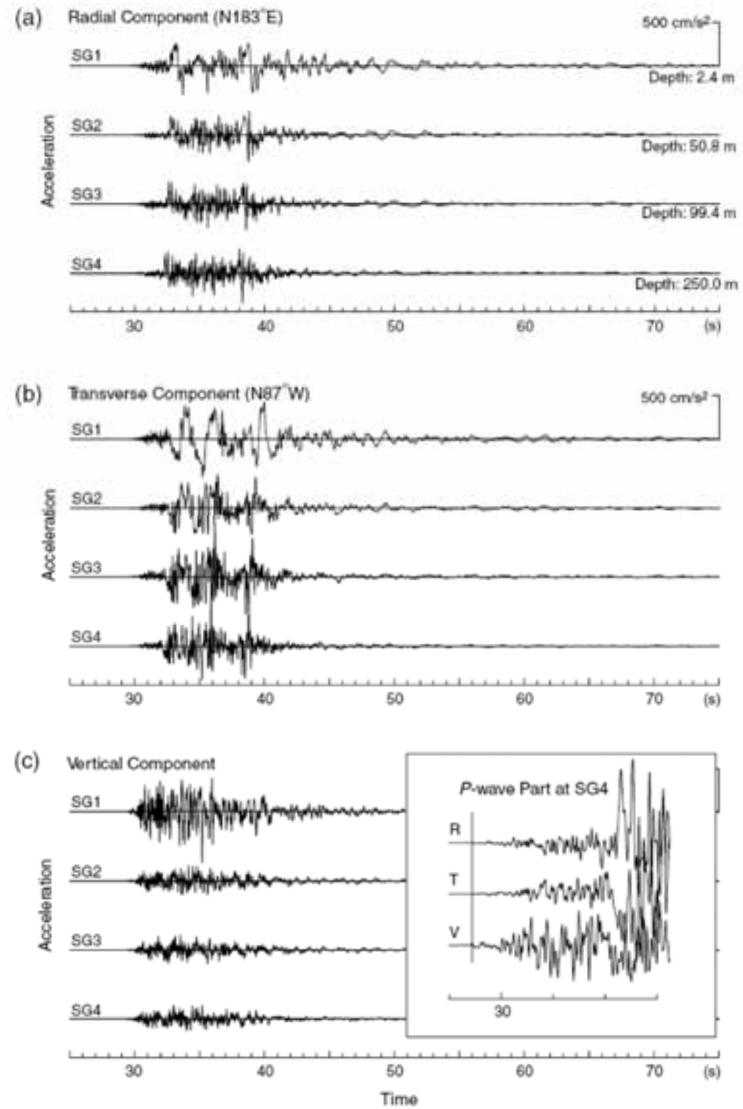


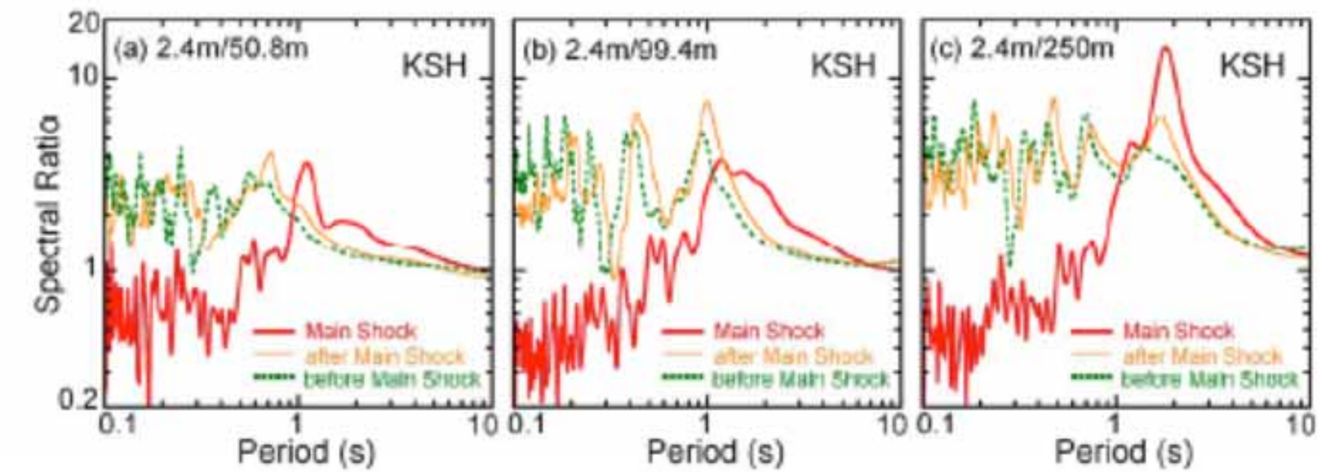
Non-linear behavior, Kariwa-Kashiwazaki NPP

Obvious from vertical array recordings (main shock / aftershock)

BUT

Highly variable within the NPP site





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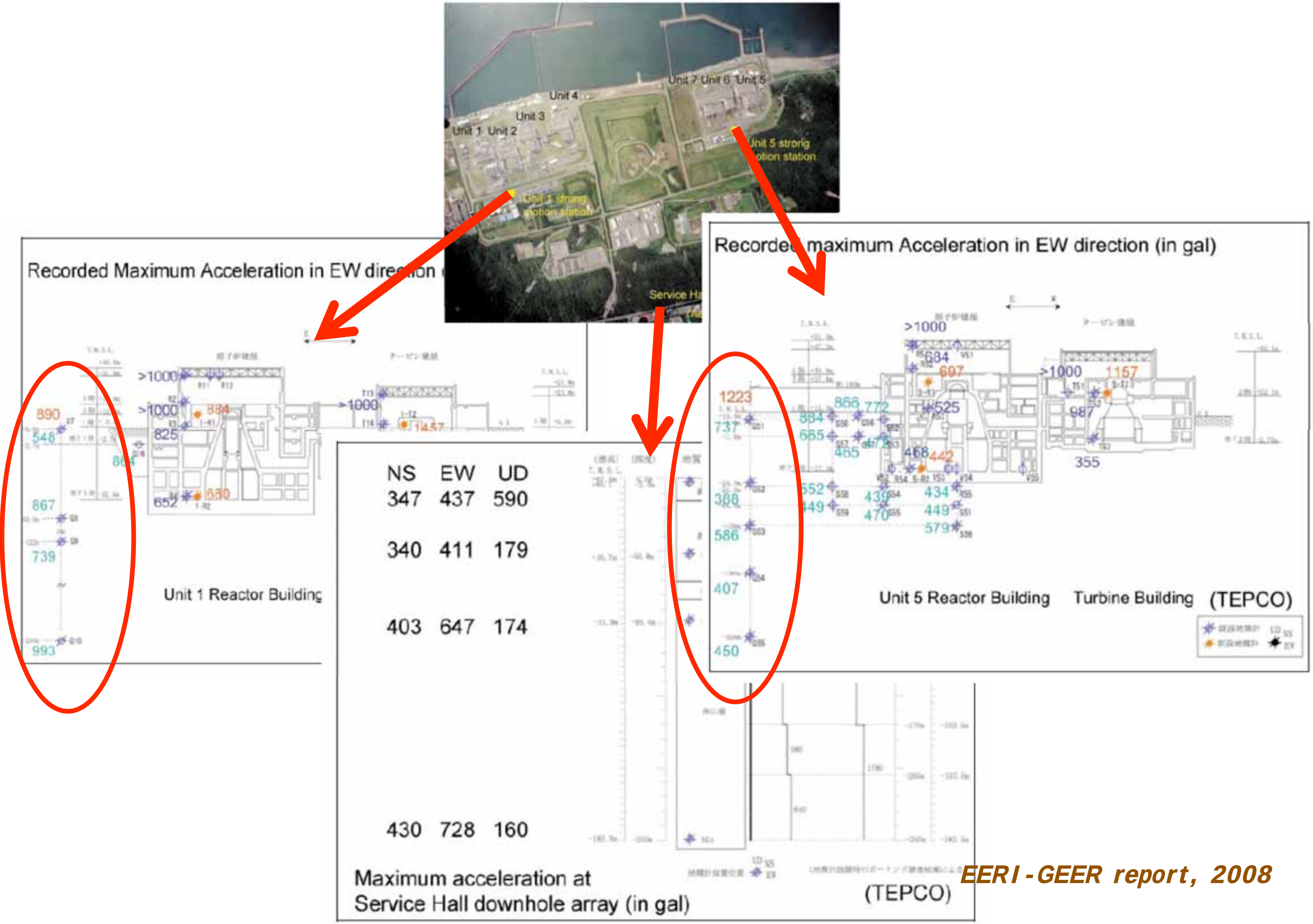
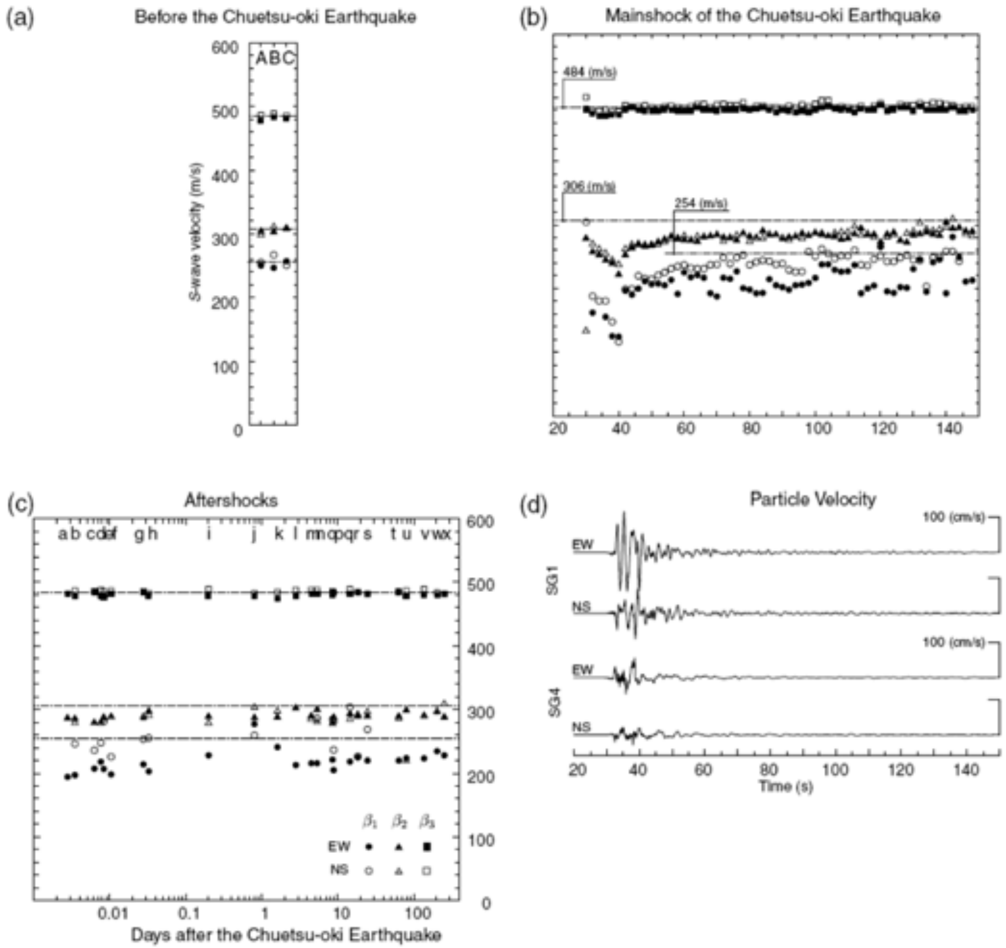
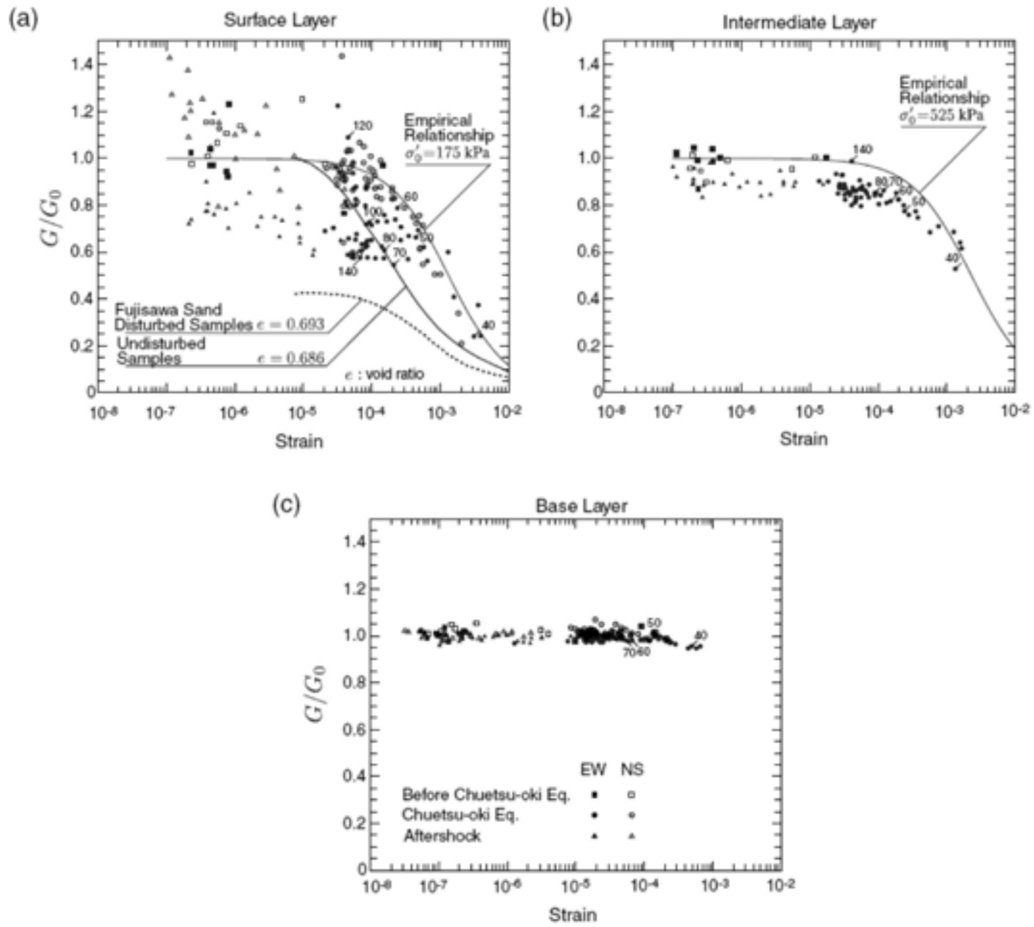
From Sekiguchi et al., 2008; Mogi et al., 2010



EERI-GEER report, 2008

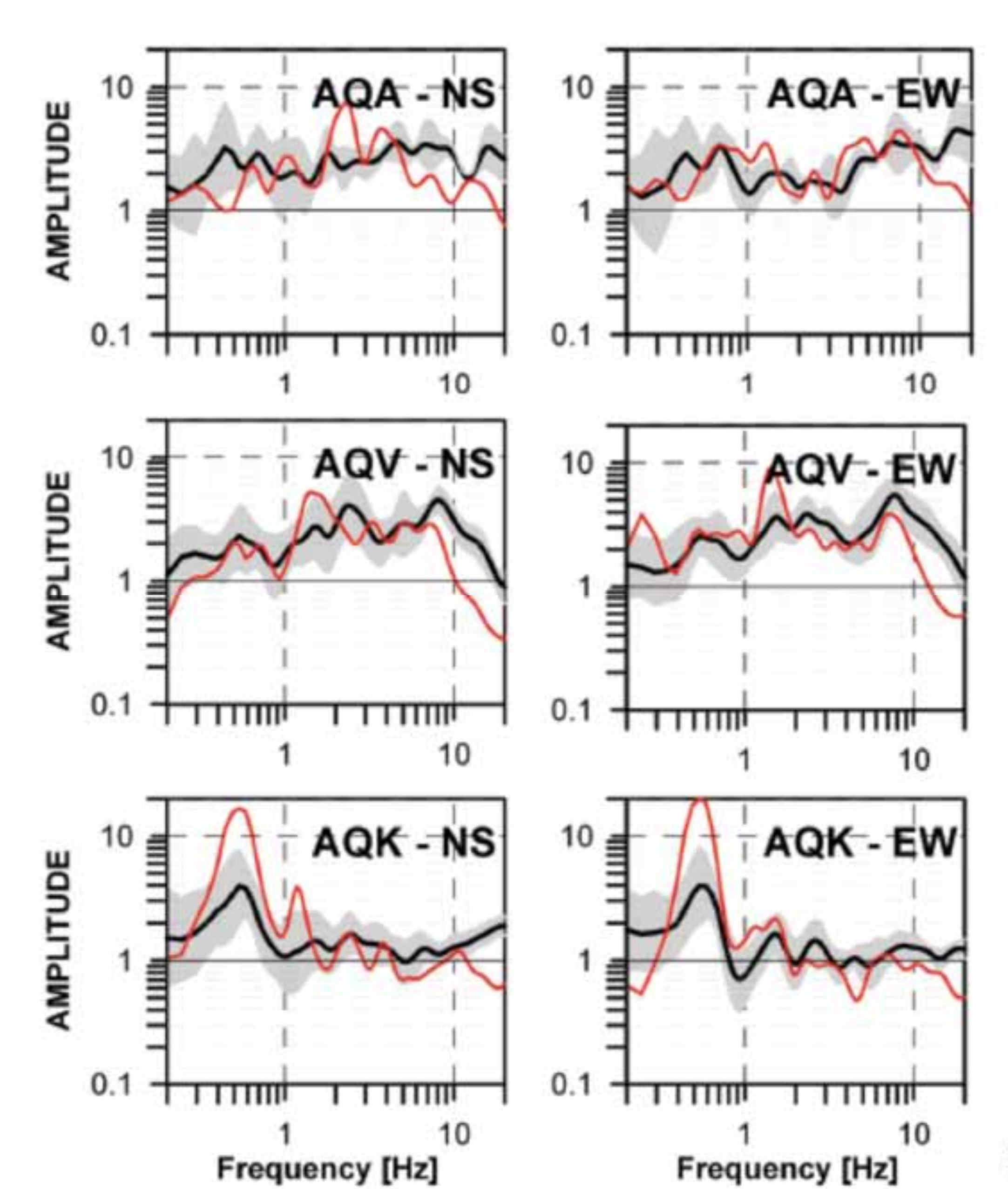
Reversible velocity changes, consistent with lab measurements

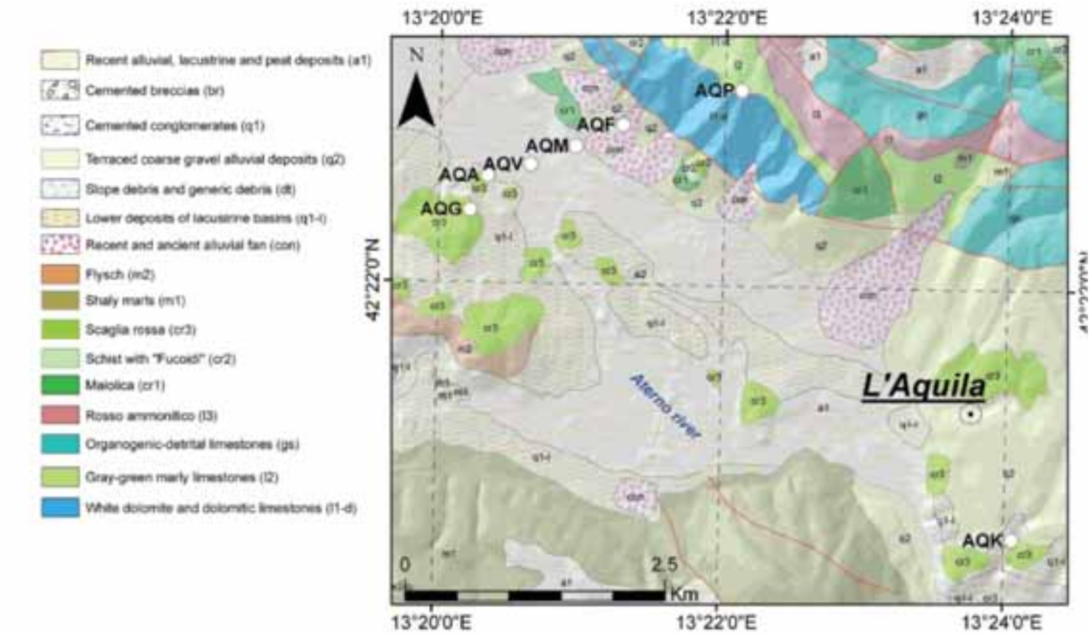




From Mogi et al., 2010

NL behavior in L'Aquila ?





Indirect evidence from HV ratios

(No vertical array)

From Amori et al., 2010

C 2010

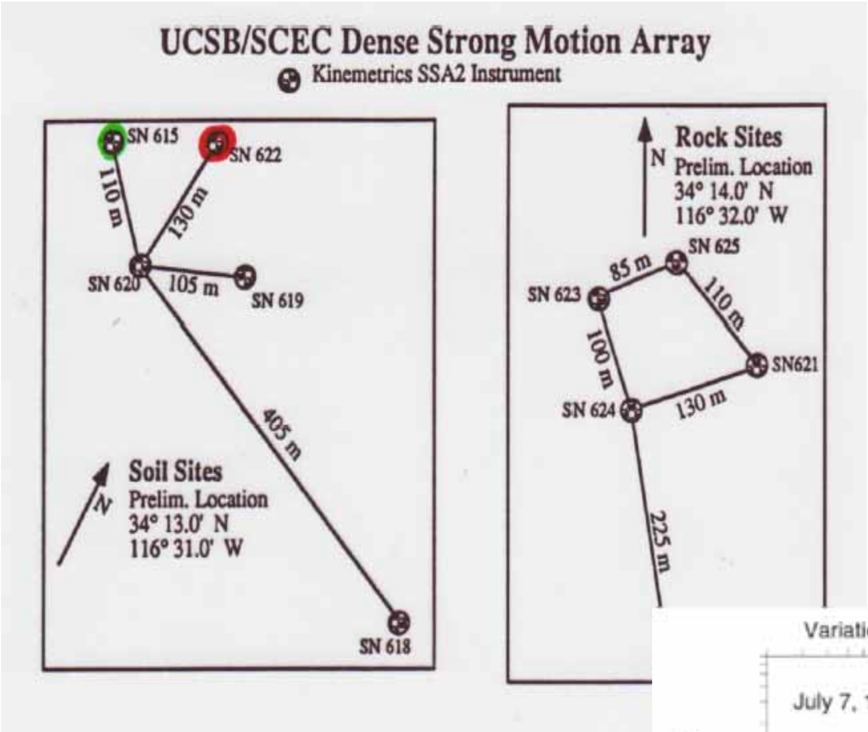
Short wavelength spatial variability

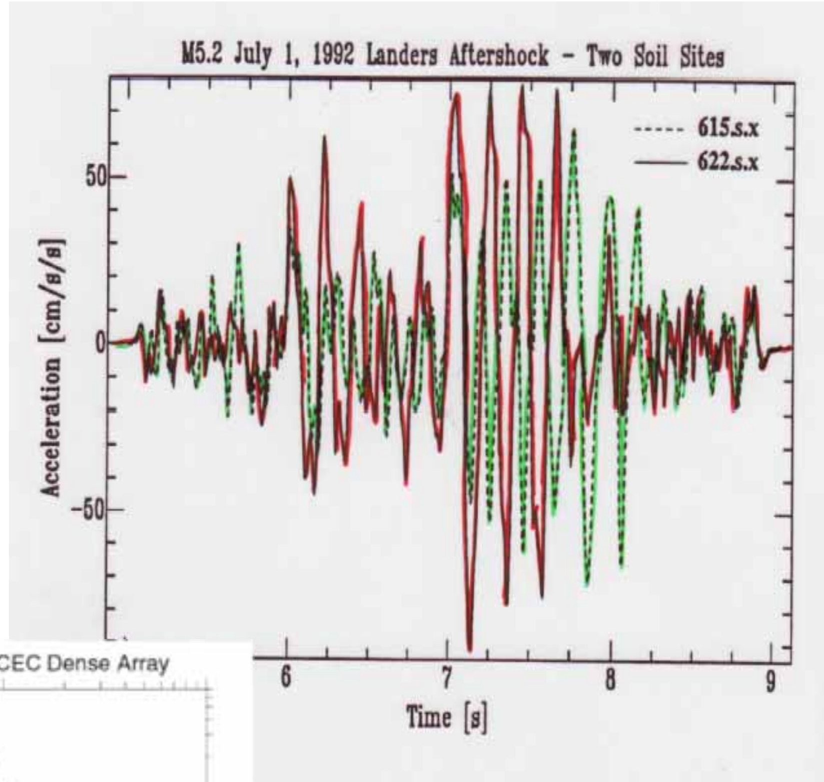
(cf. H. Igel presentation)

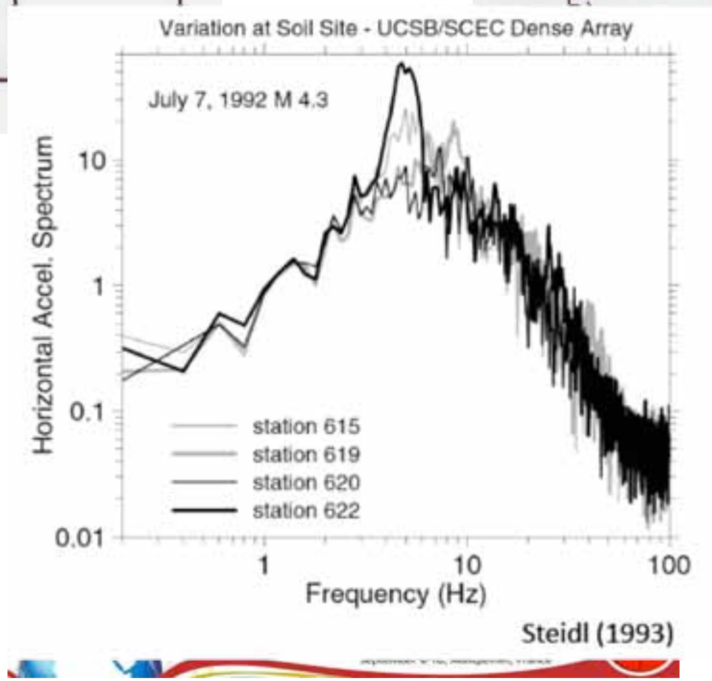
Multiple origins

- oblique incidence
- complex wavefield
  - near source
  - near site
  - scattering

Old example : Landers aftershocks (Steidl, 1993)







Example : Rio Dell Bridge, N. California

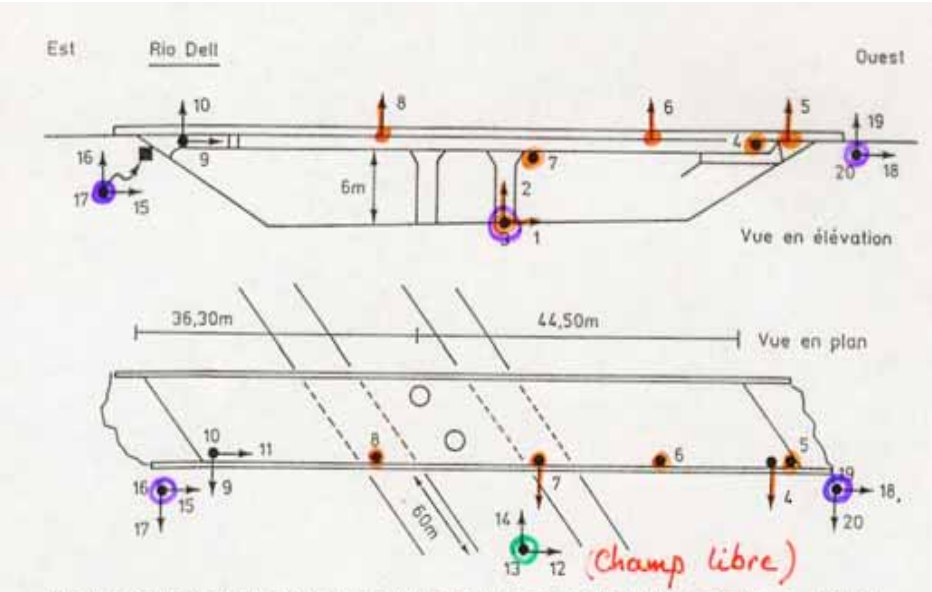
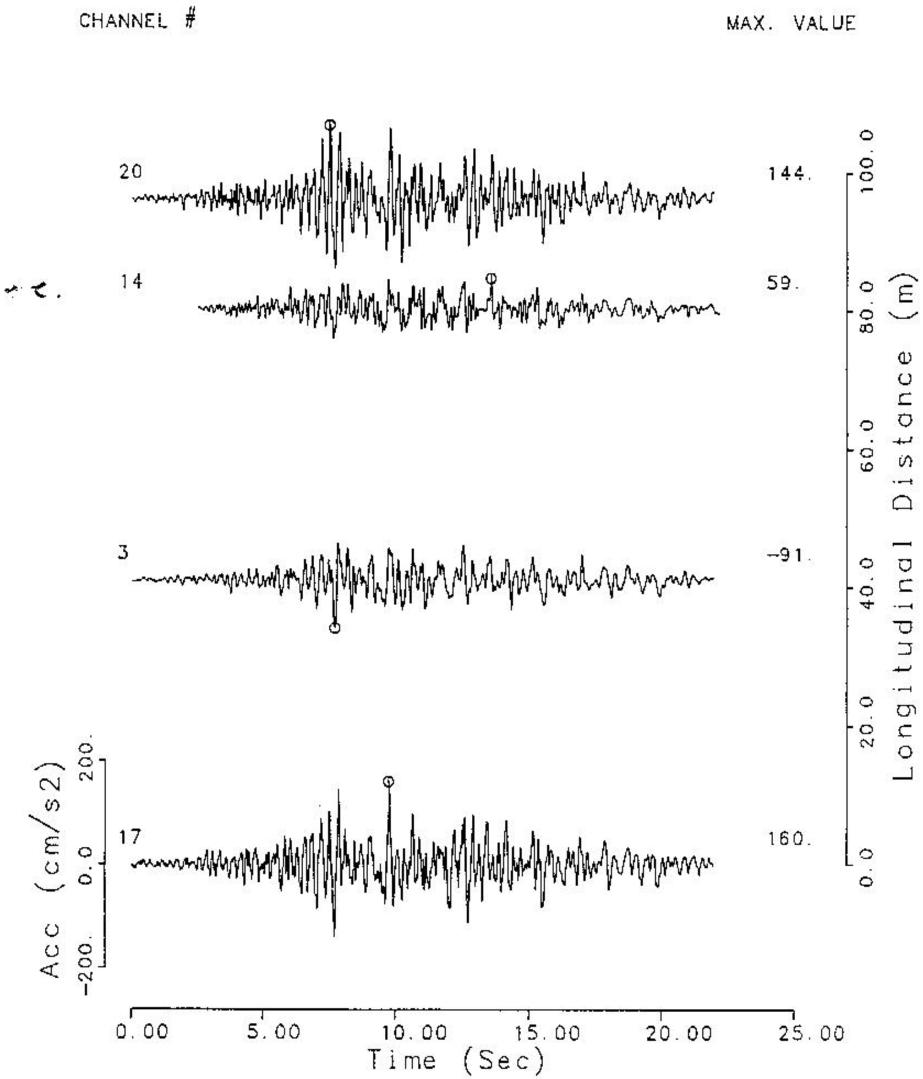


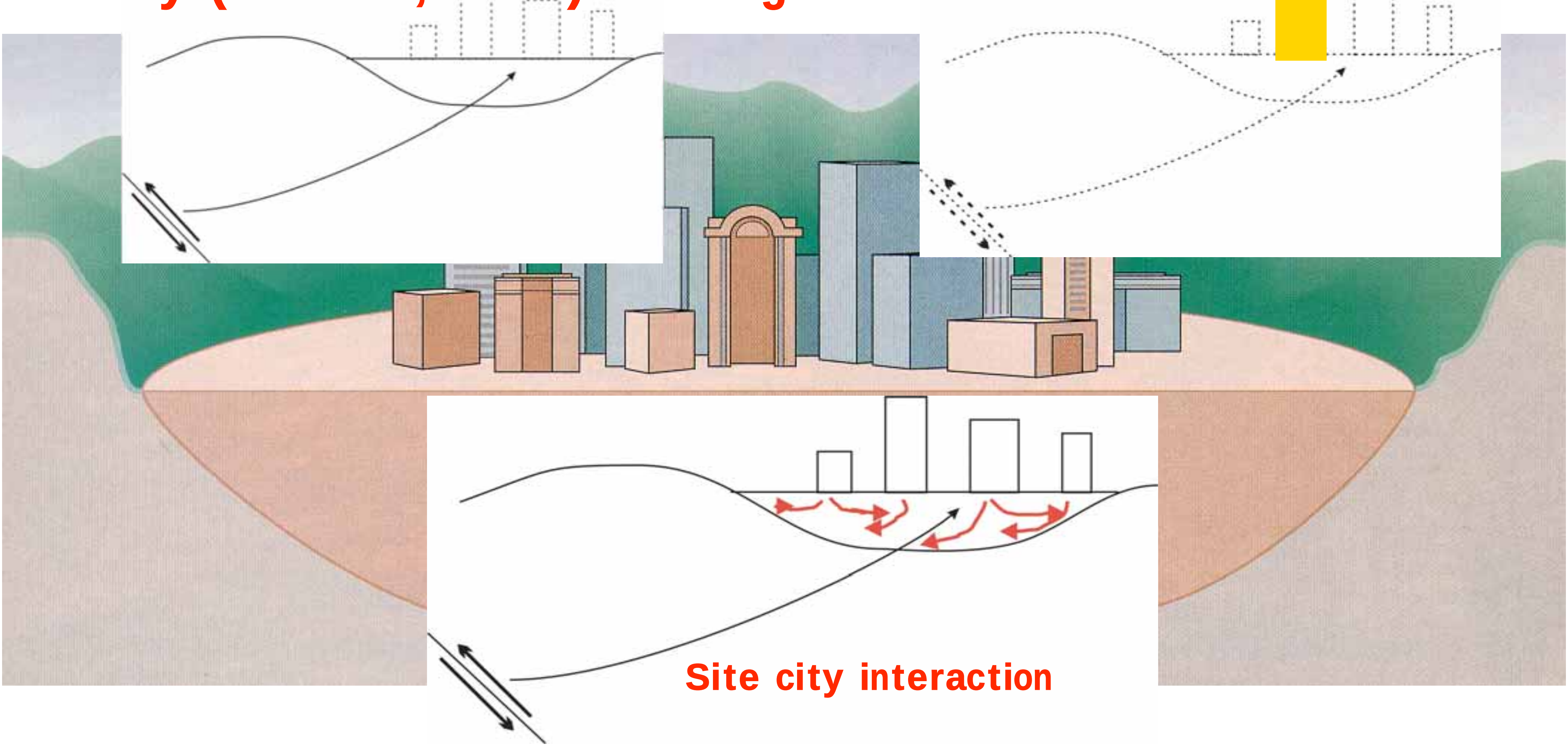
Fig. 4 — Plan et schèma d'instrumentation de l'ouvrage de Rio Dell [d'après Shakal *et al.*, 1984].



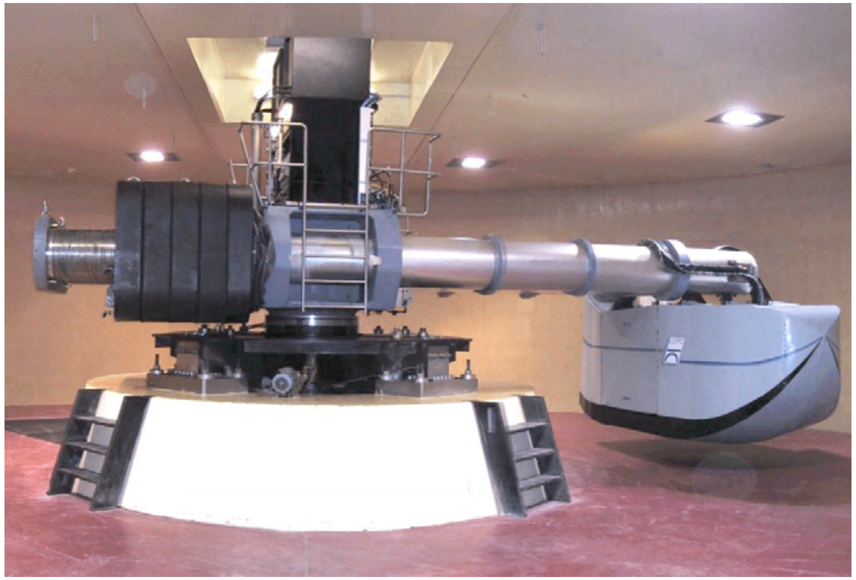
Dense cities on soft sites

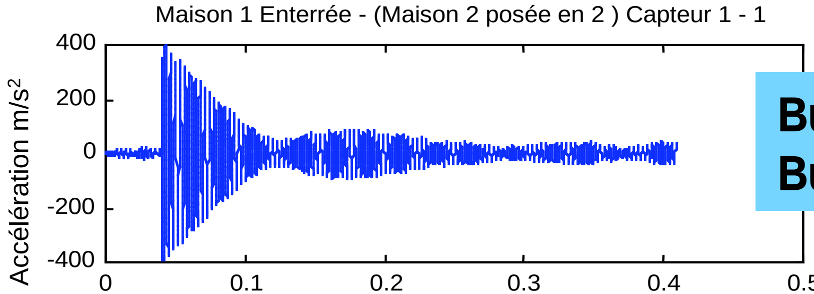
The seismologist viewpoint **The engineer viewpoint**

? May (massive, stiff) buildings mod

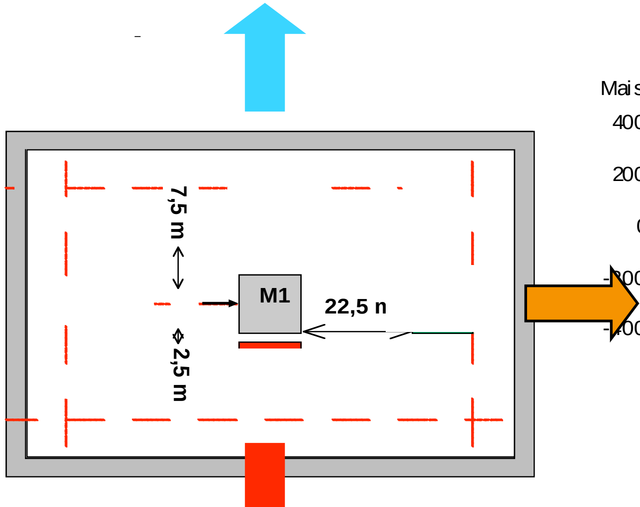


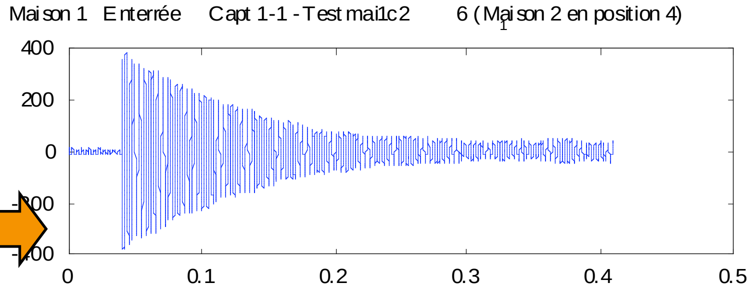
SSSI : Experimental evidence from centrifuge testing





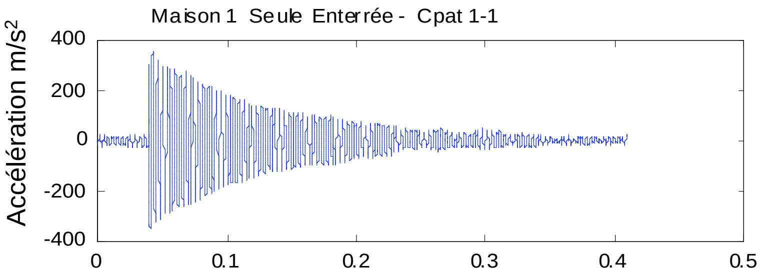
Building 1 with Building 2 at 7,5 m

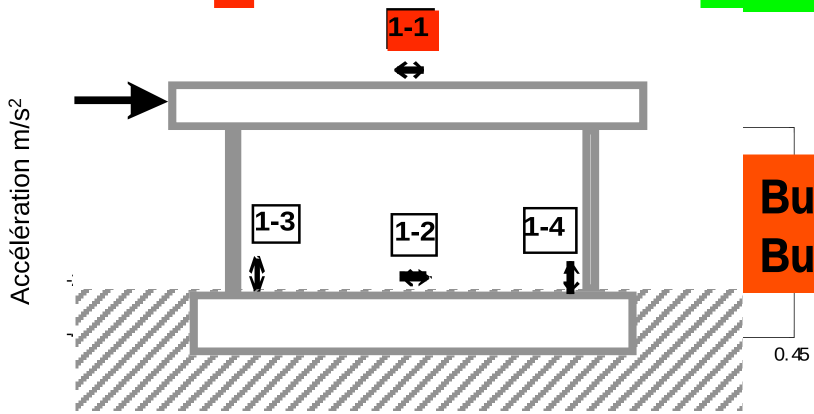




Building 1 with Building 2 at 22,5 m

Reference : Building 1 alone





Building 1 with Building 2 at 2,5 m

Maison 1

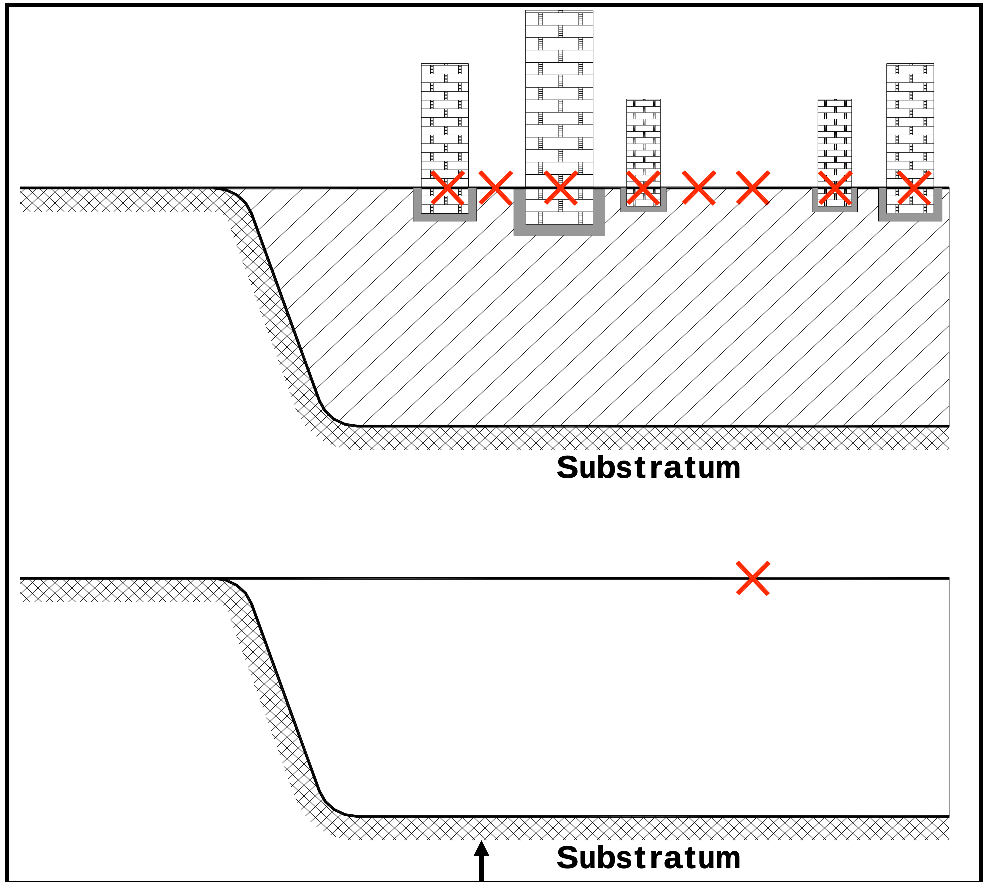
Ground motion : BEM results for Mexico City

(after Clouteau / Ishizawa, 2003)

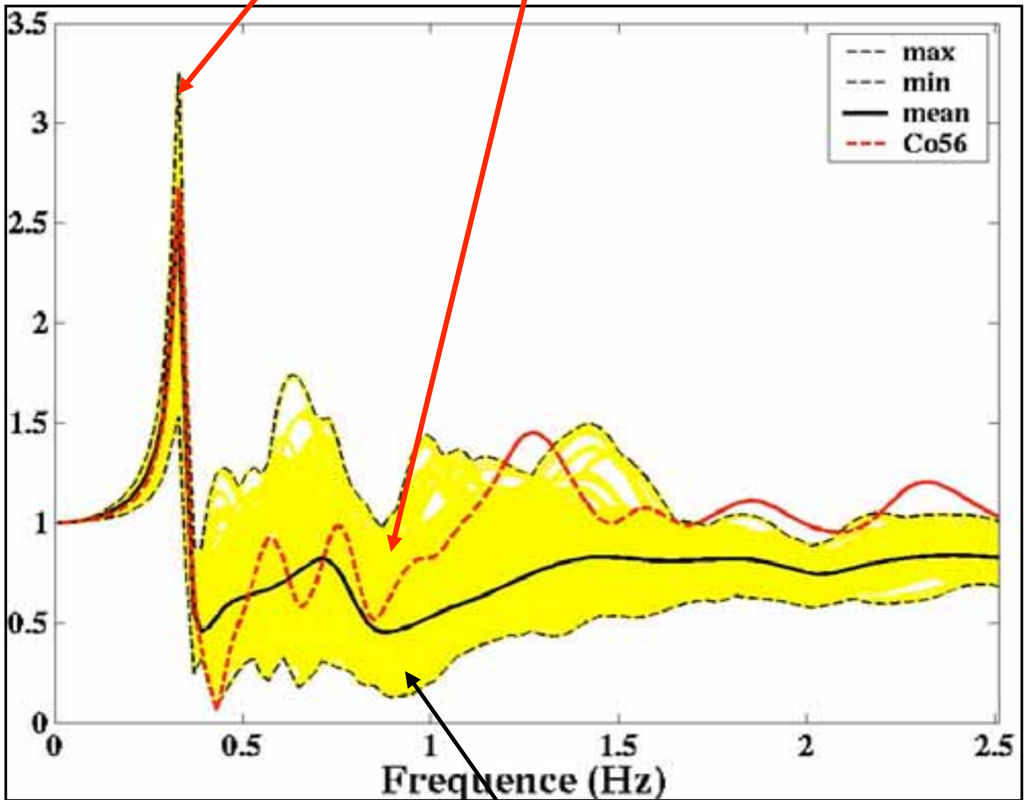
City effect

With buildings vs without buildings

Modification of average response



SH



Scatter on ground response

Main tools

Observations

Numerical simulation

(Shallow geophysics and geotechnics)

Main tools / Observations

Direct estimation of site amplification

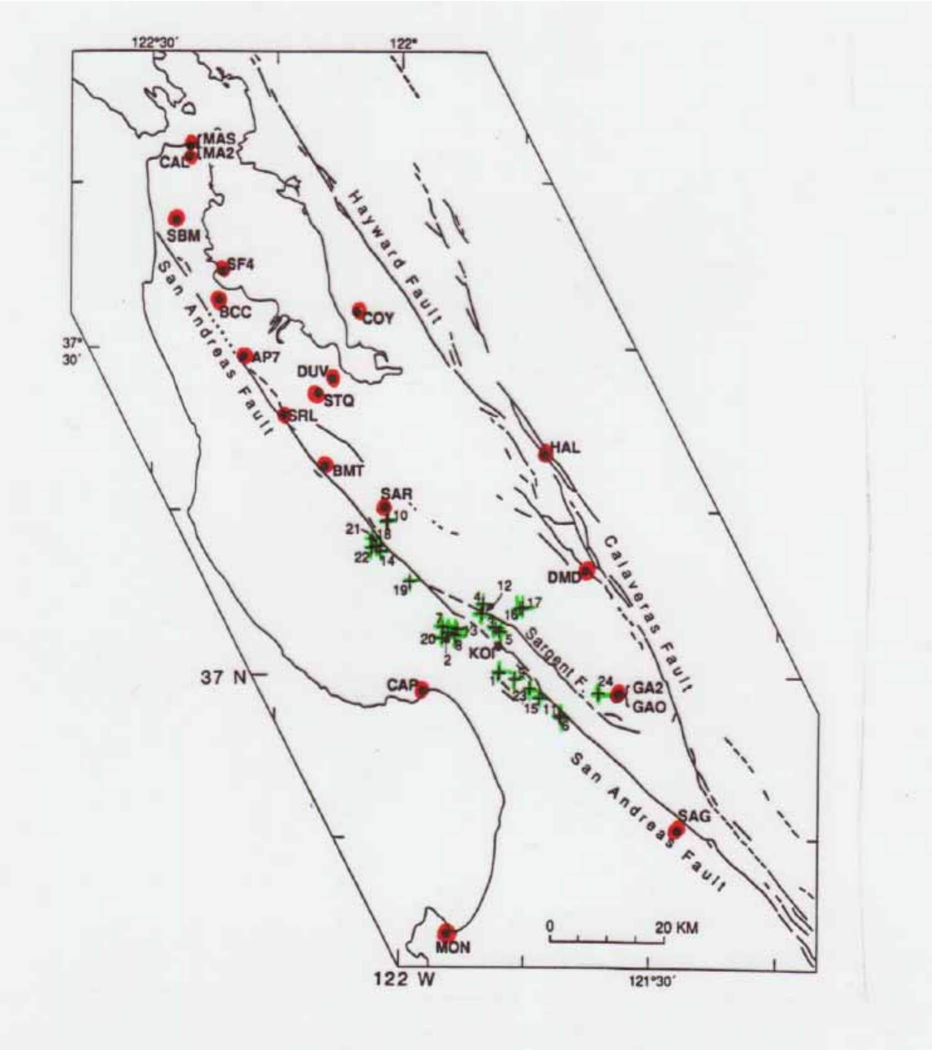
- Single station estimates : H/V
- Site / reference spectral ratio ➔ "small" inter-station distance
- Generalized inversion techniques ➔ "average" reference
  - require sensitive instruments

- 2D arrays : very few, not so dense
- Vertical arrays

- Amplitude / phase

Generalized inversion

Main interest : does not require a specific nearby reference site



Basic equation :

$$O_{ij}(f) = E_j(f) \,.\, P_{ij}(f) \,.\, S_i(f)$$

Propagation term :

$$P_{ij}(f) = 1./r_{ij}$$

$$= (1./r_{ij})^{\gamma} \,.\, e^{-\pi f t_{ij} / Q(f)}$$

(---> no account for focal mechanism, or directivity effects...)

Final equations :

$$\ln(E_j(f_k)) + \ln(S_i(f_k)) = \ln(O_{ij}(f_k)) - \ln(P_{ij}(f_k))$$

K(J + I) unknowns

Maximum KIJ equations

-----> weight σ_{ijk} depending on signal to noise ratio

(From Hartzell, 1992)

Generalized inversion of S-wave displacement spectra

Assumptions:

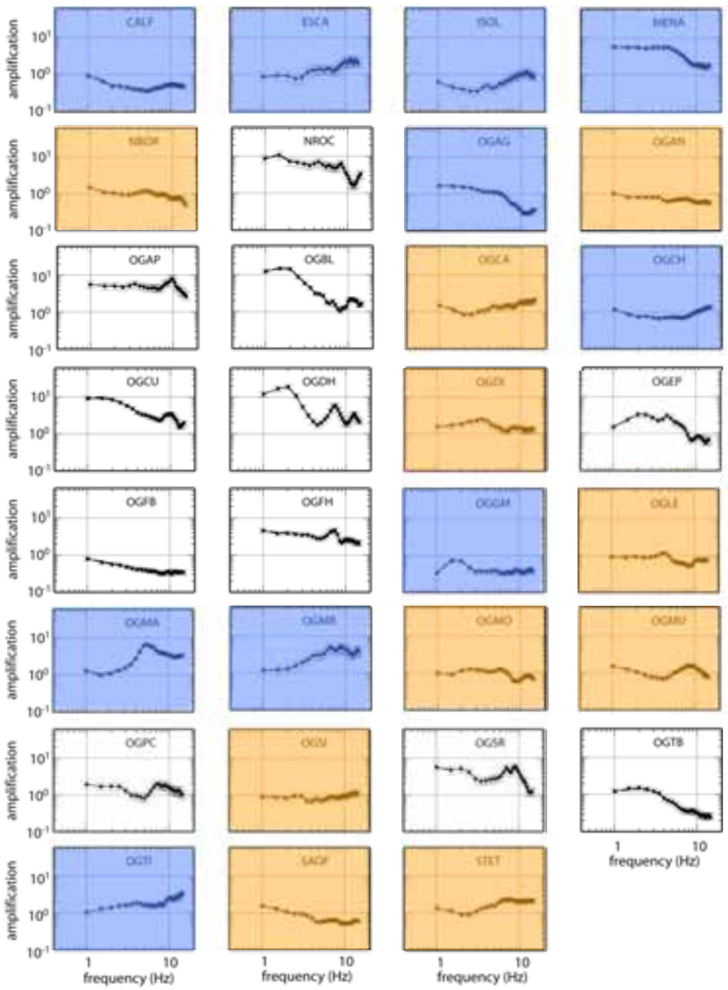
- ✓Far-field approximation (Dist>15 km)
- ✓Brune's type source (1970)
- ✓Average radiation pattern
- ✓v_S constant along the path
- ✓Geometrical decay constant between 15 and 200 km
- ✓$Q(f)=Q_0 f^{\alpha}$

$$A_{ij}(r_{ij}, f_k) = \underbrace{\frac{2R_{\theta\varphi} M_{0i}}{4\pi\rho v_S^{3}} \times \frac{1}{1+\left(\frac{f_k}{f_{ci}}\right)^{2}}}_{\text{Source}} \times \underbrace{\exp\left(-\frac{\pi r_{ij} f_k}{Q(f_k) v_S}\right) \times \frac{1}{r_{ij}^{\gamma}}}_{\text{Propagation}} \times \underbrace{S_j(f_k)}_{\text{Site}}$$

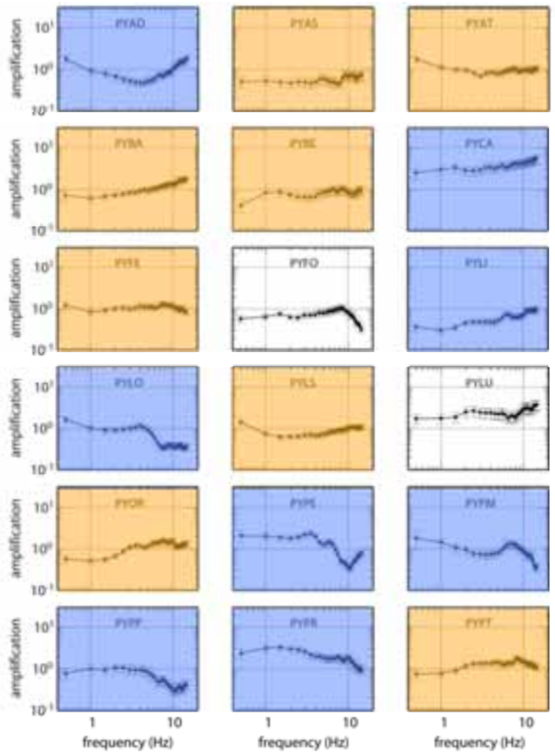
Drouet, Chevrot, Cotton, Souriau, 2008, BSSA, in press

Generalized inversion for estimating site amplification factors for French accelerometric sites

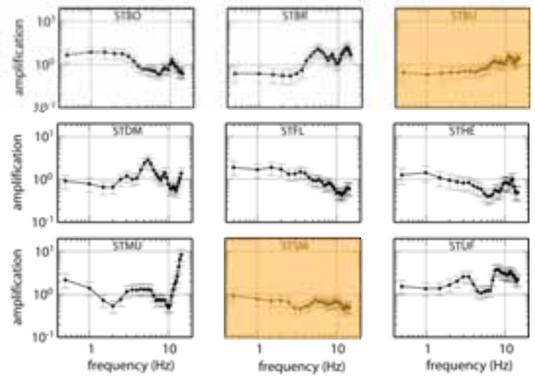
Alps:

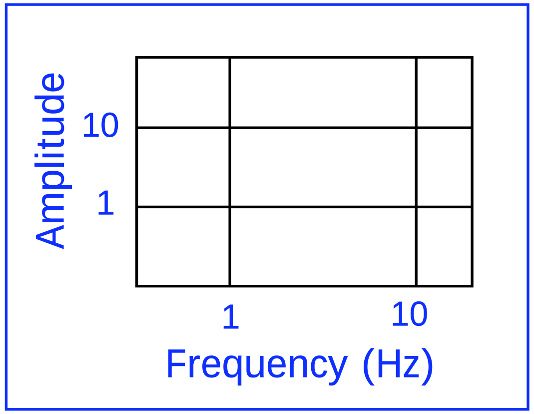


Pyrenees:



Rhine Graben:





Drouet et al., 2008

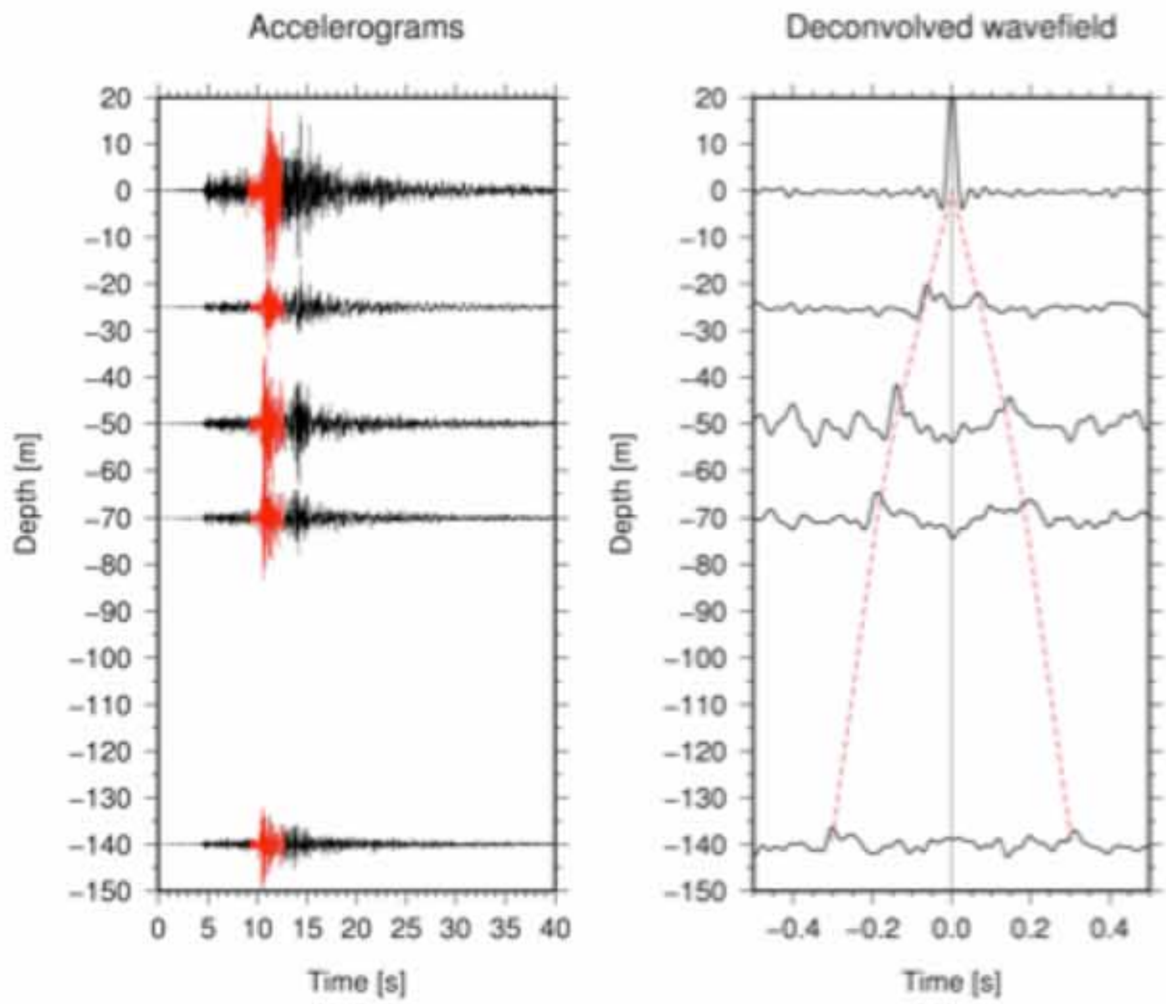
Vertical arrays

Deconvolution

- S-wave velocity profile
- Damping

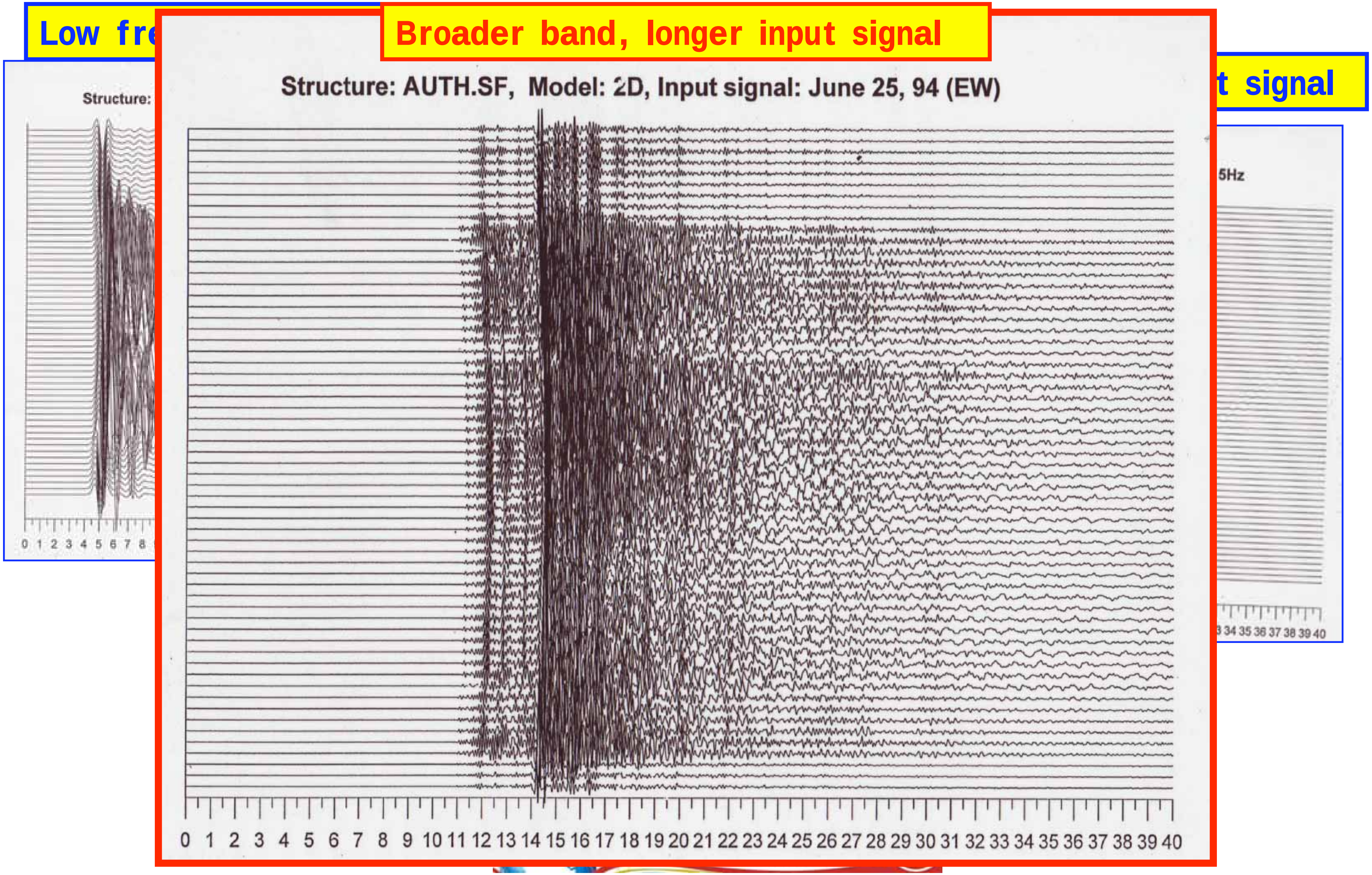
- NL characteristics

Still too few in the EuroMed area



(Parolai, 2010)

Amplification vs Duration / Phase



Amplification vs Duration / Phase

Known techniques

- group delay (Sawada et al., Beauval et al.)
- sonogram (Parolai et al.)
- time-frequency analysis

Still missing

- systematic investigations in parallel in amplification studies

Main tools / Observations

Direct estimation of site amplification : reference / non-reference

- Site / reference spectral ratio ➔ "small" inter-station distance
- Generalized inversion techniques ➔ "average" reference
- single station estimates : H/V
- Vertical arrays (? depth)
- Amplitude / phase

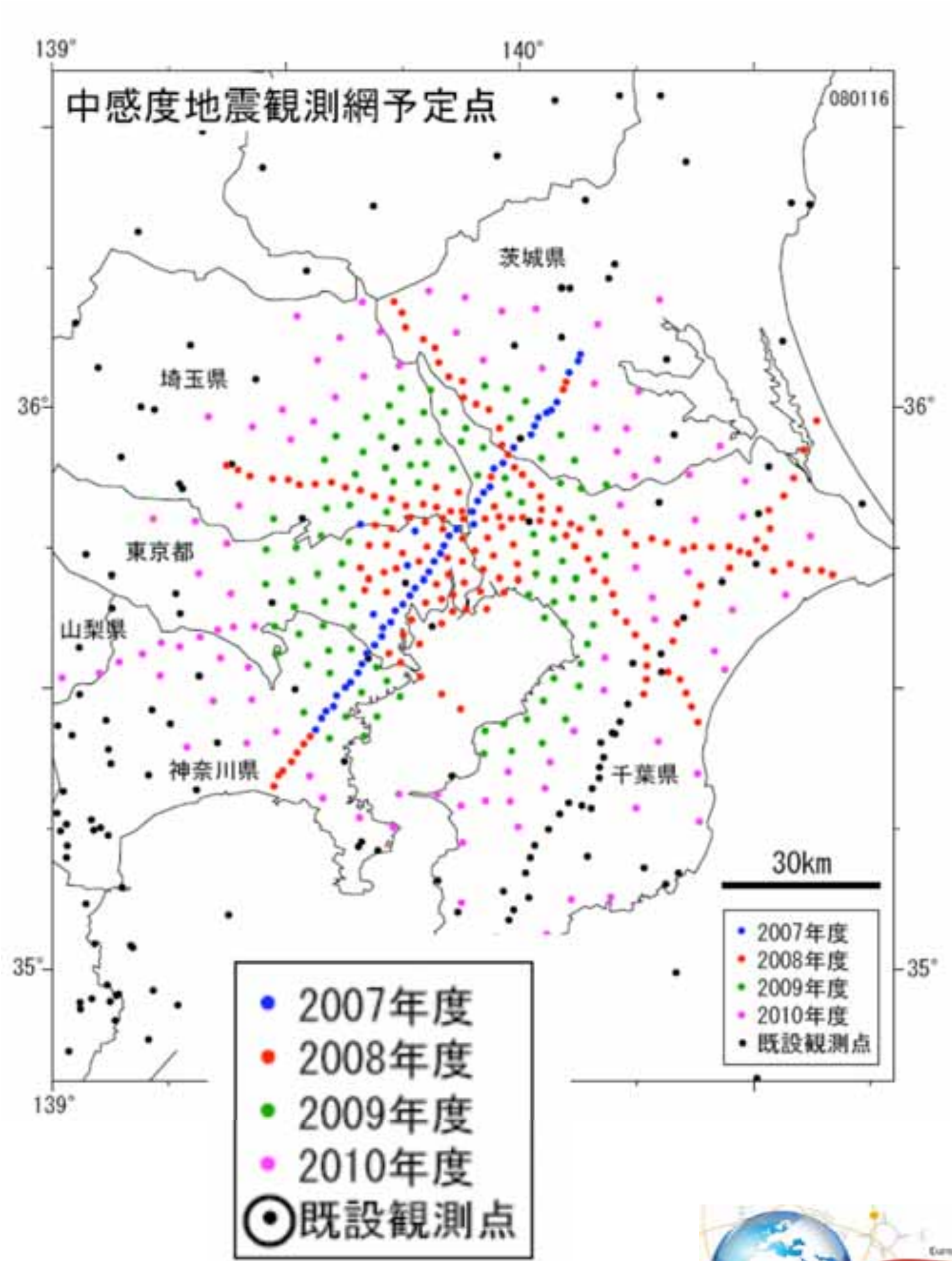
Seismological observations as an exploration tool for subsurface structure ?

- Small-scale tomography / inversion : ex Tokyo

Interpretations and statistical studies : link with site conditions at considered observation sites : need for metadata !

- permanent stations (SM, BB)
- temporary stations

Example : Ongoing studies in Tokyo (dedicated semi-permanent array)



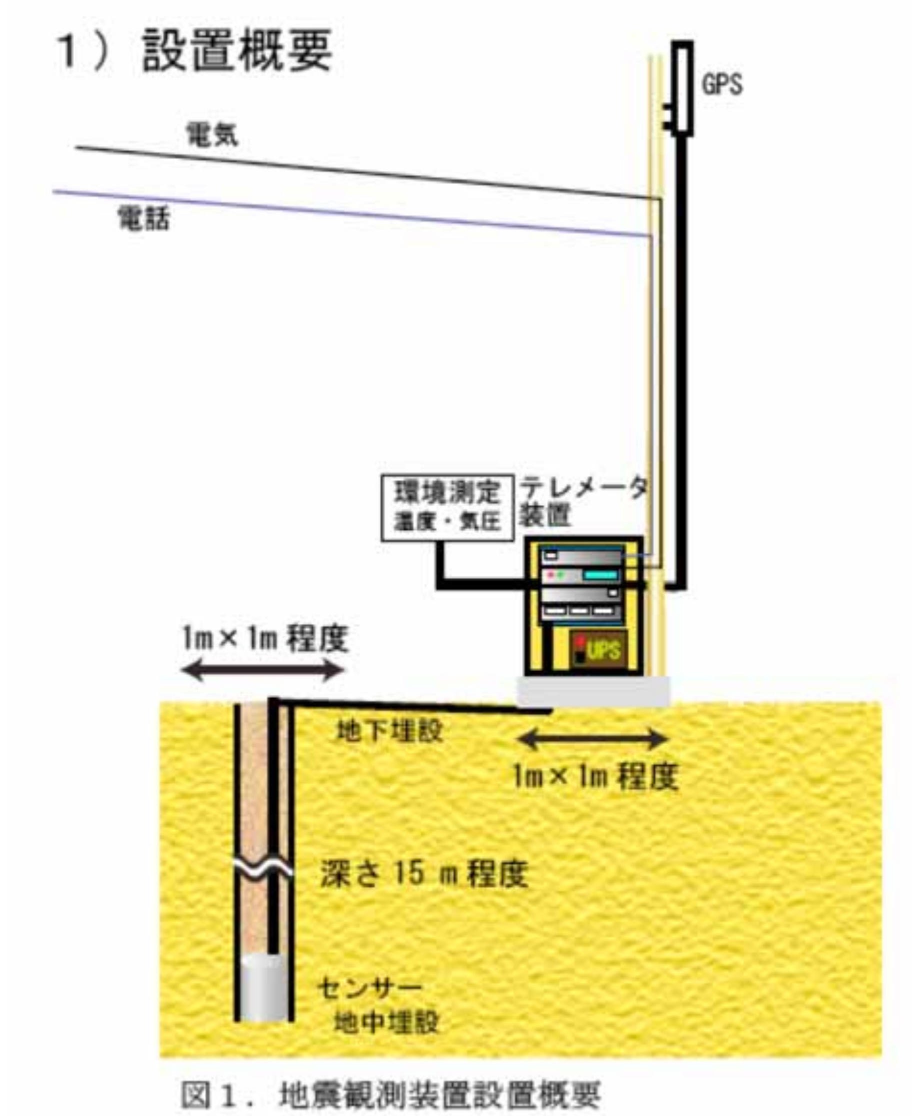


図１．地震観測装置設置概要

(Courtesy : T. Yamanaka / S. Tsuno, TITech)

Main tools / Observations

Direct estimation of site amplification : reference / non-reference

- Site / reference spectral ratio ➔ "small" inter-station distance
- Generalized inversion techniques ➔ "average" reference
- single station estimates : H/V
- Vertical arrays (? depth)
- Amplitude / phase

Seismological observations as an exploration tool for subsurface structure ?

- Small-scale tomography / inversion : ex Tokyo

Interpretations and statistical studies : link with site conditions at considered observation sites : need for metadata !

- permanent stations (SM, BB)
- temporary stations

THE example to follow: Japan

  - EuroMed instrumentation : a step behind
  - Too few test sites

- usefulness of a dedicated large pool (several hundreds) of compatible mobile stations at the European level (for temporary, very dense studies on small, typically ct-scale areas)

Main tools / Numerical simulation

Invaluable tool in understanding the physics of site effects

- Various excellent teams and techniques in Europe
- BEM, FDM, FEM, SEM, DGM, DEM

Verification / validation issues

- still faces big challenges for actually predicting them for complex 3D structures. Numerous sophisticated codes do exist, but their use without due caution can be harmful
- Verification = evaluate the accuracy of current numerical methods when applied to realistic 3D applications
  - ➔ cross-checking that different codes provide similar results on same cases
- Validation = (successful) comparison with instrumental observations
  - ➔ quantify the agreement between recorded and numerically simulated earthquake ground motion
  - (source + path + site)
- **Recent initiatives / projects in Europe**
  - SPICE, QUEST, NERA
  - ESG2006, Cashima

Present capabilities : at reach up to frequencies around 4-5 Hz ?

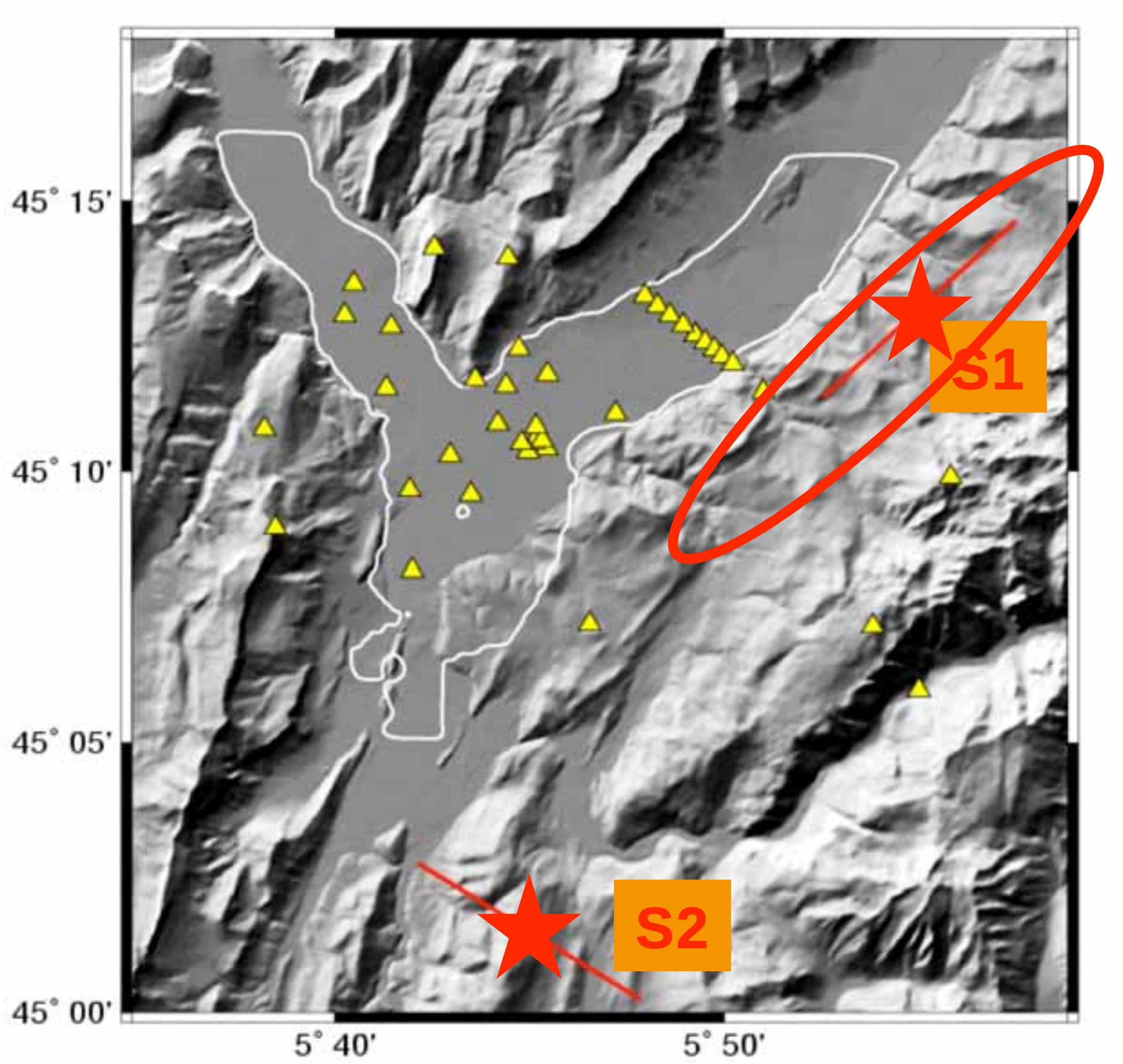
Example : the ESF2006 3D benchmark (Grenoble)

2 real weak events

- W1, W2

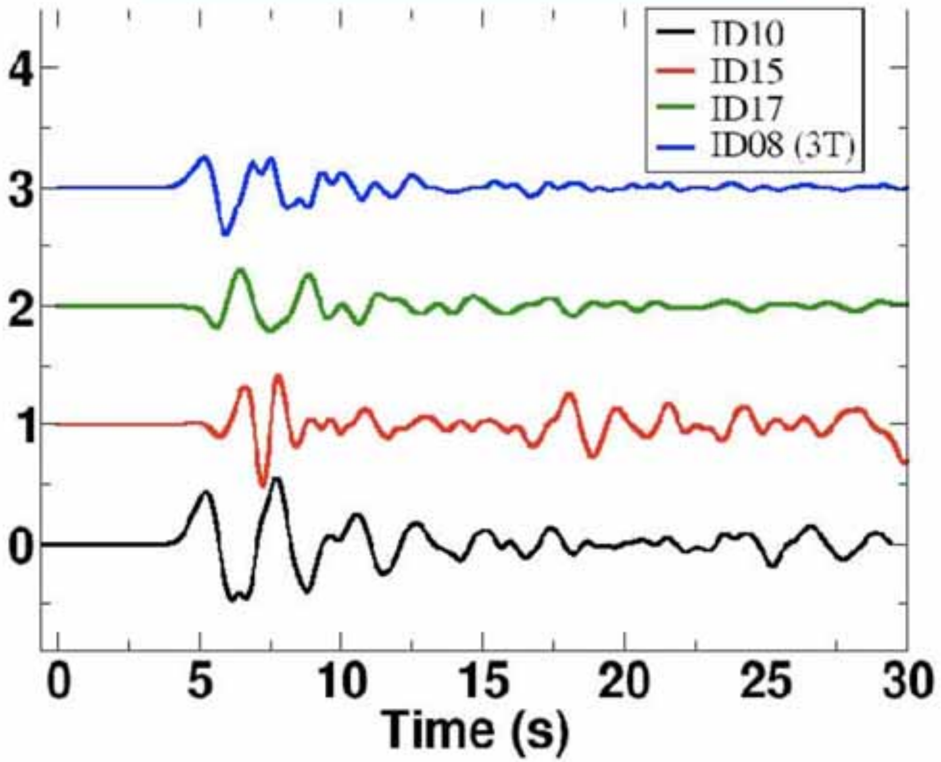
2 hypothetical strong events

- S1, S2 (M=6)
- Extrapolation from W1, W2
- Source : imposed geometry and kinematics

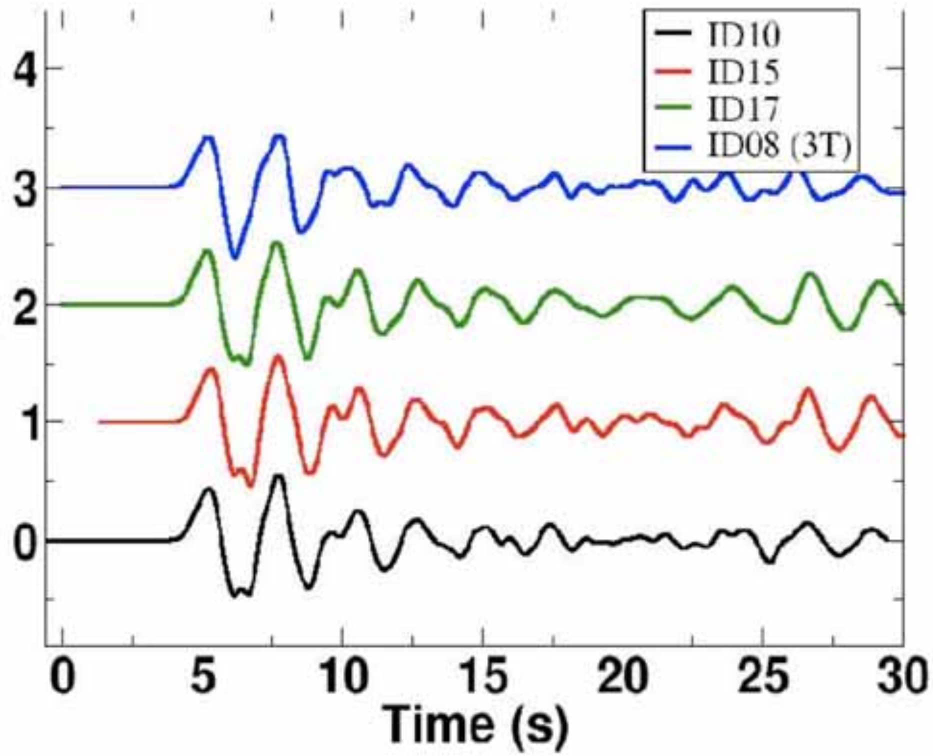


Iteration process : 3 teams (/6)

September 1, 2006



April 8, 2007



ID15 : bug in basin model definition

ID17 : bug in extended source definition

ID08 : bug in extended source definition

EuroseisTest Verification and Validation Project

Final Workshop

June 3-4, 2010 - Cadarache

E-2VP
EUROSEISTEST
VERIFICATION AND
VALIDATION PROJECT

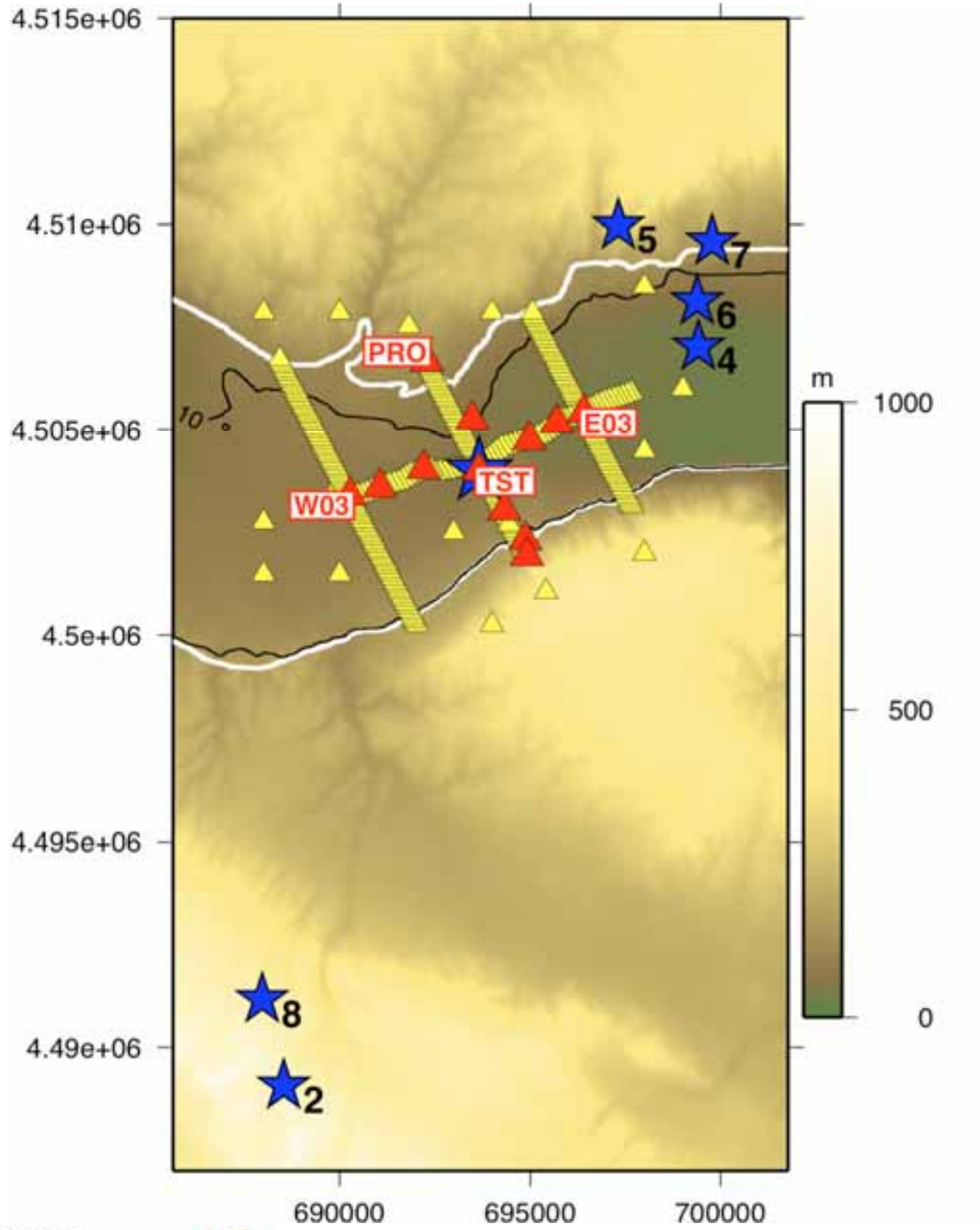
LGIT Grenoble

ARISTOTLE UNIVERSITY OF THESSALONIKI

cea
ILL NEUTRONS FOR SCIENCE

Cashima Project

The Cashima / Euroseistest site



Cashima / Euroseistest components

Initial checks

- Site selection → Volvi / Euroseistest
- Contacting several teams (about 10)
- Careful scheduling with 3 phases for iteration; 1 kick-off meeting + 4 workshops (May 2008, Fall 2008, Spring 2009, Fall 2009, Spring 2010 = Final)

Verification : cross-comparison of different simulation techniques

- 3D : Up to 4 Hz
  - Plane wave / point source
  - With and without damping
  - Discrete layering / smooth gradient
- 2D: Target = 8-10 Hz
  - Linear / Non-Linear

Validation : comparison with actual recordings (3D only)

- local, moderate magnitude events

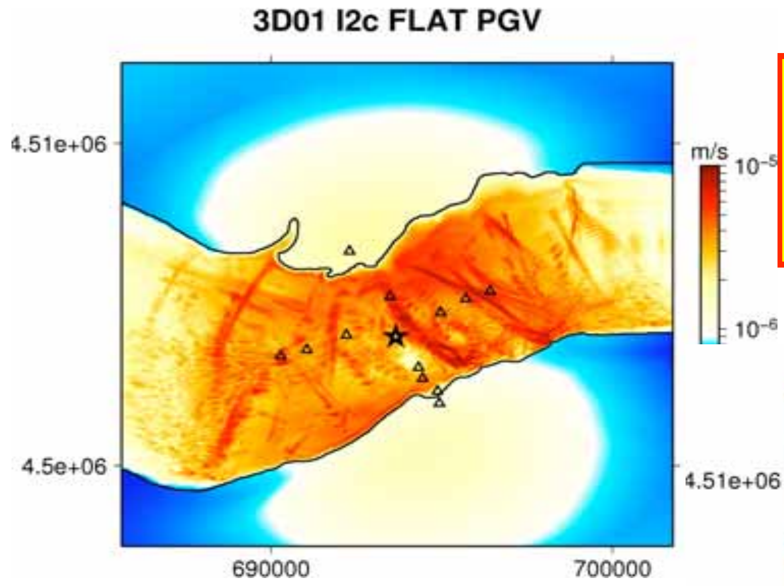
Conclusions 1 - Verification

3D

- numerical simulation of ground motion is not yet a ”press-button” procedure,
- Good match up to 4 Hz obtained between various simulation techniques indicates a very encouraging level of maturity.
  - teams and codes who already compared their results are more likely to provide satisfactory results at the first iteration
- Emphasis on the importance of
  - the actual implementation of damping
  - the details of the discretization process for interfaces with large impedance contrast

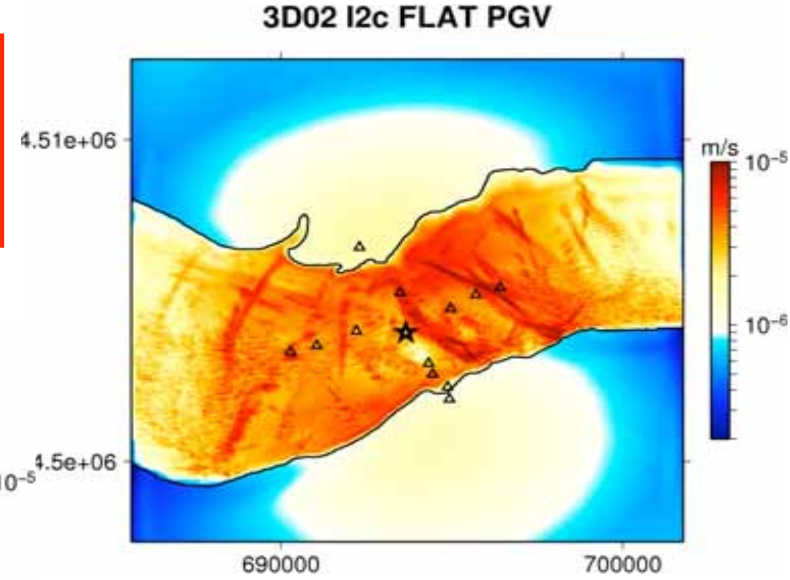
- **2D NL : not yet mature, ongoing**
  - Usefulness of preliminary checks on 2D L
  - Key importance of damping in NL models
    - classical "Seed like" curves yield strong NL effects at least in deep deposits
    - ? Large effects at high frequencies because of damping ?

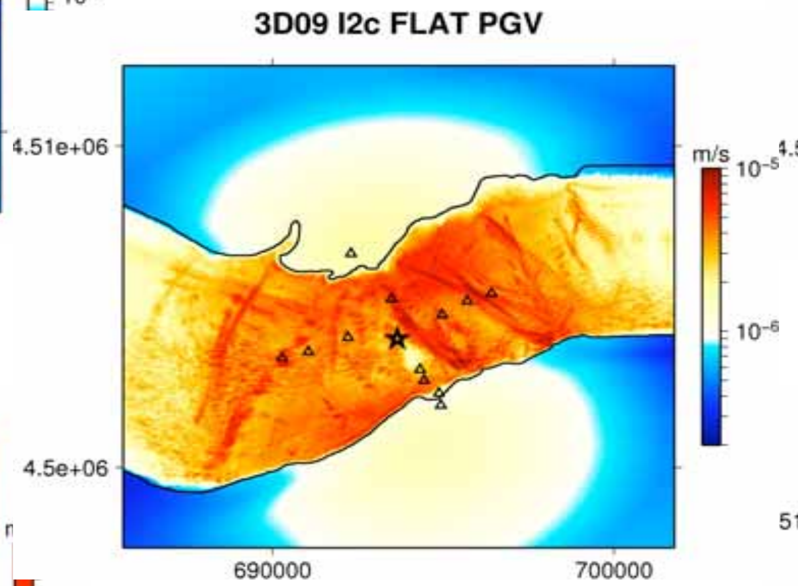
Verification 2 : layered model, NO damping

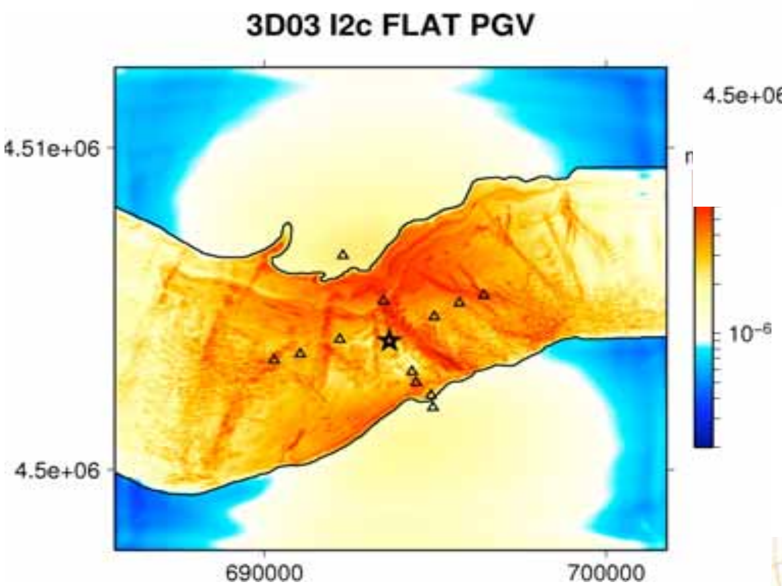


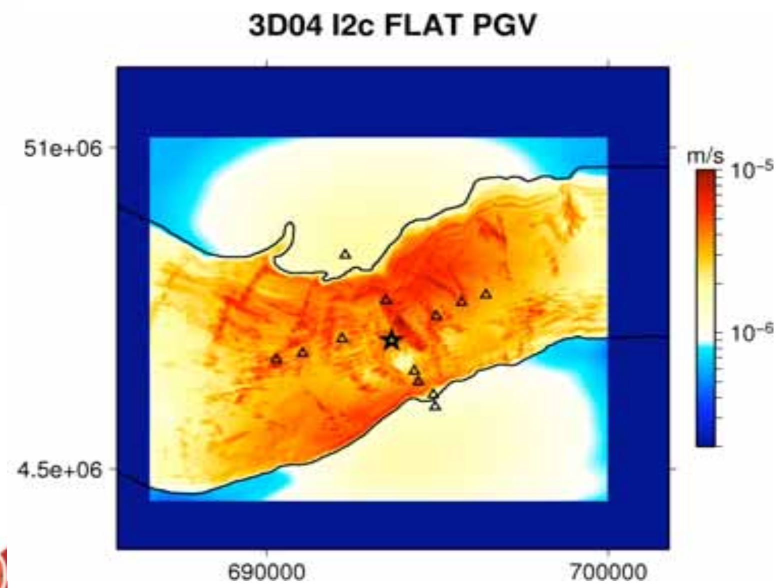
Rather satisfactory

PGV maps

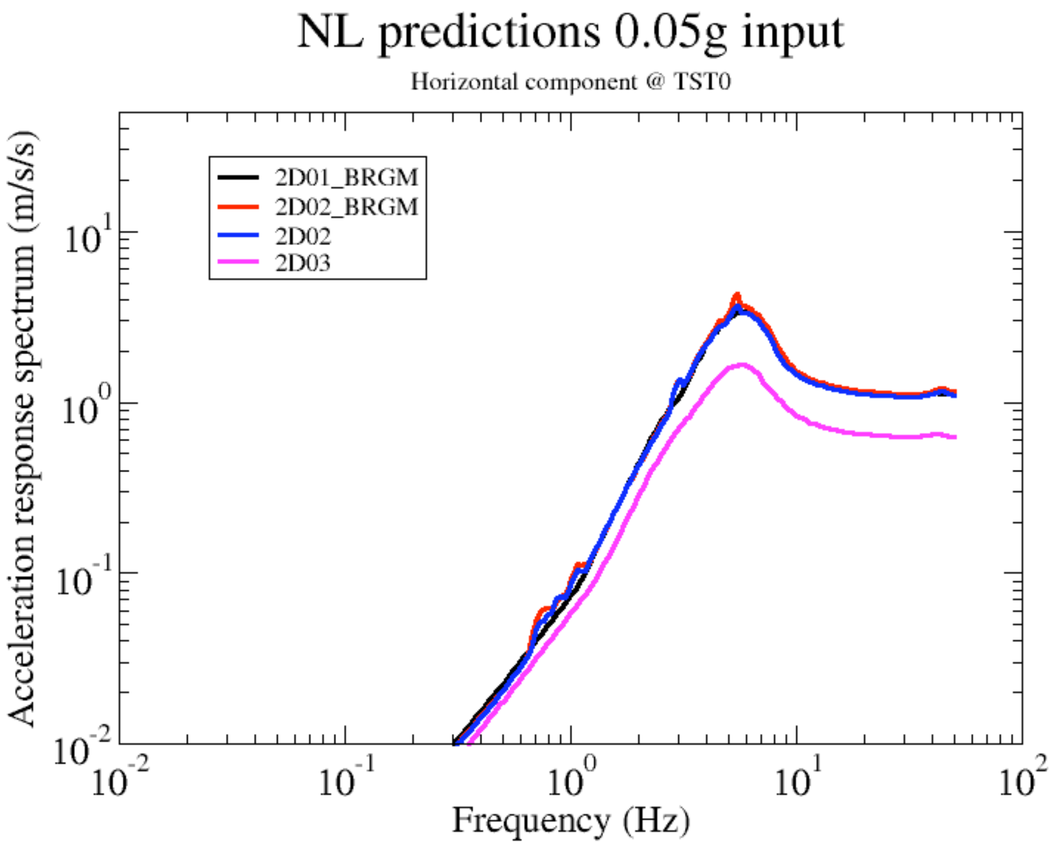


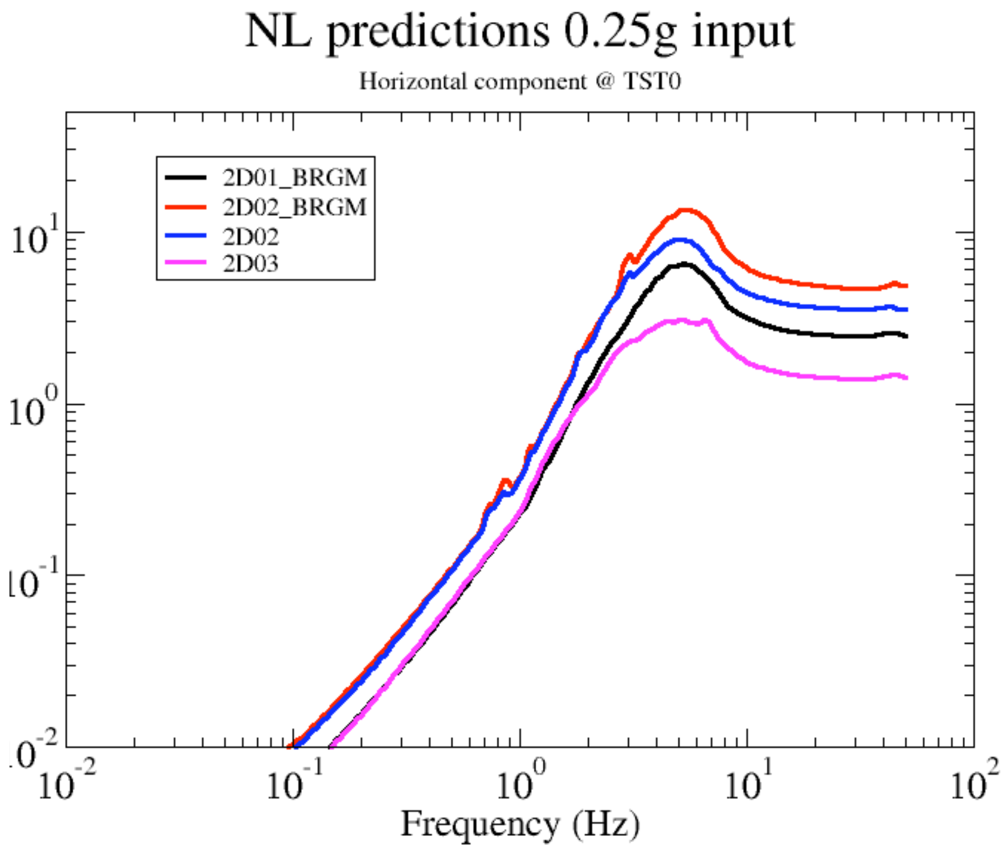






NL verification : Model to model comparison of response spectra





Significant variability in NL modelling results

Conclusions 2 - Validation

Limited to local, weak to moderate magnitude events with significant high frequency contents

- ➢ Satisfactory match of ”overall” characteristics (amplitude, envelope, duration)
  - to be balanced by
- ➢ Large differences in the details of waveforms

Limitations to increase in maximum frequency are mainly related to

- ➢ uncertainties in source parameters
- ➢ capabilities of geophysical surveys
  - underground structure at short wavelength
  - still a few very badly known parameters (e.g., material damping)

next challenge ?

ESC 2010

Engineering interface

"Routine" : building codes (Non-site specific assessment)

- Site classification : which parameter ?
  - VS30
  - ? Alternative
- Associated amplification factors / spectra

Large scale hazard/risk maps, Shake maps

- ? which simple proxy to site effect (from remote sensing)
  - slope
  - others ?

Microzonation: area specific

- Cost constraints

Site specific assessments (critical facilities)

- Open !
- Europe : instrumental approach drastically neglected
  - single station sigma, major impact on the reduction of uncertainties, and therefore hazard levels at large return periods.

ESC 2010

Needs

Reliable, affordable site survey techniques for

- sursurface conditions at SM and seismological stations
- microzonation studies at the city scale
    - (a few to hundreds of km^2)
- identification of site class for building codes (V_{S30}, f_0, ???)

Target

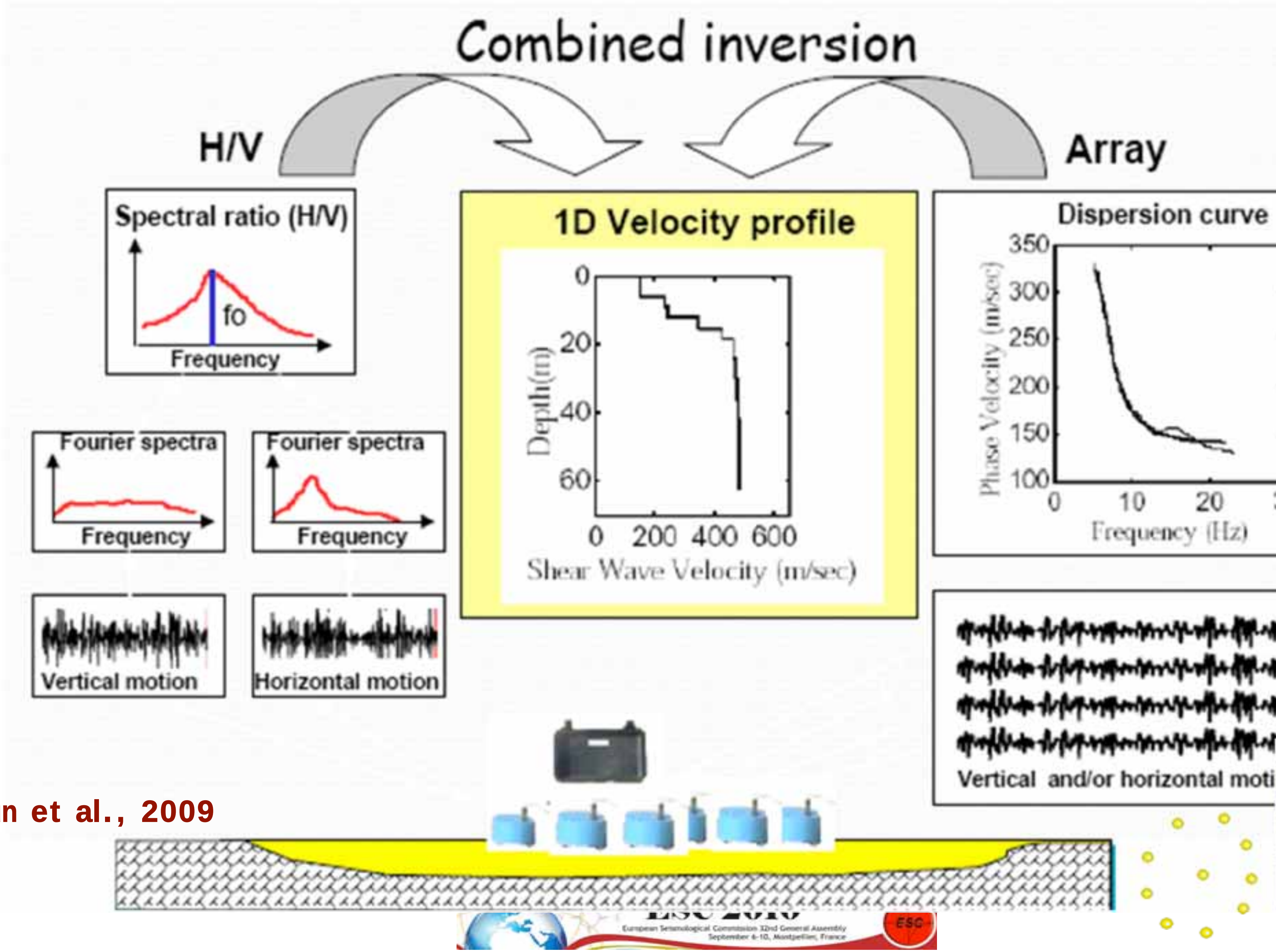
- Large depth (low frequency)
- Shallow depth over short wavelengths

Required

- wide areas or numerous sites : cost efficiency
- reliable, quantitative estimates of relevant parameters

➔ Move to non-invasive techniques

Techniques used to extract subsurface properties from ambient vibration recordings



Endrun et al., 2009

Systematic comparison with borehole data

Selection of 20 representative sites

- variable and representative subsurface geology and topography.
- Stiffness + Thickness, + 1D/2D/3D, + reliability of the existing information + EC8 classes

9 in Italy, 7 in Greece, 3 in Turkey, 1 in France

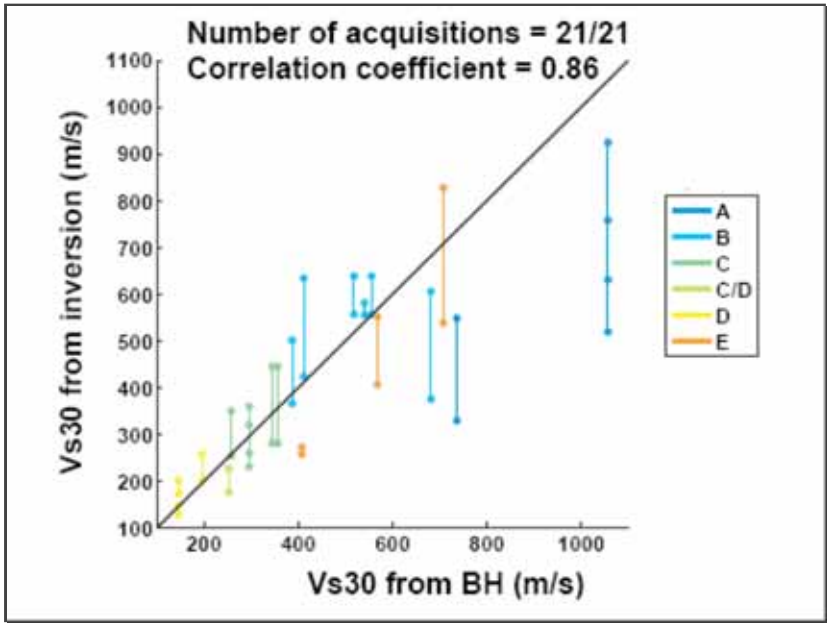
(see Renalier et al., SSA2009)

Localisation of the 19 experimental sites where the MASW and AMV measurements were acquired.

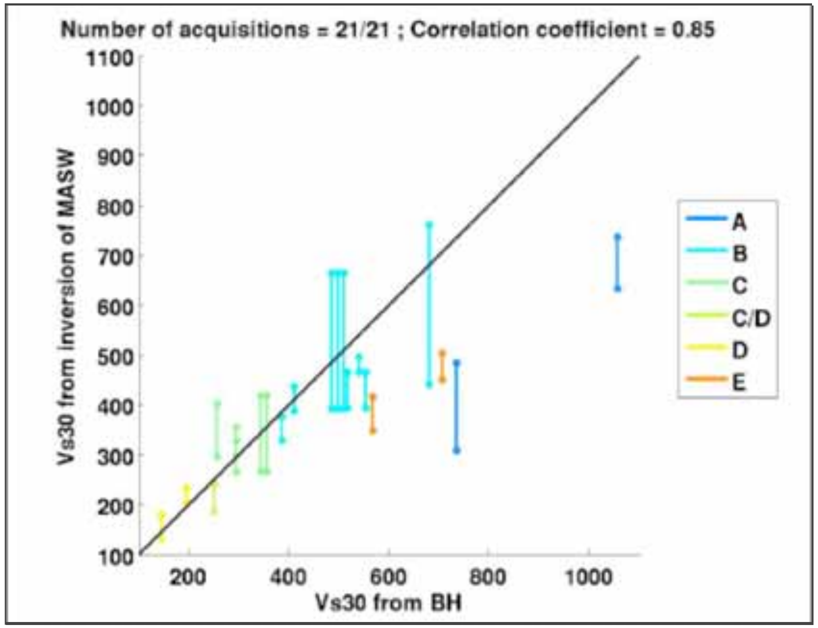
SITE CLASS	DESCRIPTION EC8 classification	NUMBER OF SITES
A	Rock or other rock-like geological formation, including at most 5m of weaker material at the surface. (Vs_{30} > 800 m/s)	2
B	Deposits of very dense sand, gravel or very stiff clay, at least several tens of min thickness, characterised by a gradual increase of mechanical properties with depth. (Vs_{30} = 360 - 800 m/s)	6
C	Deep deposits of dense or medium sand, gravel or stiff clay with thickness from several tens to many hundred of m. (Vs_{30} = 180 - 360 m/s)	5
C/D		1
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil. (Vs_{30} < 180 m/s)	2
E	A soil profile consisting of a surface alluvium layer with Vs values of type C or D and thickness varying between about 5 and 20m, underlain by stiffer material with Vs>800m/s.	3

Summary Comparison V_{S30}

AMV / BH



MASW / BH



- Good agreement for "normal to soft" sites (EC8 classes C, D, E)

- Noticeable and systematic differences for stiffer sites (EC8 classes A, B):
  - Vs30 (non-invasive) < Vs30 (invasive)

  (Similar trend reported in Moss, BSSA 2008)

  Several possible explanations

  ? Frequency range ? Averaging effect ? Anisotropy ?

  Is it a concern ?

Complementary measurements

New cross-holes close to "old" ones

Selected sites

- **Forli (EC8 B)**
- **Bagnoli Irpino (EC8 A)**
- **Sturno (EC8 A)**

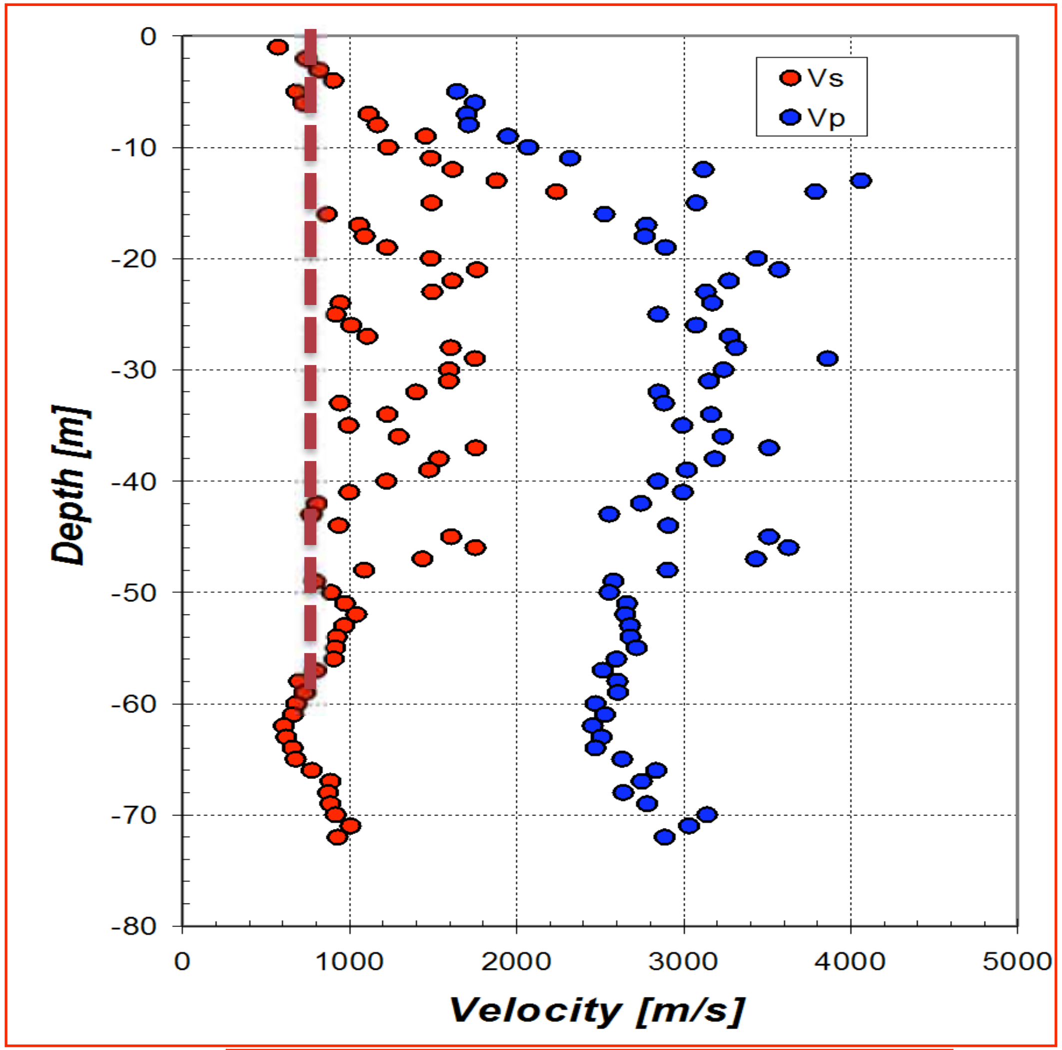
Similar results for all 3 : decrease of velocity

- **Forli : B → C**
- **Bagnoli : A → B**
- **Sturno : A → B**

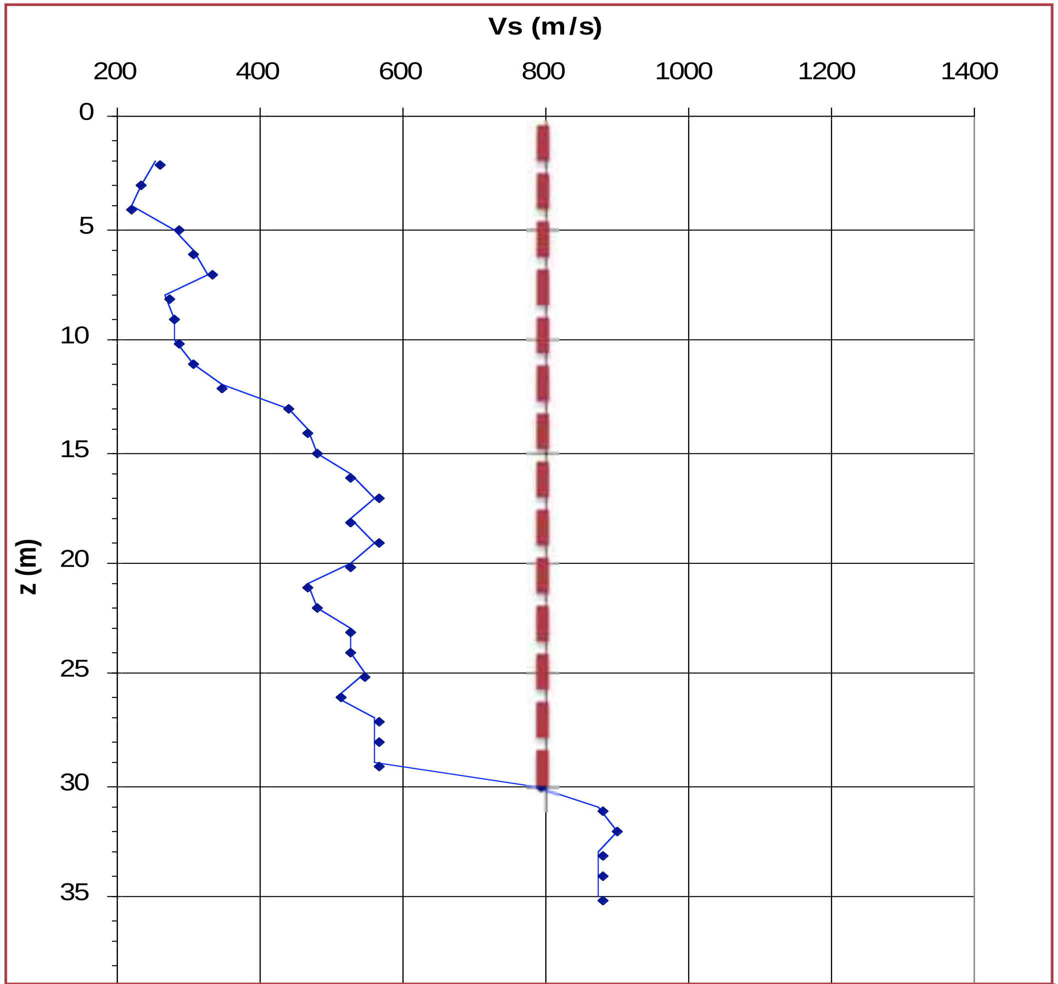
Does raise questions about the relia-bility of (old) borehole data

Hailemikael et al., 2008

Sturno (distance 1991-2007 : 45 m)



ISMES 1991; EC8=A



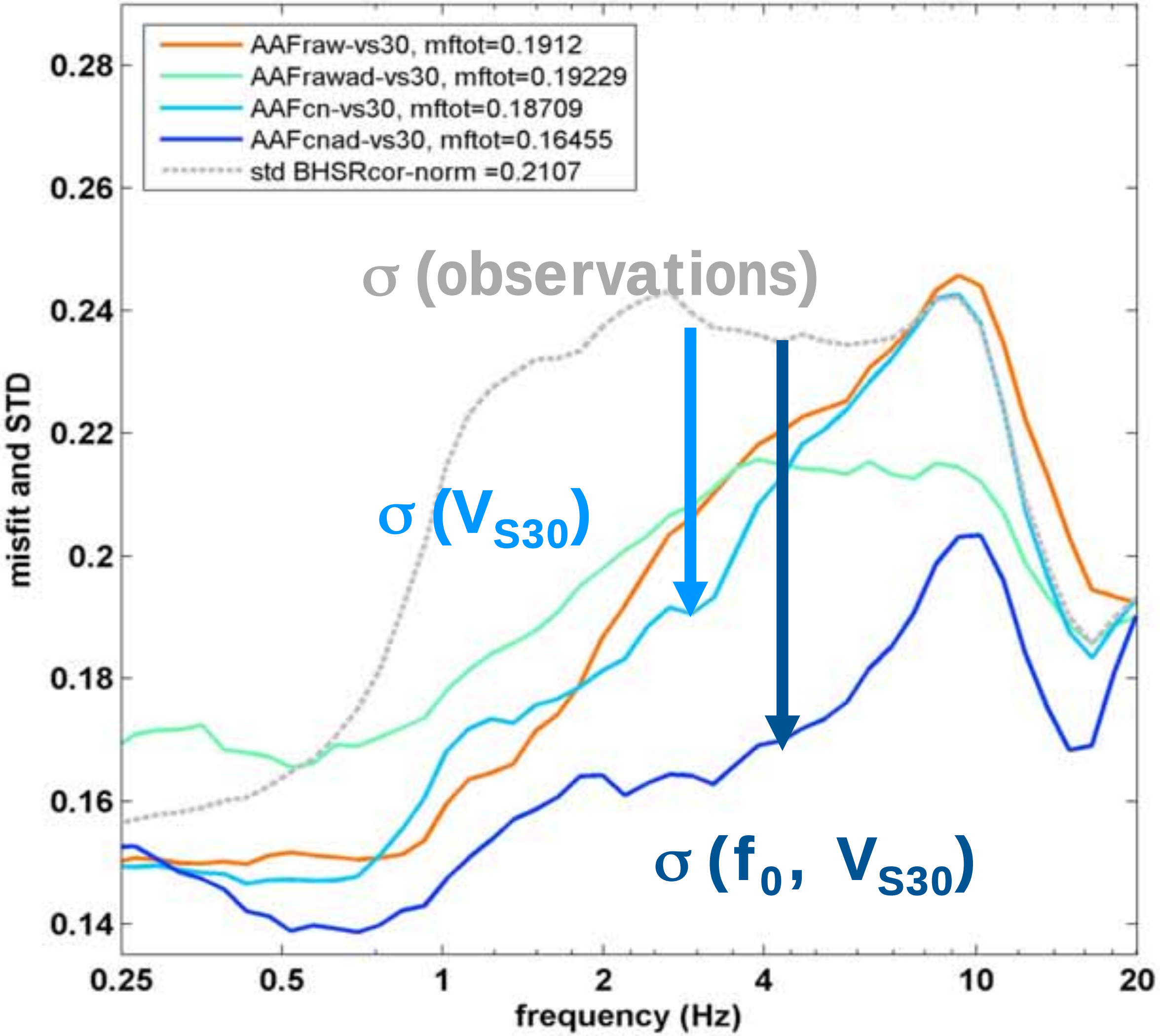
Prof. E. Cardarelli University of Rome “La Sapienza” 2007; EC8=B

Hailemikael et al., 2008

? Most relevant parameter for site conditions ?

How to best explain the variance of site amplification factors ?

Considered parameters	Misfit (log10)
V_{S5} and f_0	0.168
V_{S10} and f_0	0.164
V_{S20} and f_0	0.159
V_{S30} and f_0	0.158
f_0 only	0.159
V_{S30} only	0.174
Original σ	0.202



Best = couple of parameters f_0 and V_{S20} or V_{S30}

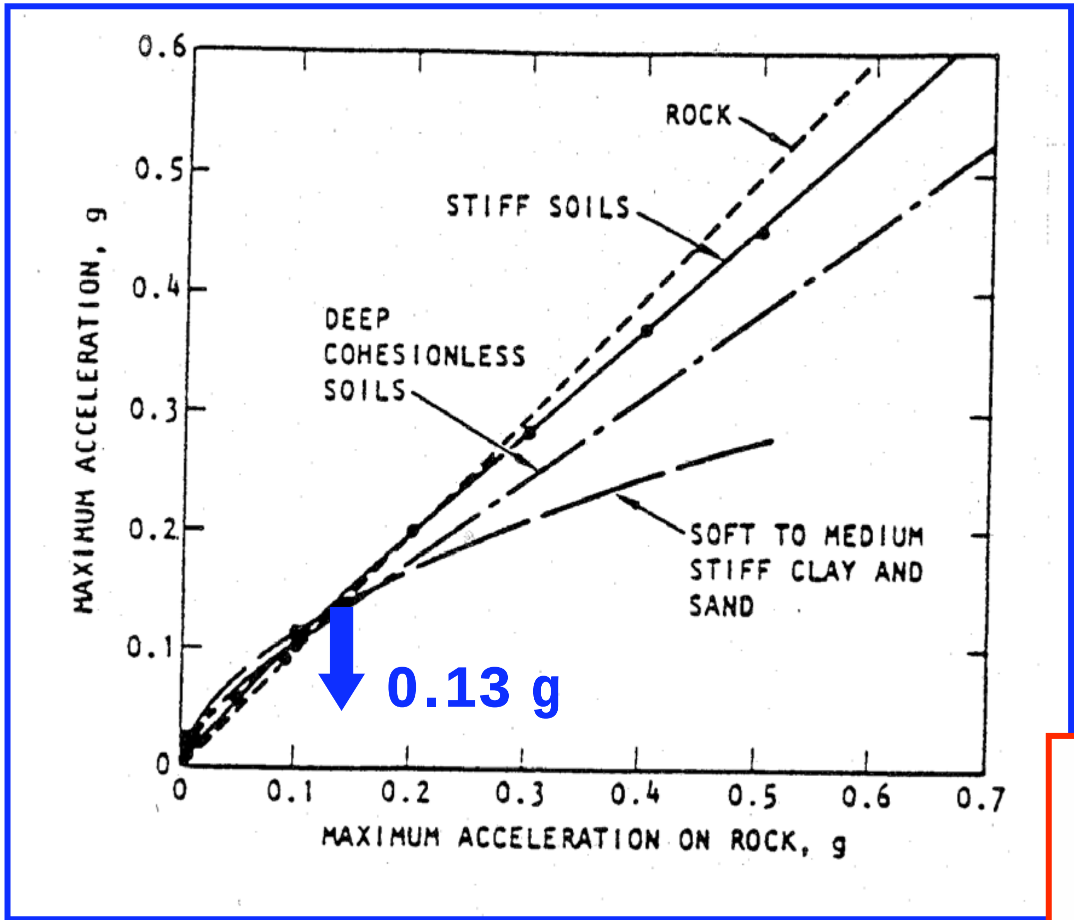
f_0 alone much better than V_{S30} alone

Cadet et al., 2010

Accounting for non-linear effects

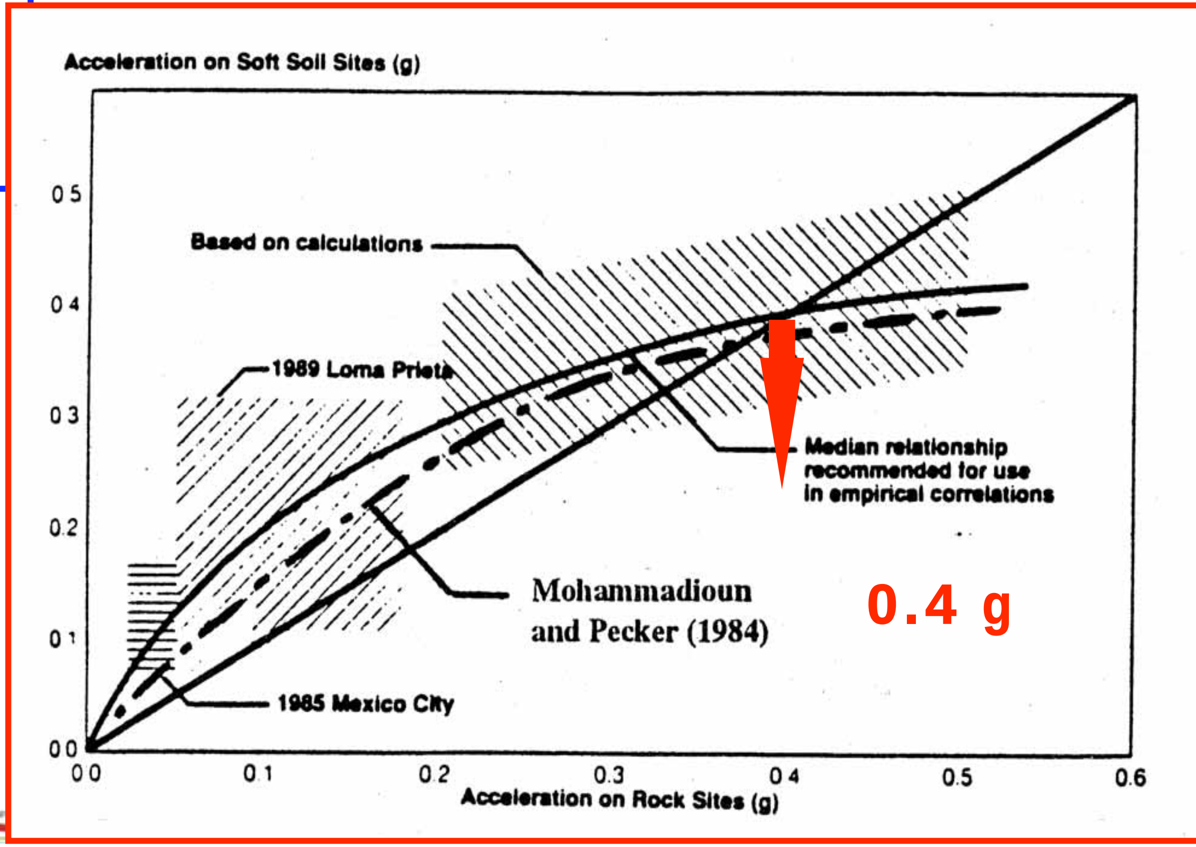
Building codes ?

? In-situ measurements ?



Before 1985

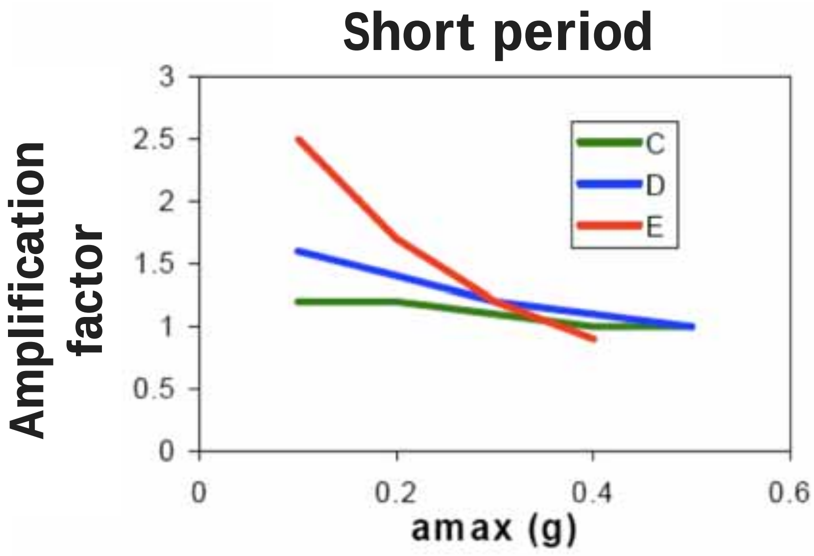
After 1990

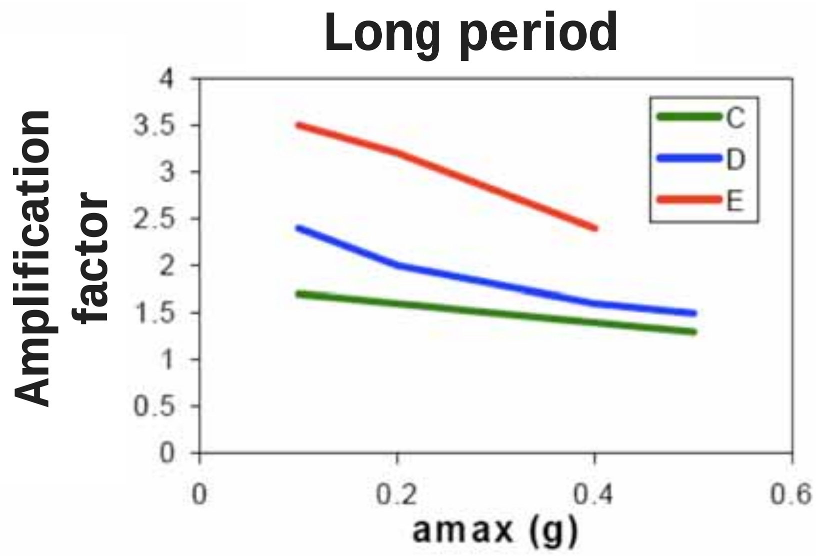


Post-1994

Separate amplification factors for short- and long- period spectra

- C = stiff soil/ weathered rock
- D = soil
- E = soft soil

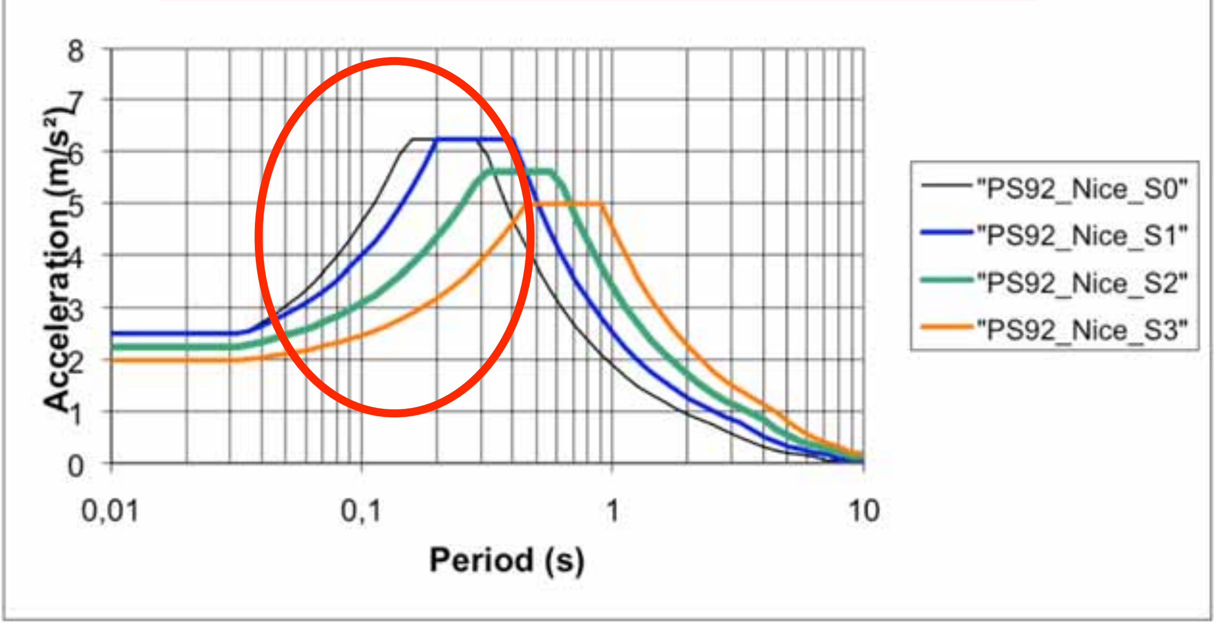


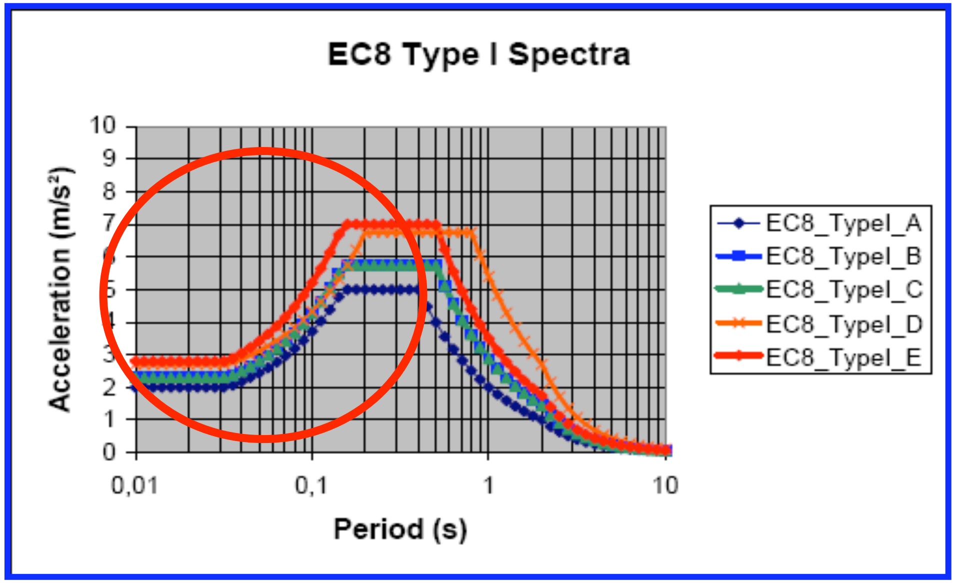


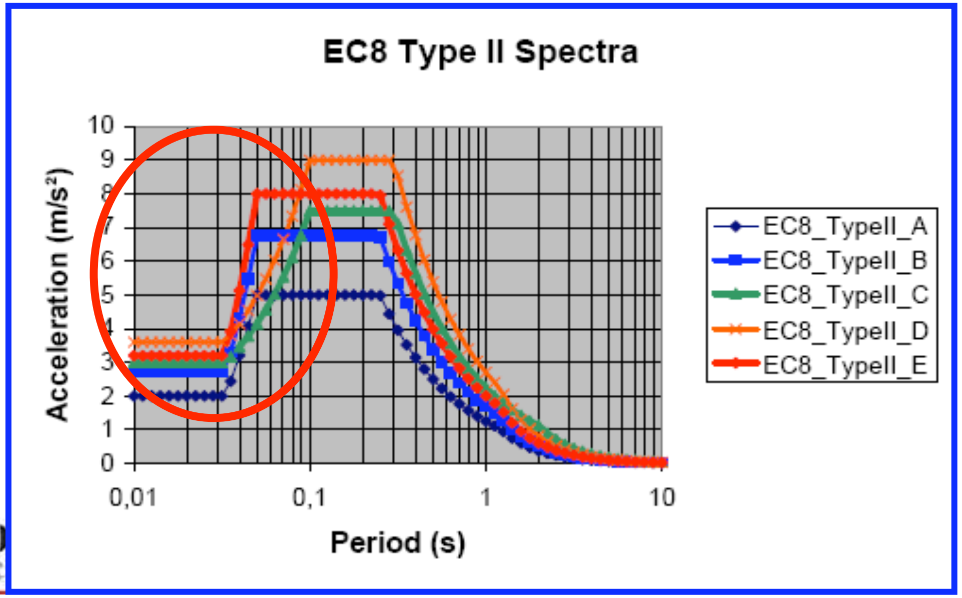
Regulatory spectra

EC8 : Hz Spectra

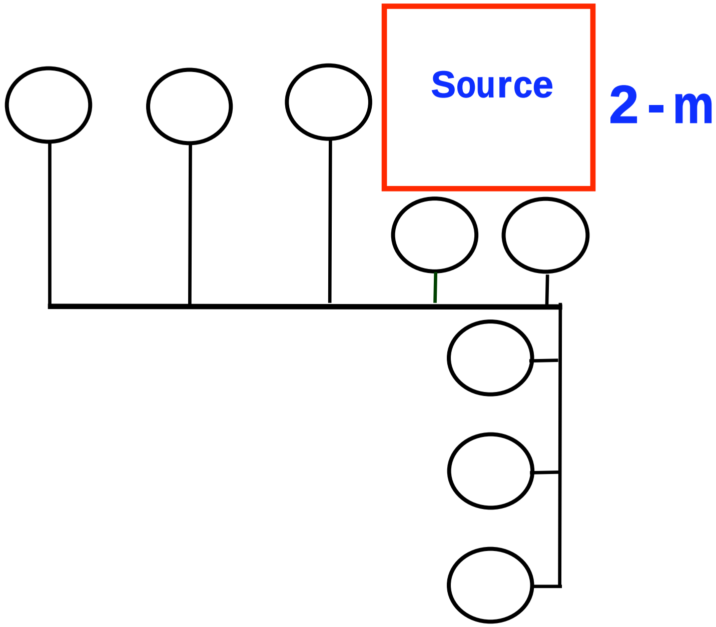
"Old" Spectra







In-situ measurement of NL characteristics



Example device (heavy and expensive...)

- Vertical Shaking
- Ground Force Estimates
- 3C Accelerometers
- Δt = 0.005-sec → f_{max} = 100-Hz
- Sweep Band: 10-Hz to 50 Hz

- and limited strains...

From Pearce et al., 2006

Proxies to site conditions for wide regional use (shake maps, hazard curves)

Inventory of possibilities

- Mandatory : available from remote sensing
- slope
- ? Other : f_0, ...

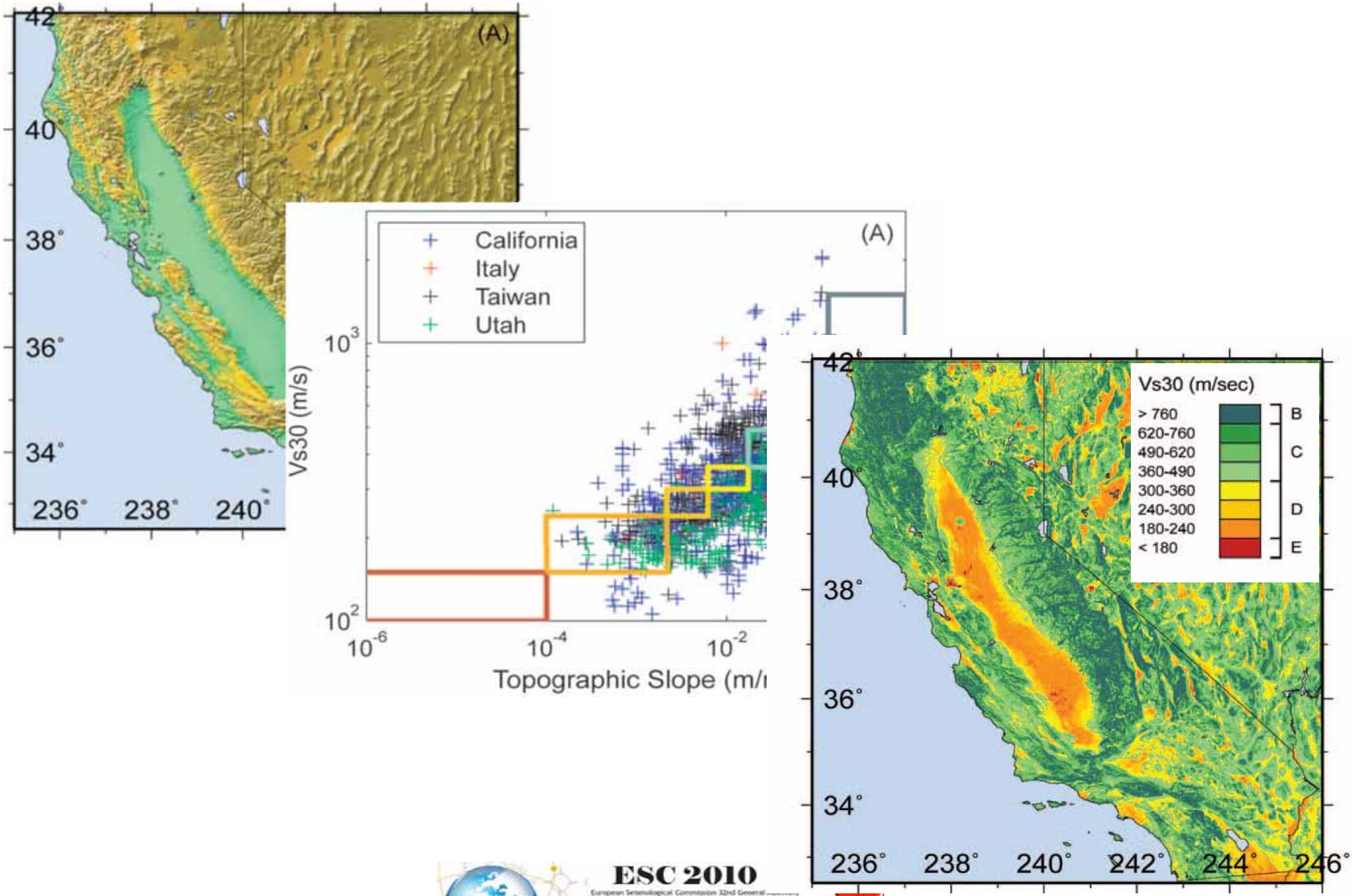
Ongoing investigations

- V_{S30} / slope FOR EUROPEAN SITES

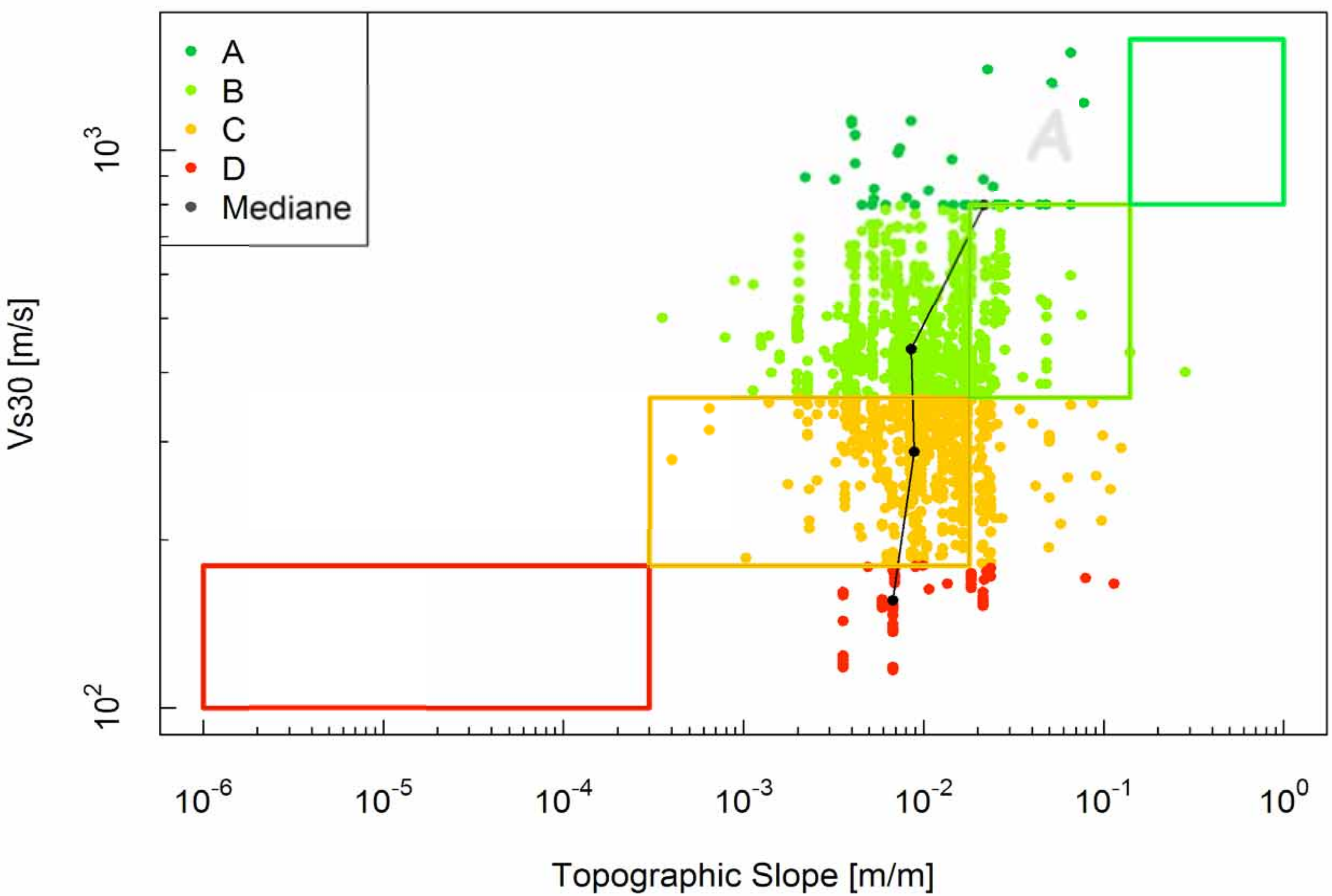
  Robustness for different data subsets (California vs Italy or Turkey ???)

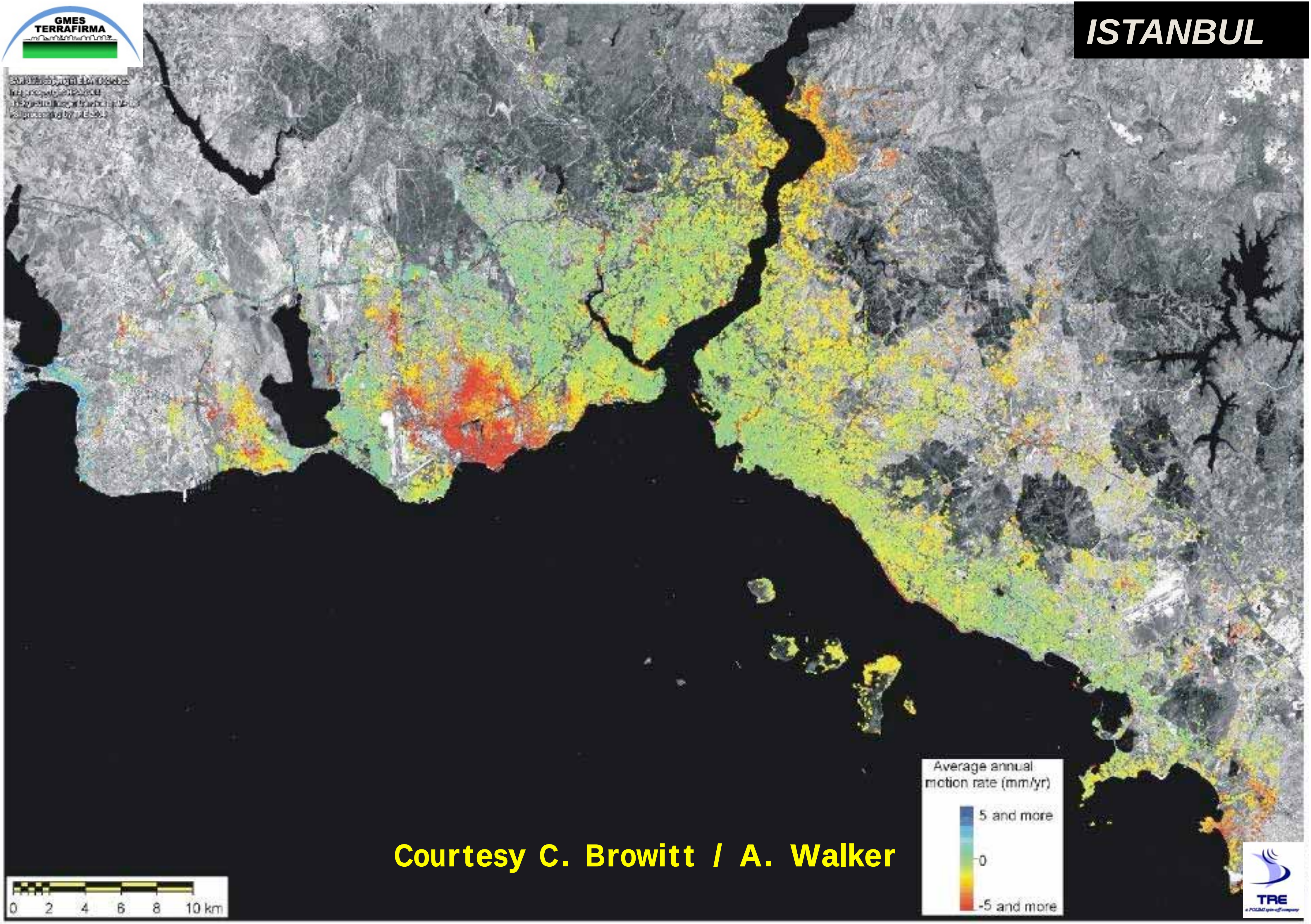
  is a weak correlation better than nothing ?
- Tests in GMPE

Proxys for shake maps : "local slope"
(proposal by Wald et Allen, 2007, 2009)

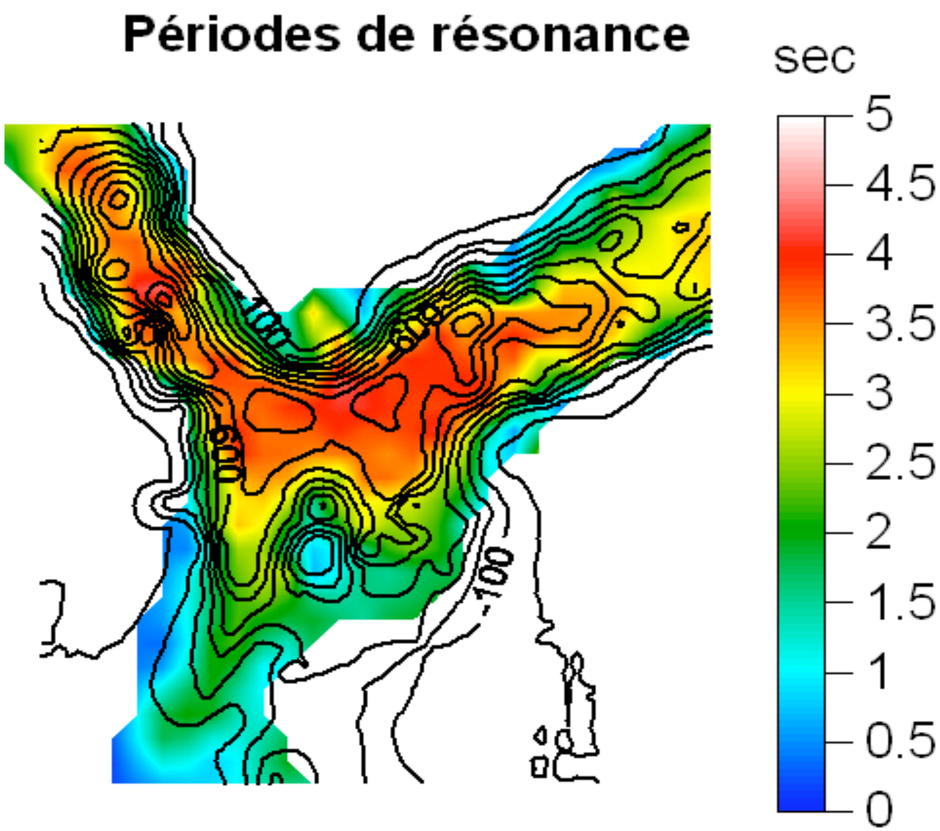


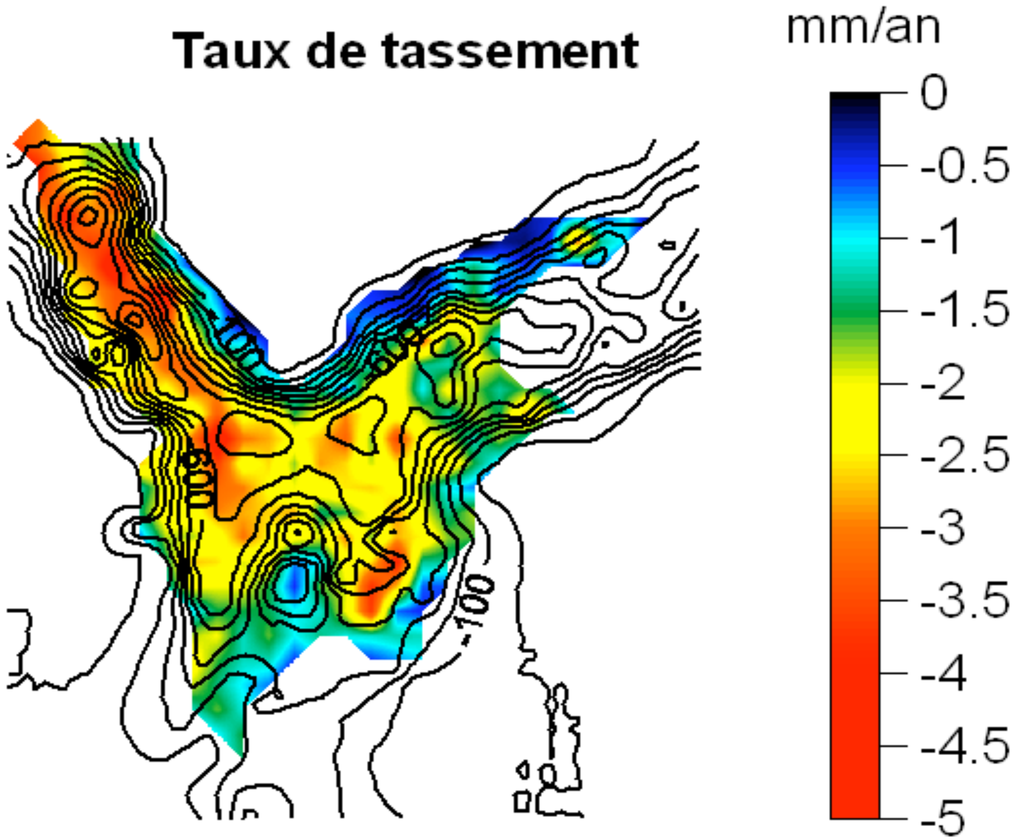
French slope vs Vs30 on SRTM30 with active tectonics settings




ISTANBUL
Average annual motion rate (mm/yr)
5 and more
0
-5 and more
0 2 4 6 8 10 km
Courtesy C. Browitt / A. Walker

f0 / subsidence rate : the Grenoble case





Courtesy S. Michel / C. Cornou

Conclusions : Challenges ahead

Improving the quality of instrumental observations in Europe

- ➢ **Site metadata (permanent SM + BB)**
- ➢ **Denser instrumentation**
  - more vertical arrays (NL)
  - more rock / site couples (NL)
  - more short aperture arrays (wavefield analysis)
- ➢ **Dedicated mobile pool for urban studies (≈ 200 stations)**
- ➢ **Critical facilities : promote the instrumental approach**
  - sensitive instrumentation, continuous recording
  - free-field, vertical arrays, + structure (SSI)

Conclusions : Challenges ahead

Imagery of "shallow" subsurface (10 m - 1 km)

- Average velocities V_{SZ}
- Velocity structure (1D-2D-3D), including deep bedrock (last contrast)
  - Cross-correlation tomography ?
- Highly heterogeneous soils (volcanic areas, slopes / landslides)
- Damping values (possibly frequency dependent)
- NL characteristics

Numerical simulation

- Verification of NL models (1D, 2D)
- More test sites for validation
  - (long term funding)

Conclusions : Challenges ahead

Engineering use

- Promote the routine use of non-invasive techniques in geotechnical engineering

  (! Warning : low cost tools – non-invasive techniques - require high expertise and good instruments !)

- Propose relevant proxies for building codes and shake maps
  - Alternative to V_{S30} for the next generation of EC8
  - Relevant remote sensing parameters (subsidence, ...)
- Propose physically sound, simple amplification factors for
  - surface topography effects
  - valley effects