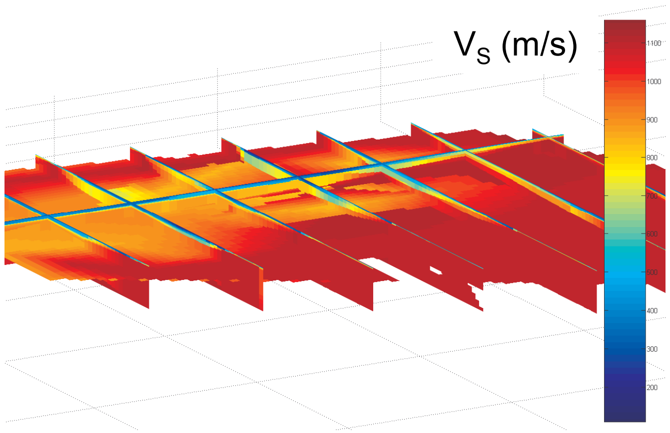
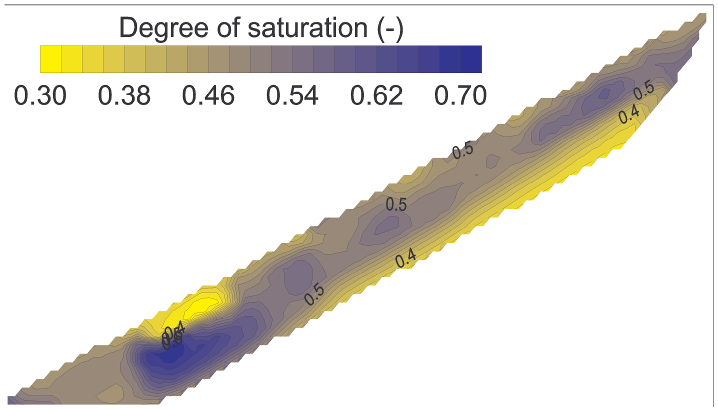
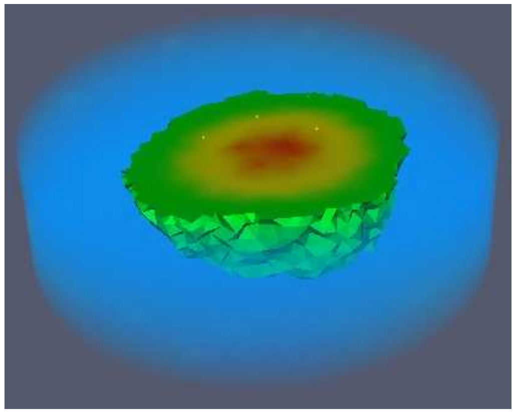
4th International Conference on Geotechnical and Geophysical Site Characterization
Recife, Brasil – September 2012

Combined use of Geophysical Methods for Geotechnical Site Characterization







POLITECNICO DI TORINO
(ITALY)

Sebastiano Foti

Outline

- Geophysical methods
  - Scope and potential for geotechnical and geoenvironmental characterization
  - In-hole vs surface methods
- Combined use
  - Different levels of integration
- Case histories
  - Levees
  - Seismic site response
  - Landslides

Geophysical parameters

Geophysical methods are indirect surveying techniques based on measurements carried out **on the ground surface or in holes**. They allow the distribution of physical properties of the subsurface to be estimated and correlated with engineering information.

- Density
- Electrical Conductivity (or Resistivity)
- Electrical Permittivity
- Magnetic Suscettibility
- Chargeability
- Seismic velocities (Elastic Moduli)

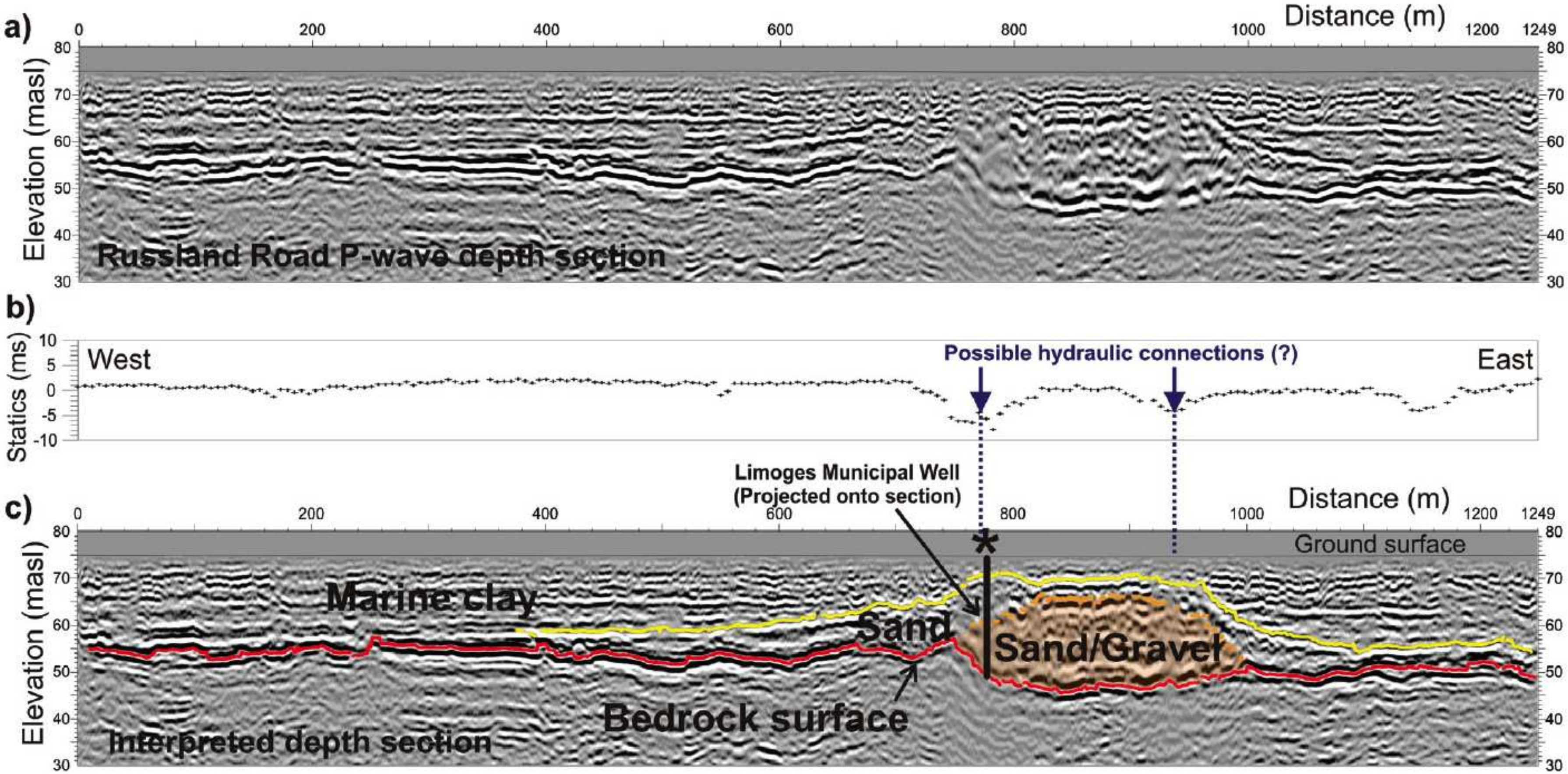
Geotechnical and geoenvironmental site characterization

In the context of site characterization for engineering purposes, the role of geophysical methods is twofold:

- evaluation of geometrical boundaries to model subsoil conditions (e.g. stratigraphy but also physical inclusions or hydrogeological features);
- evaluation of physical/mechanical parameters of direct use for geotechnical modeling.

Identification of stratigraphic sequence / local litography

Seismic methods: e.g. seismic reflection to identify an acquifer



Pugin et al., 2009

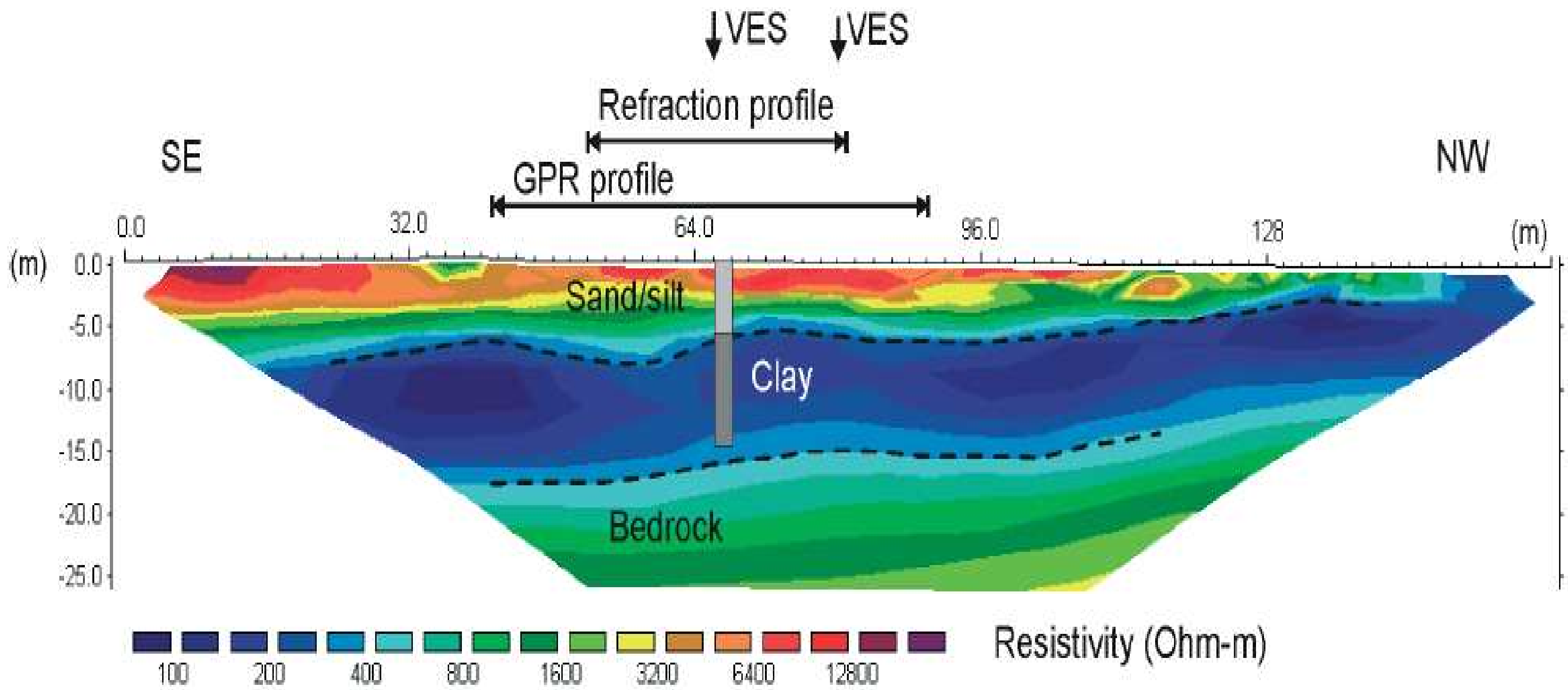
In combination with conventional investigation:

e.g. boreholes logs allow calibration / identification of litography

geophysical surveys allow for 2D/3D extension

Identification of stratigraphic sequence / local litography

Non-seismic methods: e.g. electrical methods to identify clays below sands

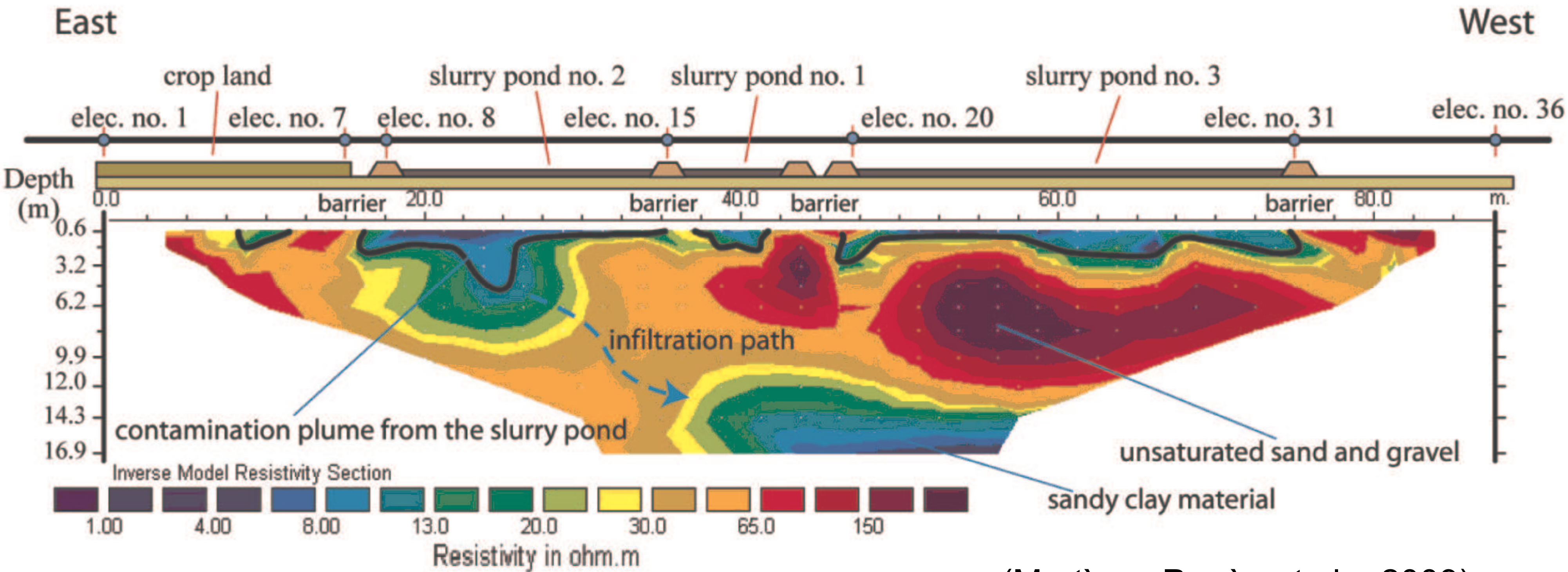


Turesson and Lind, 2005

Powerful tools to investigate lateral variations at the site
(e.g. for assessing the potential for differential settlements)

Hydrogeological / environmental applications

Electrical Resistivity Tomography (ERT)

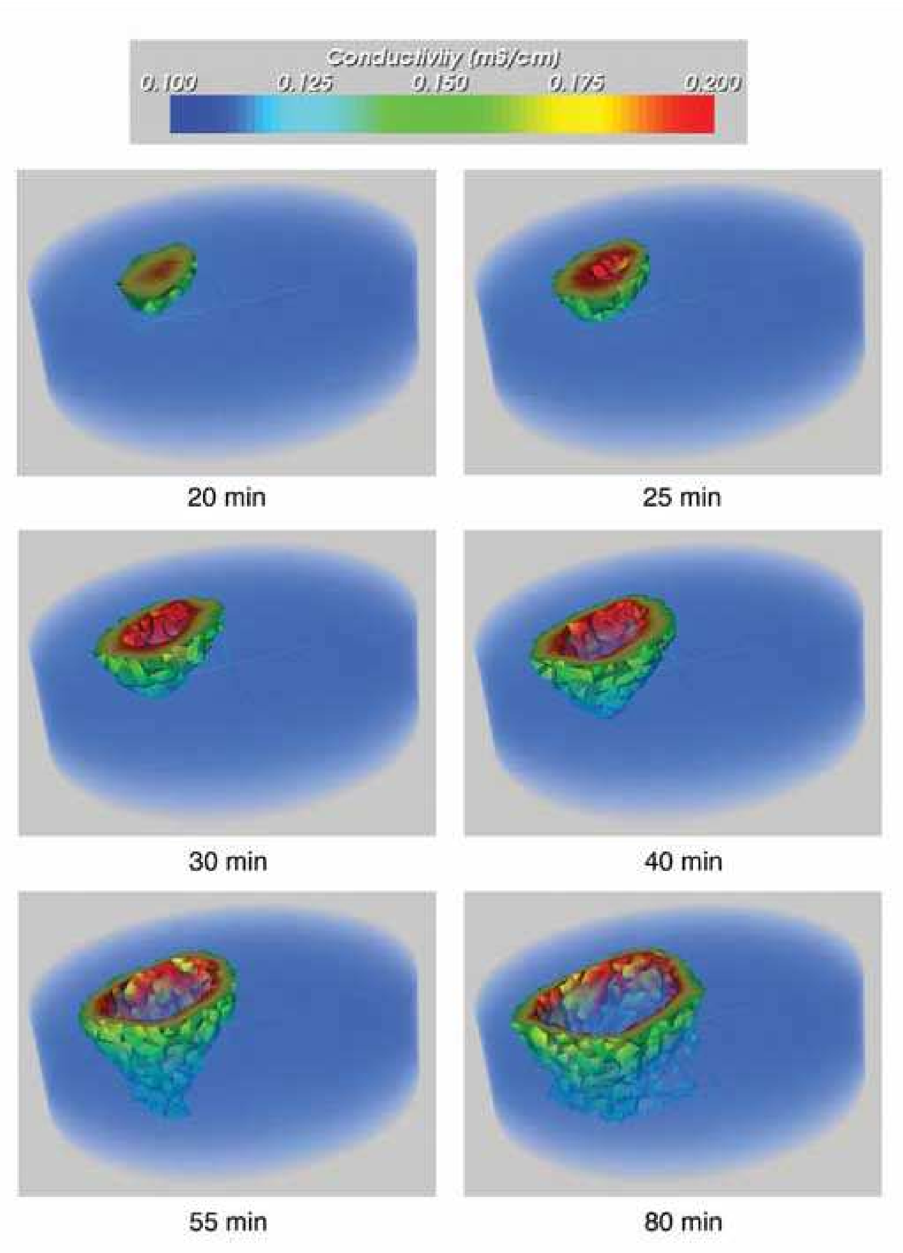


(Martìnez-Pagàn et al., 2009)

Resistivity is sensitive to:

- pore fluid content → Saturated vs unsaturated(for coarse materials)
- pore fluid conductivity → Identification and monitoring of plumes

Monitoring in environmental applications



Example:
3D resistivity tomography on lab soil samples for diffusion of conductive plume monitoring. (Comina et al., 2011).

Geotechnical and geoenvironmental site characterization

In the context of site characterization for engineering purposes, the role of geophysical methods is twofold:

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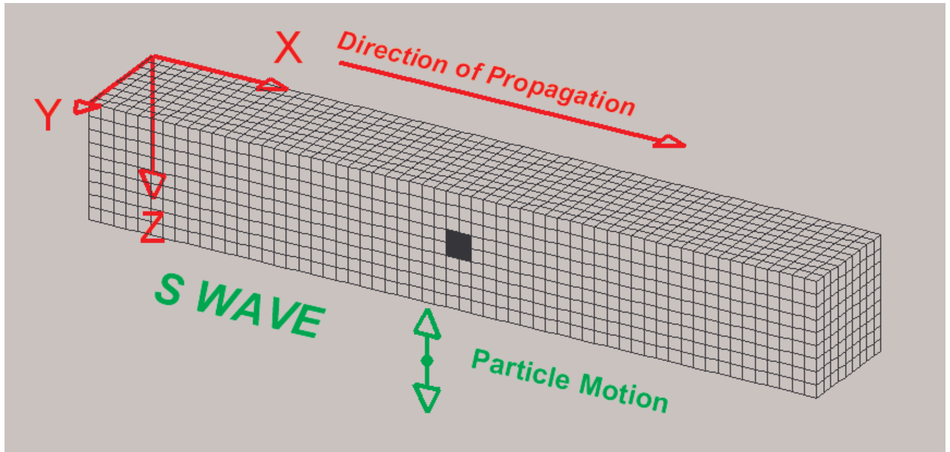
Seismic methods



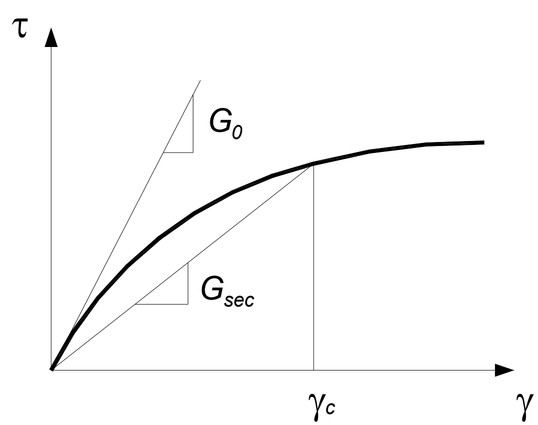
Animation courtesy of
Dr. L. Braile, Purdue University

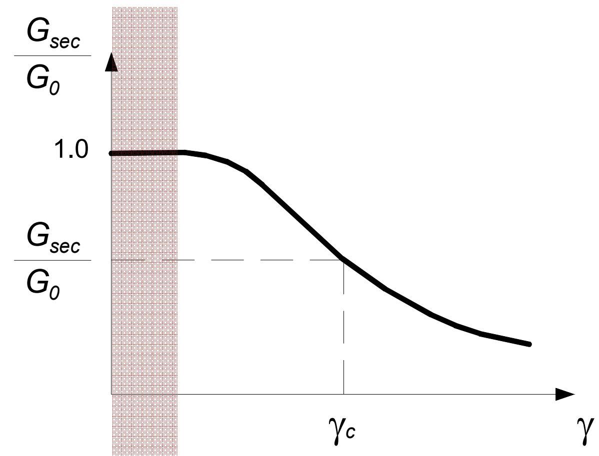
In a linear elastic medium

$$G = \rho V_S^2$$

In soils

$$G_0 = \rho V_S^2$$



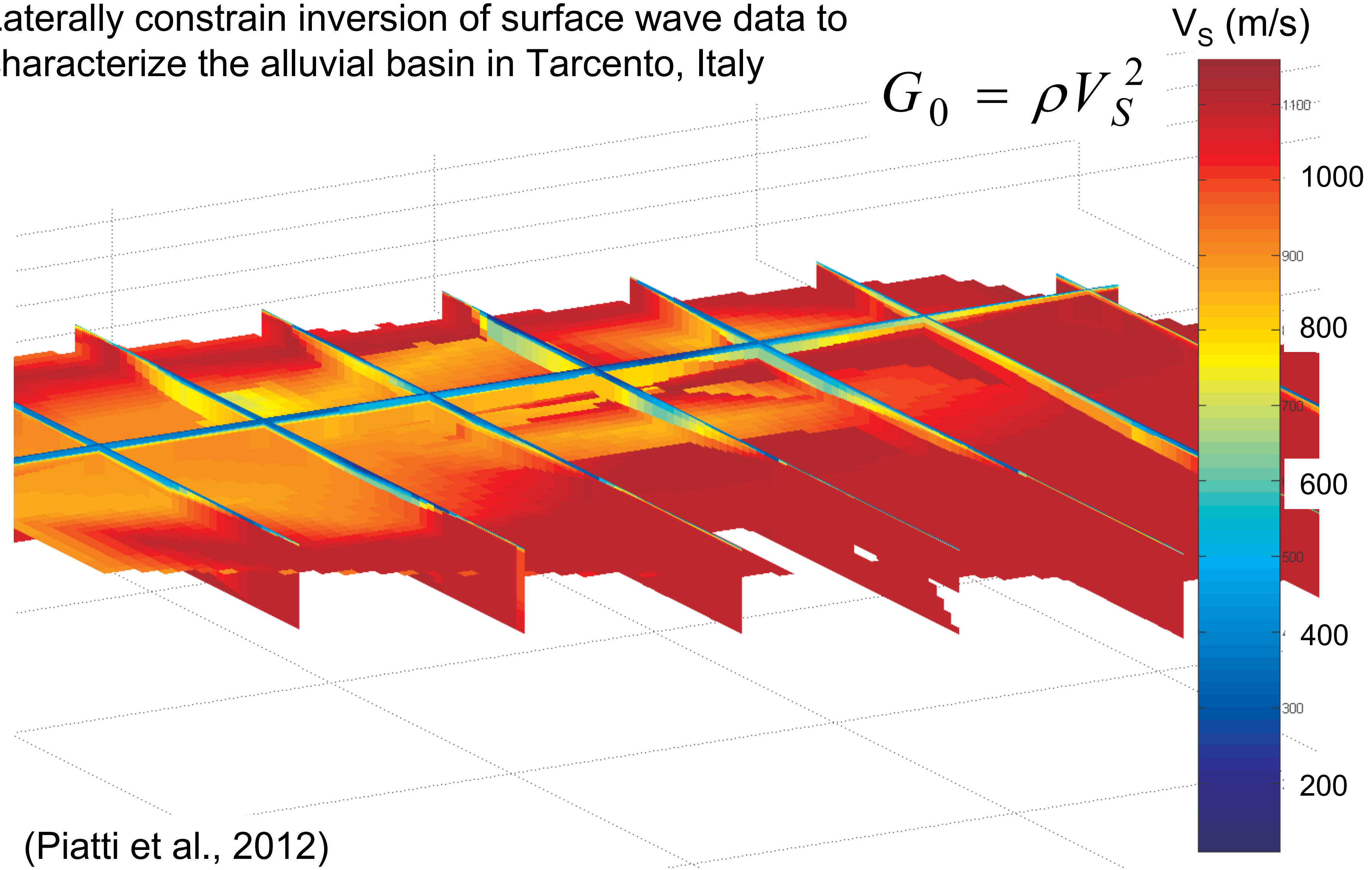


Strain range of geophysical test

3D V_S model

Laterally constrain inversion of surface wave data to characterize the alluvial basin in Tarcento, Italy

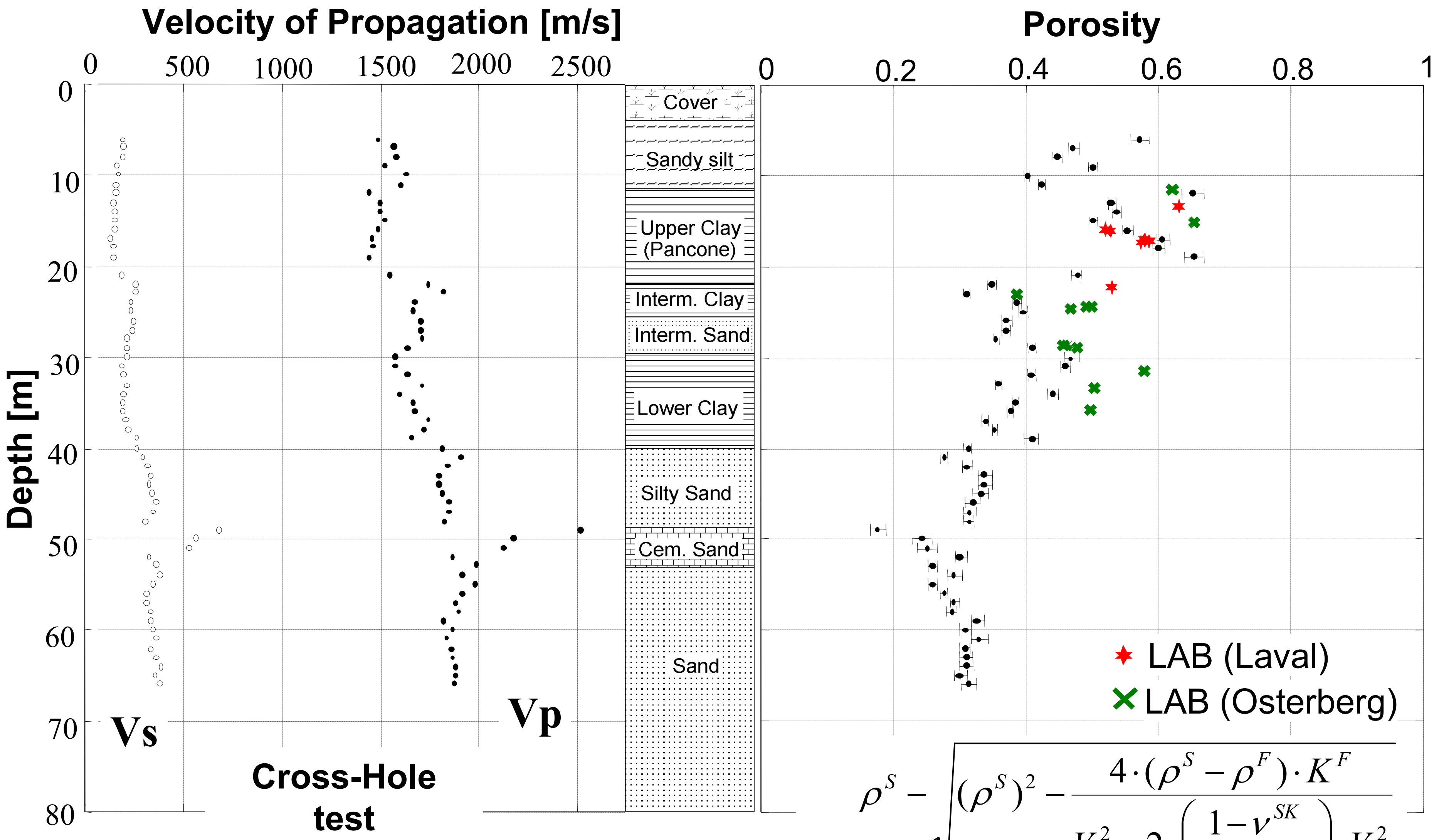
$$G_0 = \rho V_S^2$$



(Piatti et al., 2012)

Soil porosity from seismic velocities

Leaning Tower of Pisa site



$$n = \frac{\rho^S - \sqrt{(\rho^S)^2 - \dfrac{4\cdot(\rho^S - \rho^F)\cdot K^F}{V_P^2 - 2\cdot\left(\dfrac{1-\nu^{SK}}{1-2\nu^{SK}}\right)\cdot V_S^2}}}{2\cdot(\rho^S - \rho^F)}$$

(Foti et al., 2002)

Non seismic methods

Quantitative use of geophysical parameters other than seismic velocities is less straightforward and typically require the use of empirical correlations with geotechnical parameters

Example: electrical conductivity of soils

Trasport parameter related to:

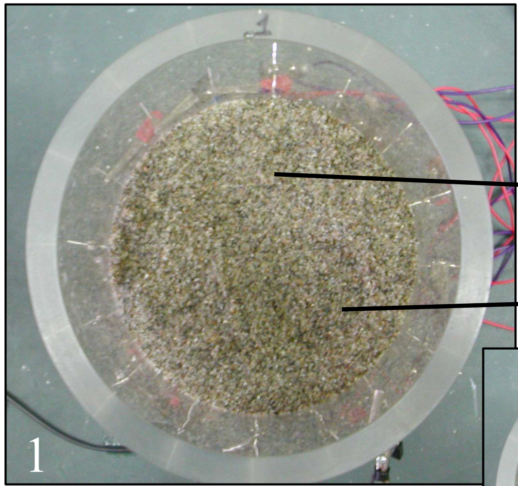
- fluid properties (solubility of ionic species, concentration); σ_w : pore fluid conductivity
- mineralogy and specific surface of the solid grains;
- porosity and fabric

Archie	$\sigma_t = \sigma_w n^m S_r^p$	n: porosity S: saturation
Bruggeman	$\sigma_t = \sigma_w n^{3/2}$	m = 3/2 : theoretical
Waxman & Smits	$\sigma_t = X (\sigma_w + \sigma_s)$	σ_s : clay surface conductivity

Example at Lab scale

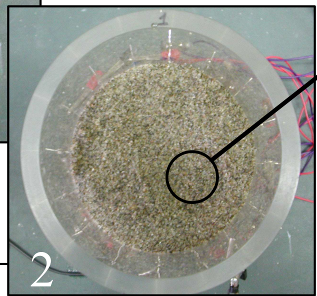
Polito – 2D ERT (Borsic et al., 2005)

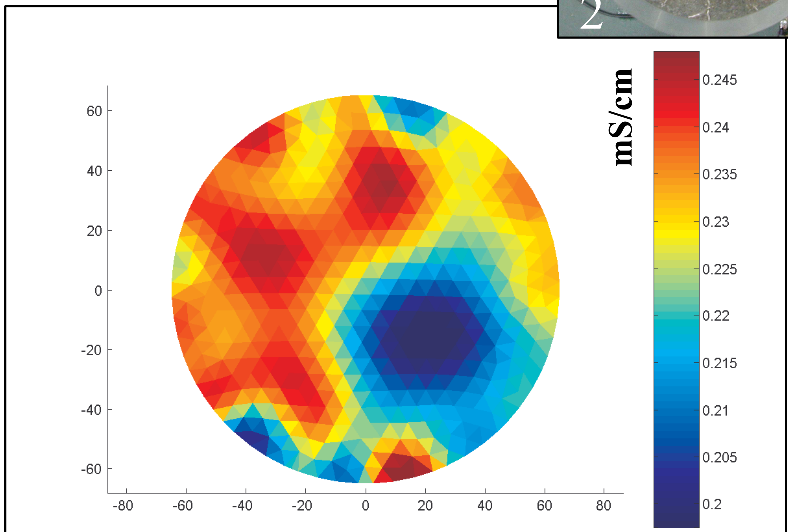
Identification of zones with different compaction levels in sand



Coarse Matrix
n ≈ **0.48**

Dense Inclusion
n ≈ **0.43**





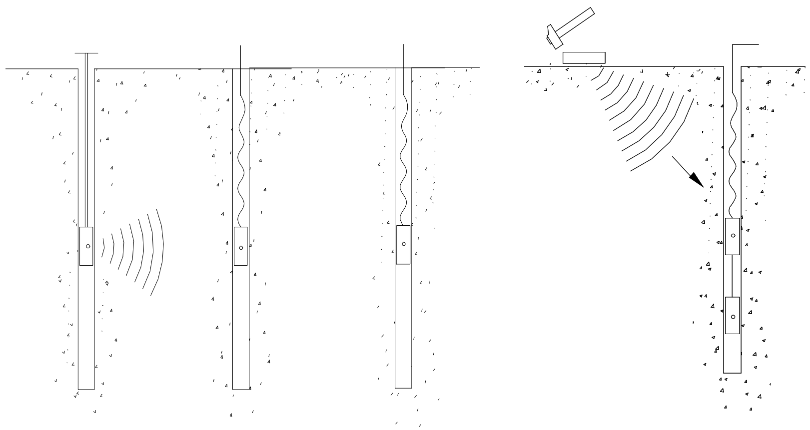
3. Tomographic reconstruction

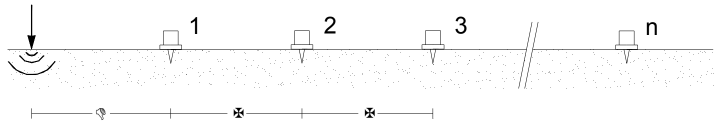
Estimated values with Bruggeman equation

Matrix n ≈ **0.46**

Inclusion n ≈ **0.42**

In-hole vs surface methods
(Invasive vs Non-invasive methods)

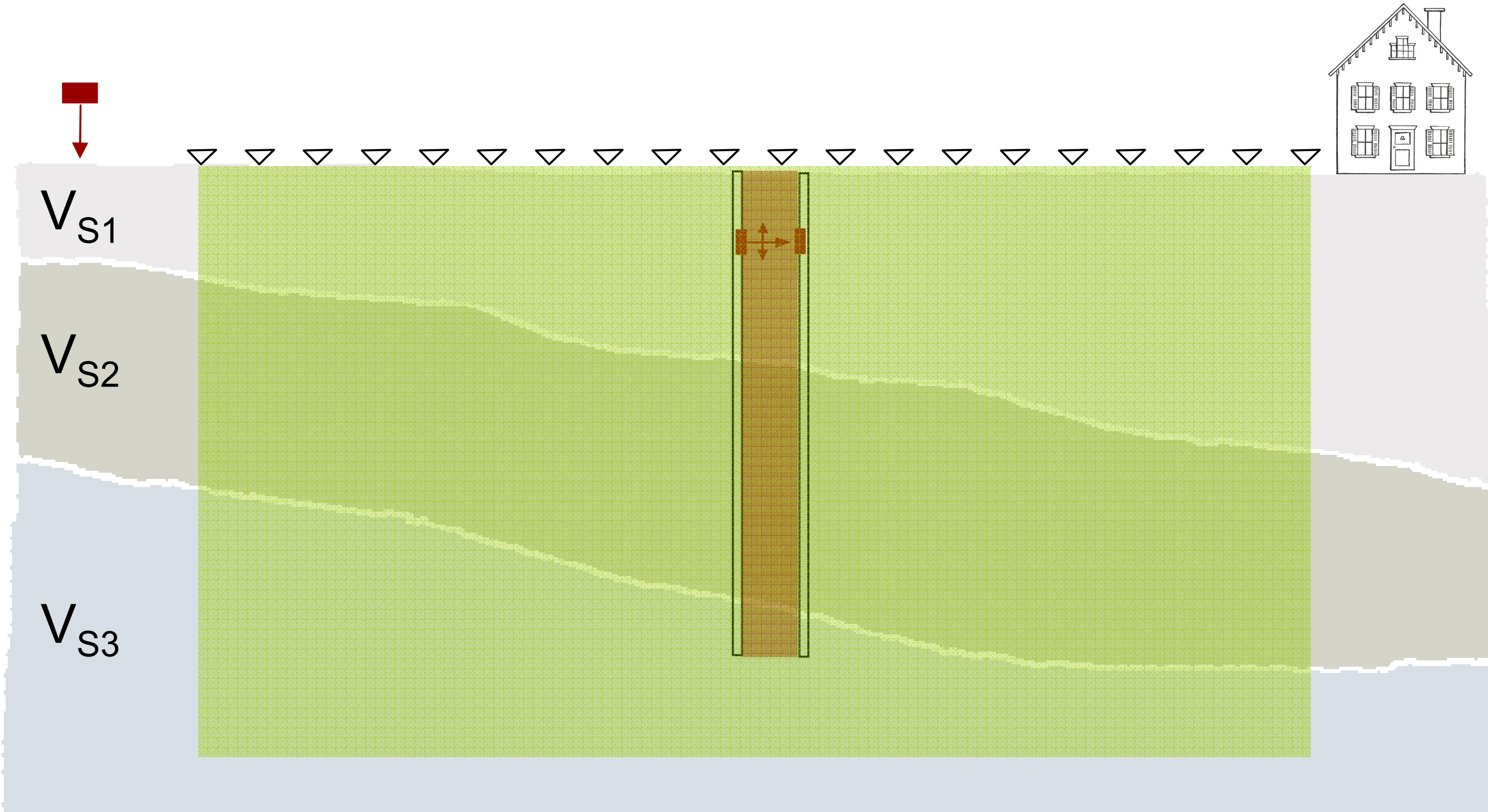




Surface Waves Methods SWM
(SASW, MASW, microtremors)
Seismic Refraction
(P-waves or SH-waves)
Seismic Reflection
(P-waves or SH-waves)

Cross-Hole Test (CHT)
Down-Hole Test (DHT)
Seismic Cone (SCPT)
Seismic Dilatometer (SDMT)
P-S Suspension Logging
Vertical Seismic Profiling (VSP)

In-hole vs surface methods



In-hole vs surface methods

	Invasive Tests	Non-Invasive Tests
Advantages	Direct measurements: simple and accurate interpretation Good resolution also at great depth Easier standardization Additional information from borehole logging or the penetration of the cone	Costs and flexibility (in time and space) Non-intrusive (e.g. important for waste landfills) Average properties (dynamic behaviour of the whole soil deposit) Large volumes are investigated
Disadvantages	Costs and necessity of planning well in advance Local measurement	Complex interpretation (indirect measurements based on inversion procedures or heavy processing) Accuracy and resolution at depth

Flexibility of Surface Methods

U. Texas - Austin

Deep exploration
large amplitude signals
→ reliable data at very low frequency

ALL FIT IN A BACKPACK

For shallow experiments

Inverse methods

From the **measurement along a boundary** we want to estimate the **properties inside the medium**

Experimental data

Numerical simulation (forward problem)

fit → Model parameters

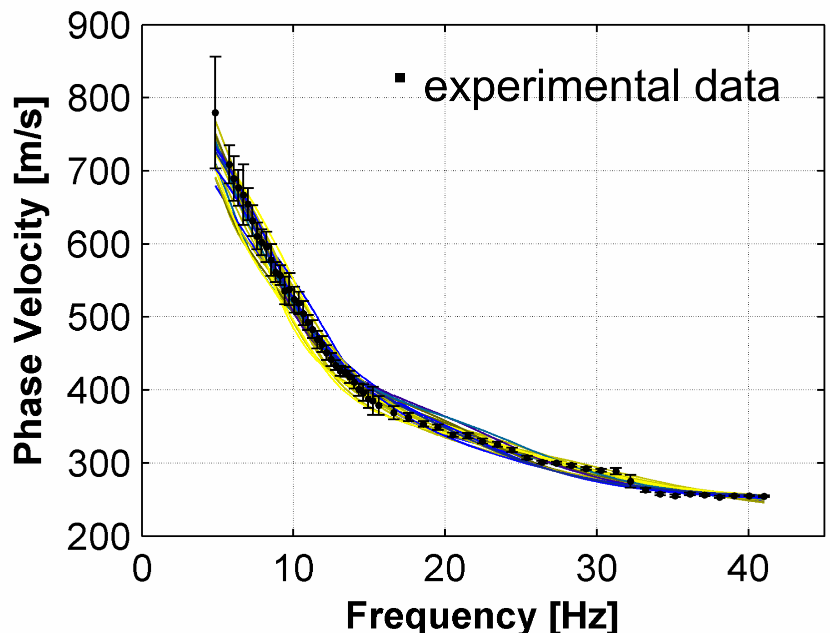
(solution of the inverse problem)

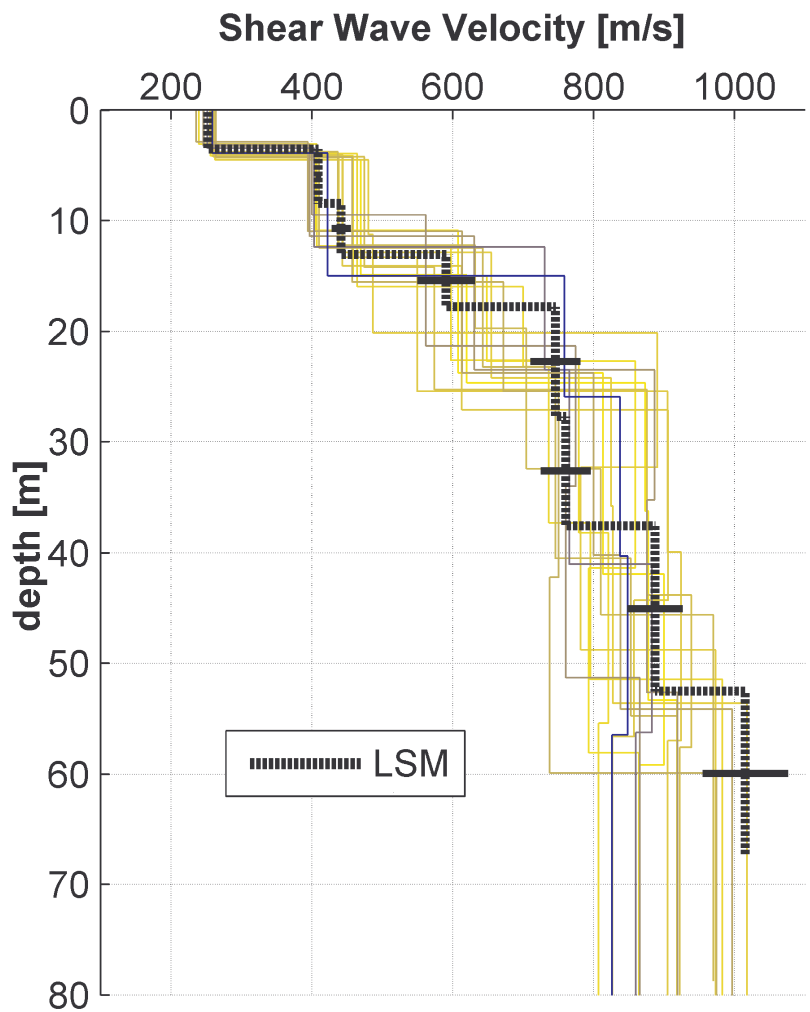
Solution non-uniqueness

(equivance of several possible solutions with respect to the experimental data)

Example: solution non uniqueness in surface wave analysis

Equivalent profiles from Monte Carlo Inversion





(Foti et al., 2009)

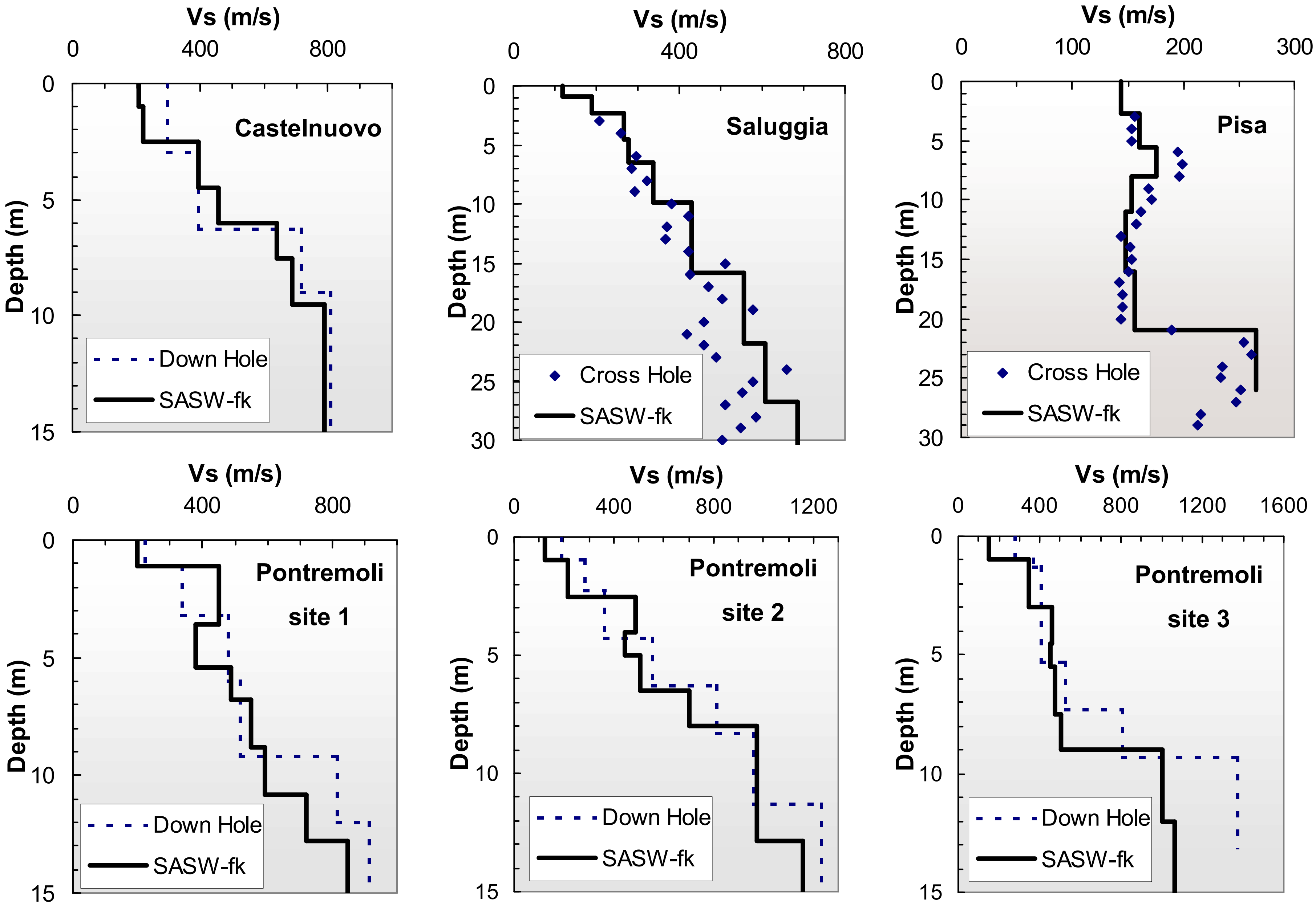
Additional information can help in contraining the solution

Combined use of geophysical methods

Synergies between different techniques can be exploited at different level of integration:

- Level 1: comparison for validation / calibration
- Level 2: data integration and data fusion (combining different information on the same medium)
- Level 3: a priori info (one method help the other)
- Level 4: joint inversion (simultaneous interpretation of different dataset)

Level 1: Comparison In-Hole methods vs SASW



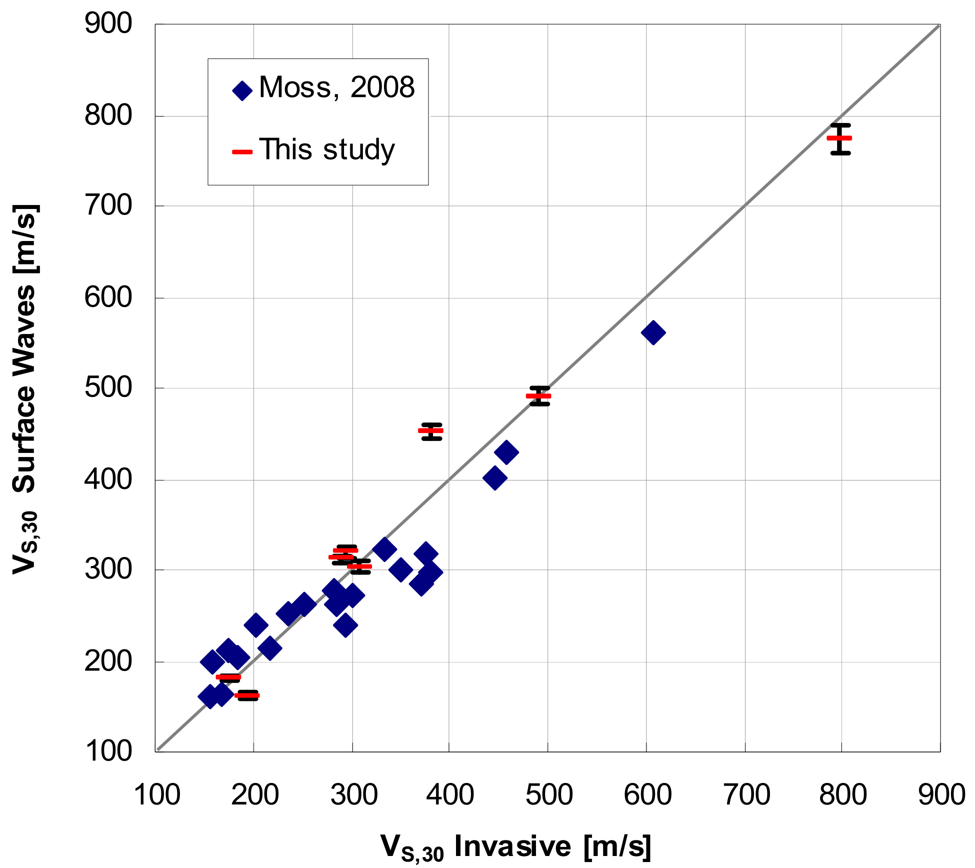
Level 1: SASW vs Invasive Methods

UBC – EC8

$$V_{S,30} = \frac{30}{\sum_{i=1..N} \frac{h_i}{V_{S,i}}}$$

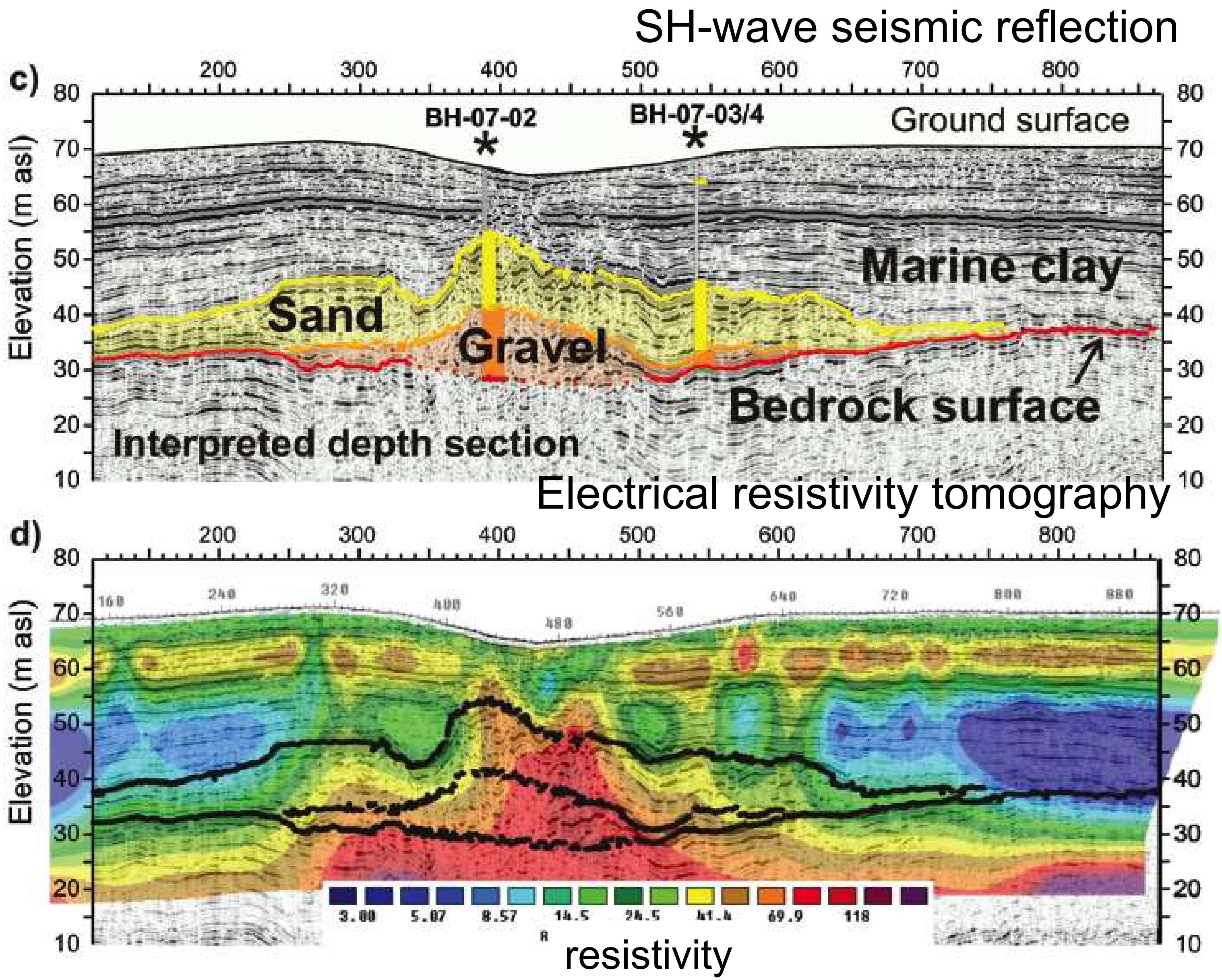
EC8
Seismic subsoil classification

Soil class	$V_{s,30}$
A	> 800
B	360 - 800
C	180 - 360
D	< 180
E (C, D su A)	



(Comina et al., 2011)

Level 2: Data integration and data fusion



Pugin et al., 2009

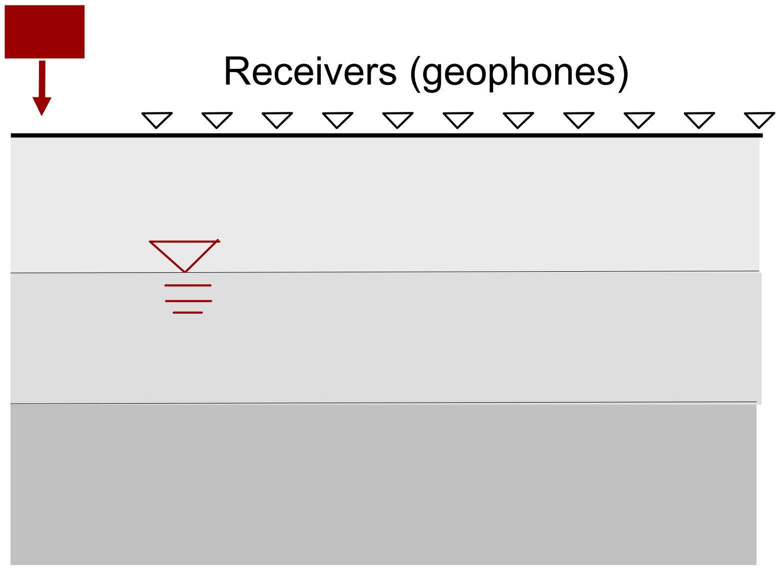
Combined use

- Level 1: comparison for validation
- Level 2: data fusion
- Level 3: a priori info
- Level 4: joint inversions

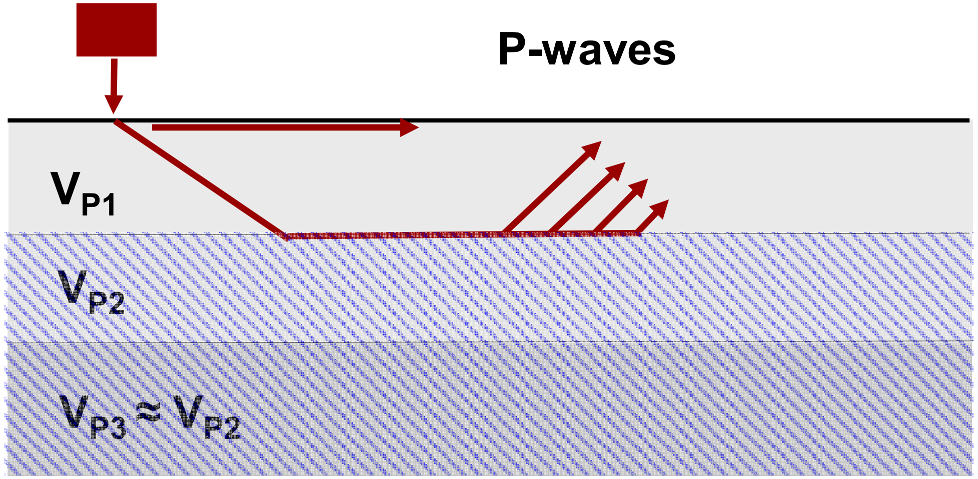
} Example: synergies of seismic refraction and surface wave analysis (SWM)

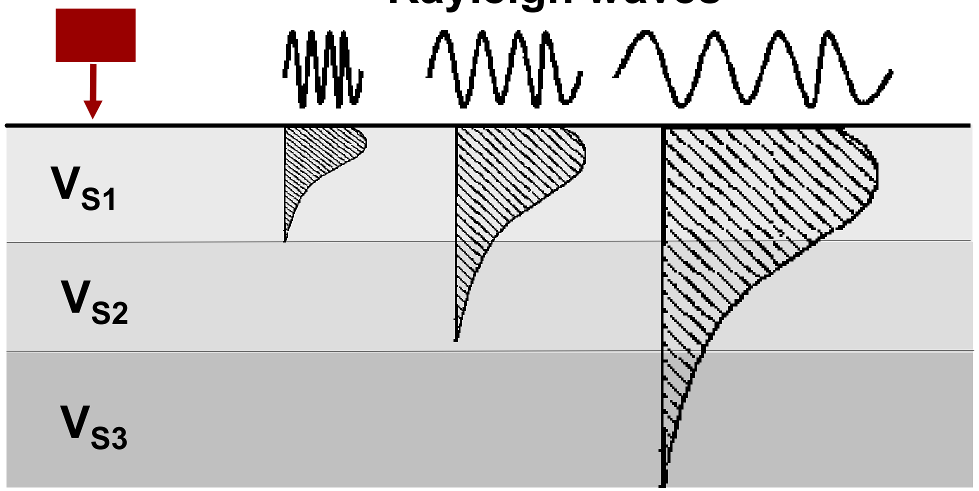
Example of synergy: SW + V_P refraction

Same testing setup and equipment

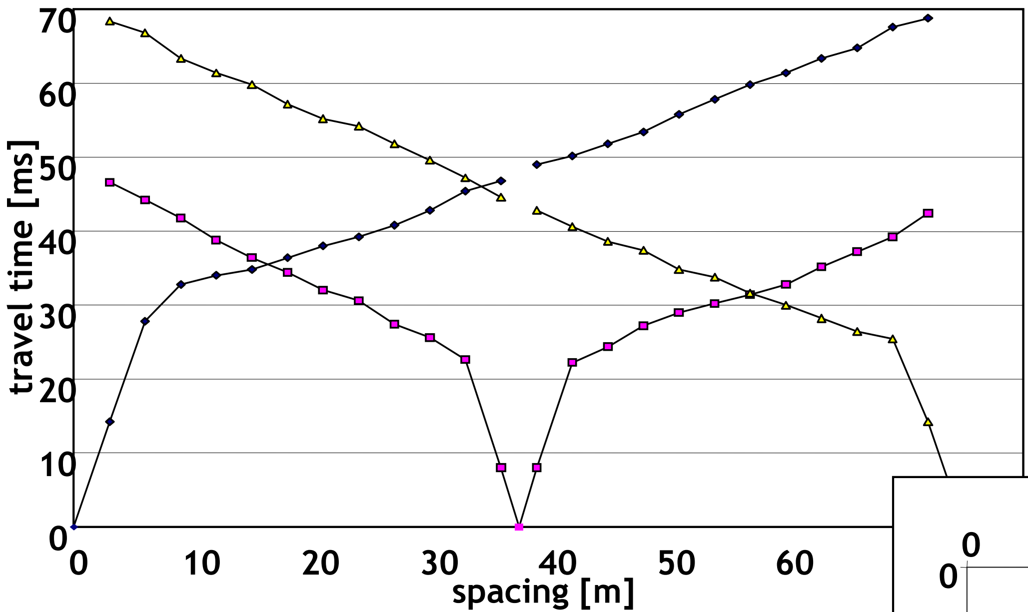


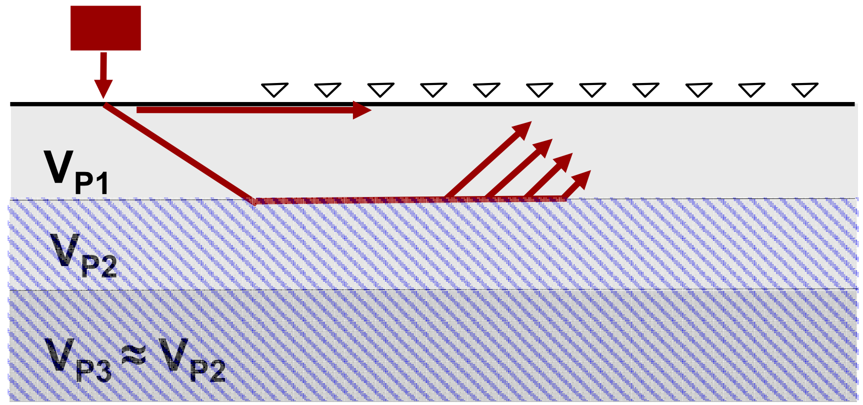
Experimental data contain both surface waves and direct/refracted P waves



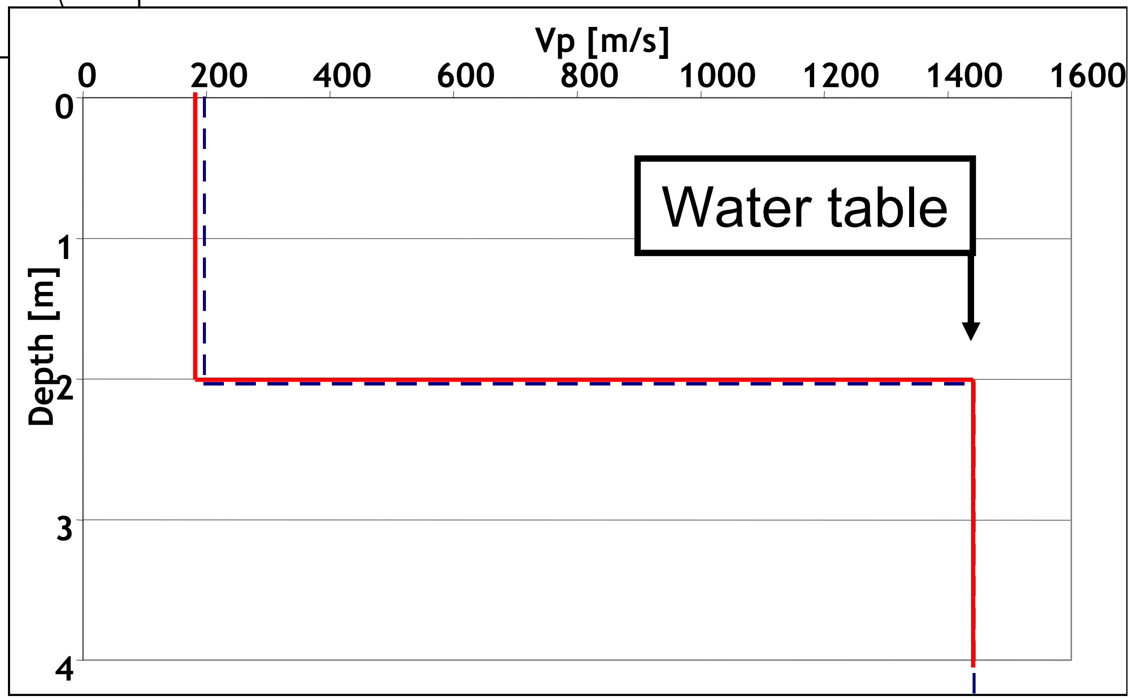


P-WAVE REFRACTION



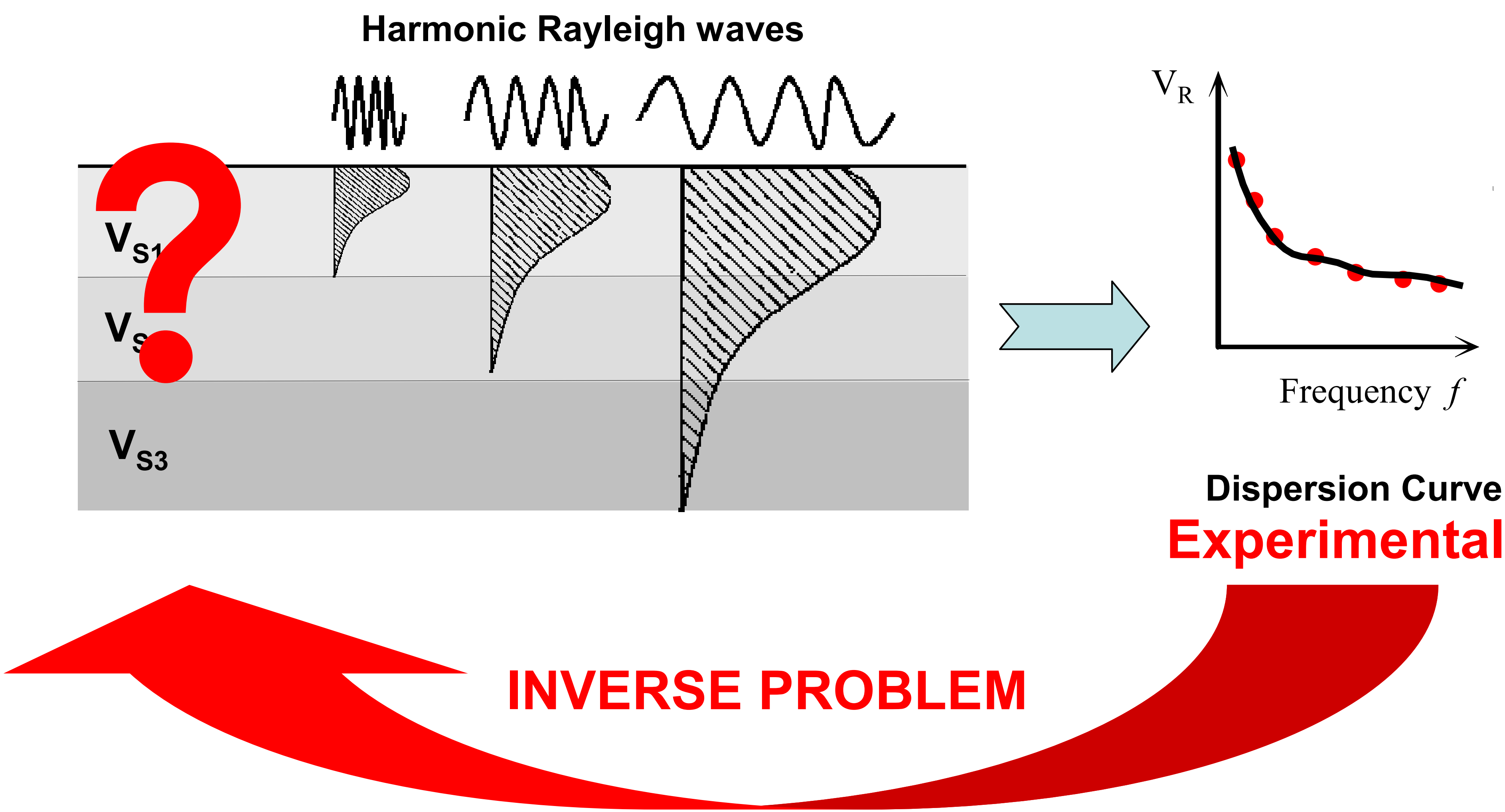


$$V_P = \sqrt{\frac{(K^{SK} + \frac{4}{3} \cdot G) + \frac{K^F}{n}}{(1-n) \cdot \rho^S + n \cdot \rho^F}}$$



Shallow water table masks variation of the mechanical properties of the solid skeleton (influence of the pore fluid)

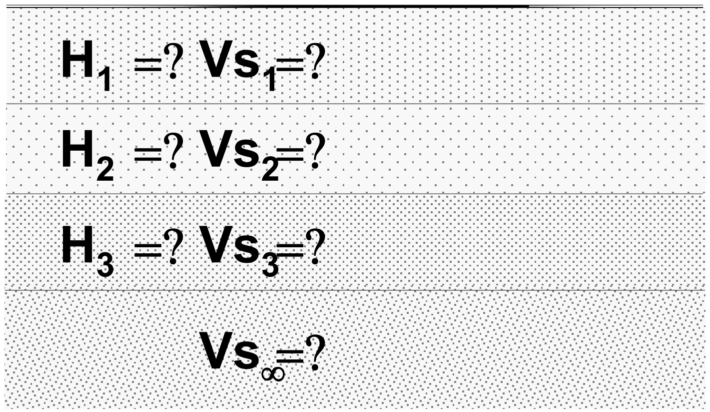
SWM concept

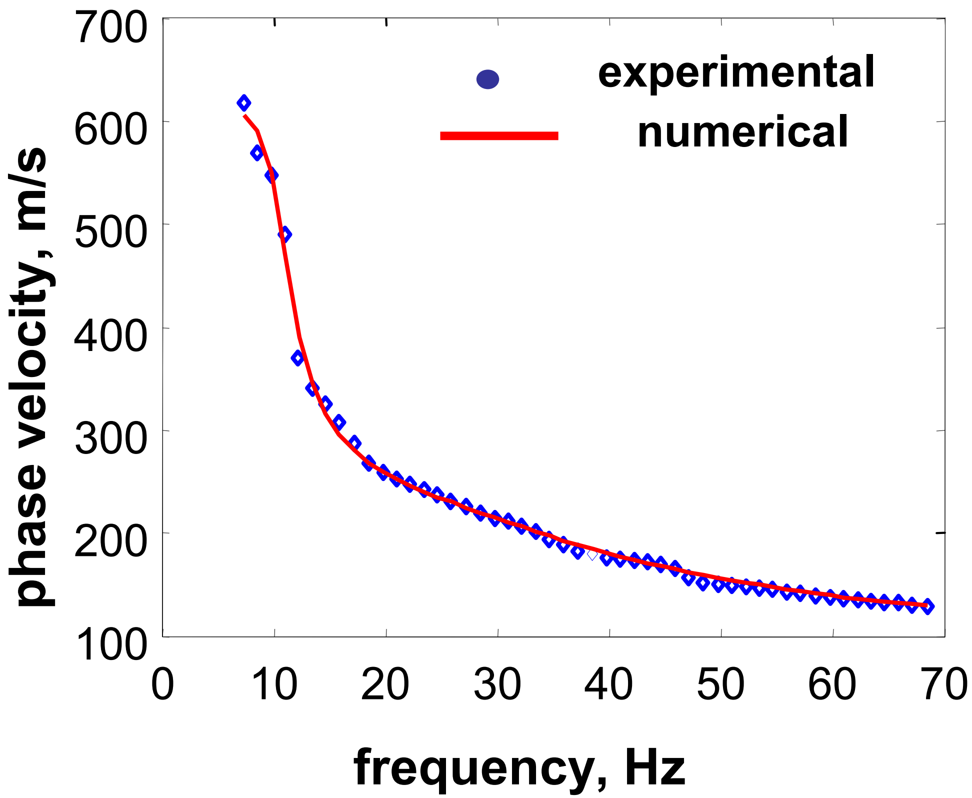

Harmonic Rayleigh waves
V
S1
V
S
V
S3
V
R
Frequency f
Dispersion Curve
Experimental
INVERSE PROBLEM

The inverse problem

Objective: to find the set of model parameters such that the difference between numerical and experimental dispersion curve is the least

Model: Stack of linear elastic layers





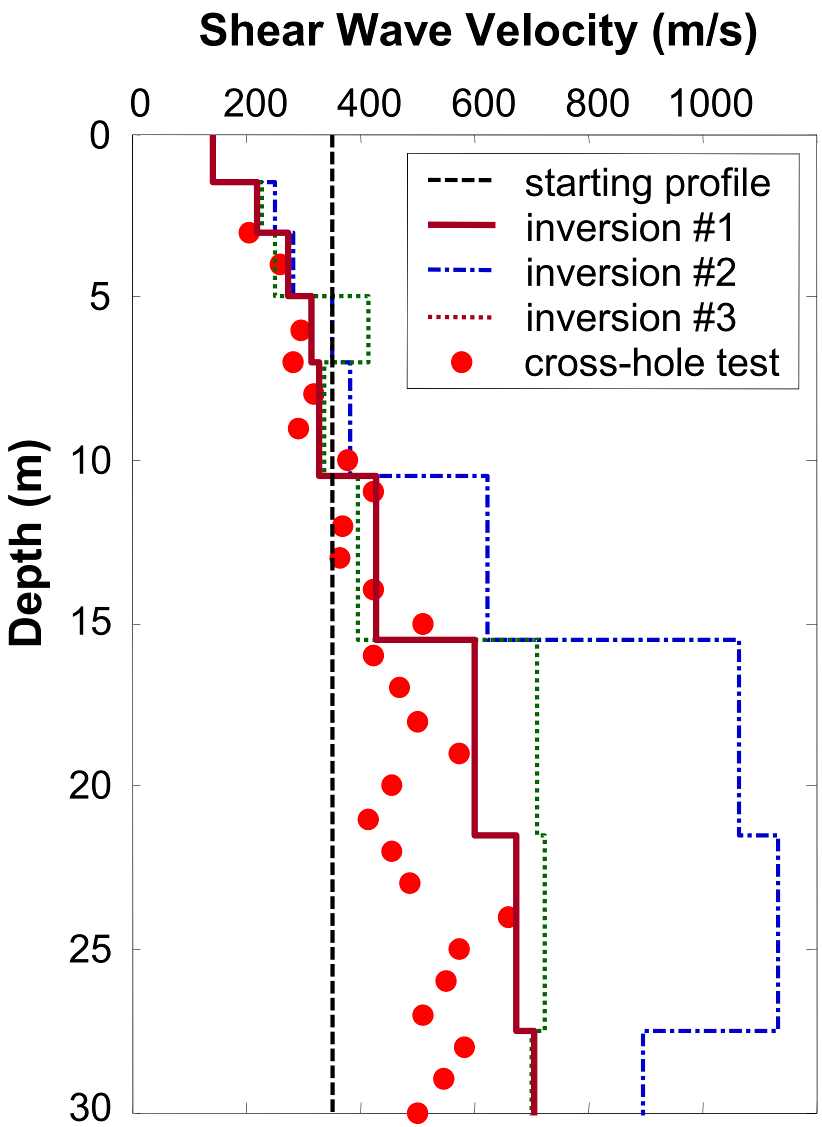
Usually ν_i and ρ_i are fixed and H_i and G_i (or V_{Si}) are the unknowns

Critical aspect: illposedness of mathematical inverse problems

Water Table Influence

	Dry Soil	Sat Soil	
Soil Density	1.2 ÷2.0	1.8 ÷2.3	Weight of water filling the voids
Poisson Ratio ν	0.1÷0.3	≈ 0.49	Undrained behavior at low frequency (f<100Hz) → no volumetric strain

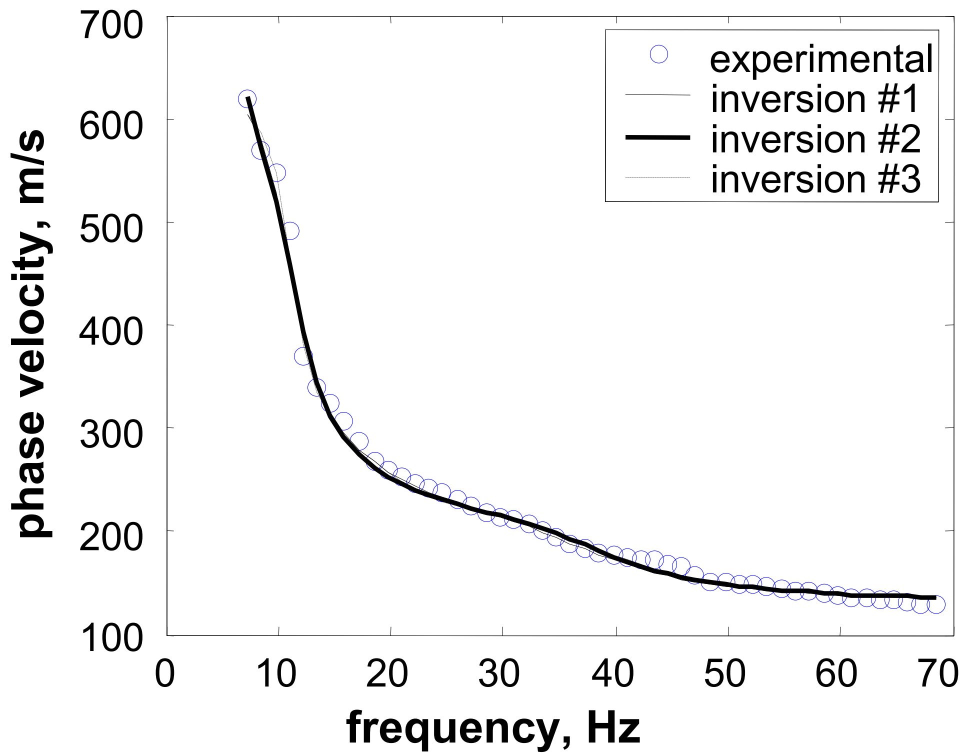
Experimental Data



Hp#1 Water table from P-wave refraction

Hp#2 No water table

Hp#3 Water table deeper than Hp #1



(Foti and Strobbia, 2002)

Level 4: joint inversion

(Piatti et al., 2012b)

A single inversion problems is solved considering all the available experimental information: the best fit parameters for both VP and VS models are obtained

A single misfit parameter include misfit on Rayleigh wave dispersion curve and P-wave travel times

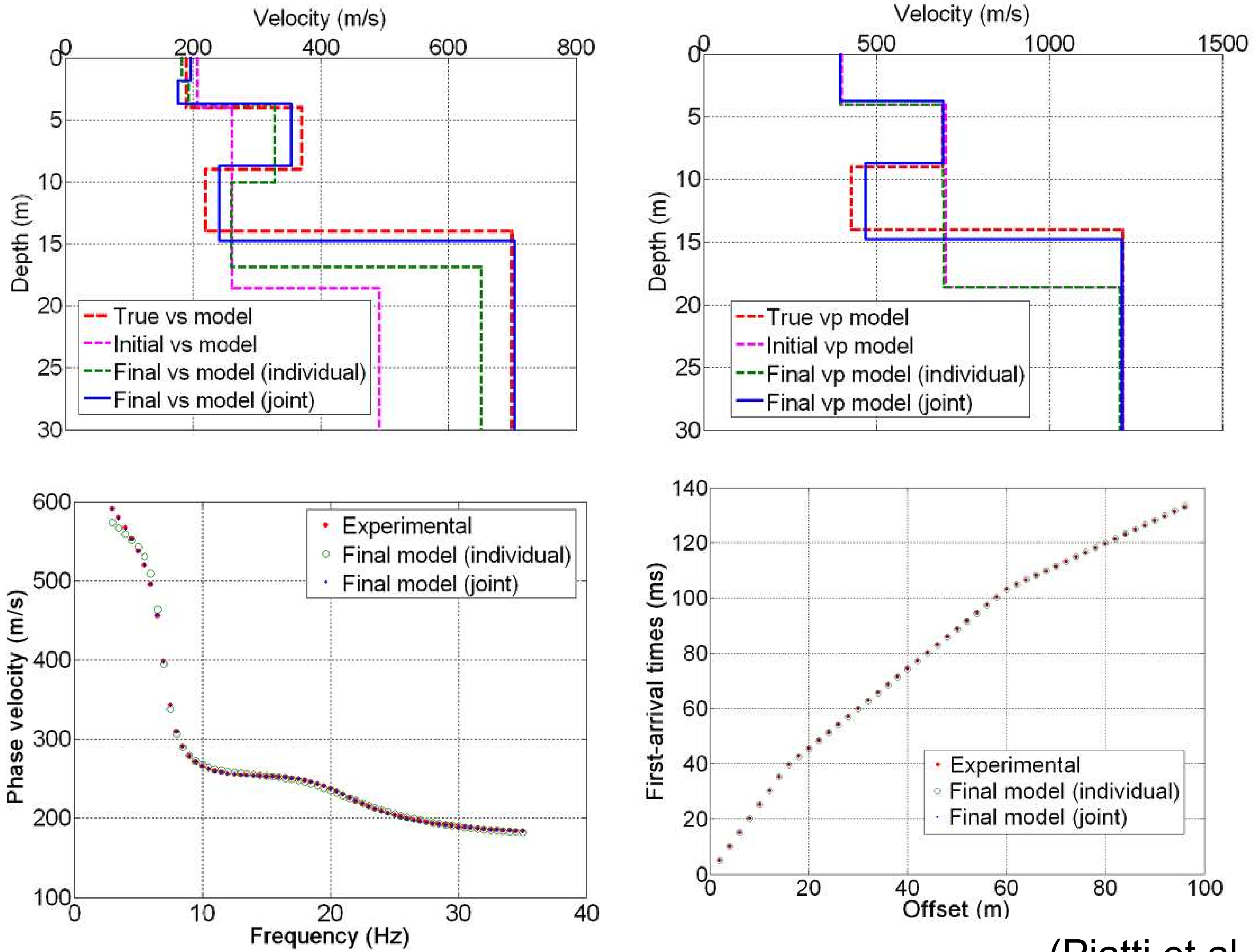
$$L=\left(\frac{1}{N+M+A}\left[\left(\mathbf{d}_{\mathbf{obs}}-\mathbf{g}(\mathbf{m})\right)^{T}\mathbf{C}_{\mathbf{obs}}^{-1}\left(\mathbf{d}_{\mathbf{obs}}-\mathbf{g}(\mathbf{m})\right)\right]\right.$$

$$\mathbf{d}_{obs}=\left[\left(\log(V_{R1}),\ \log(V_{R2}),\ ....,\ \log(V_{RN'})\right)\ \left(\log(t_1),\ \log(t_2),\ ....,\ \log(t_{N''})\right)\right]$$

$$\mathbf{g}(\mathbf{m})=\begin{bmatrix}\mathbf{g}_{SW}(\mathbf{m})\\ \mathbf{g}_{PR}(\mathbf{m})\end{bmatrix}$$

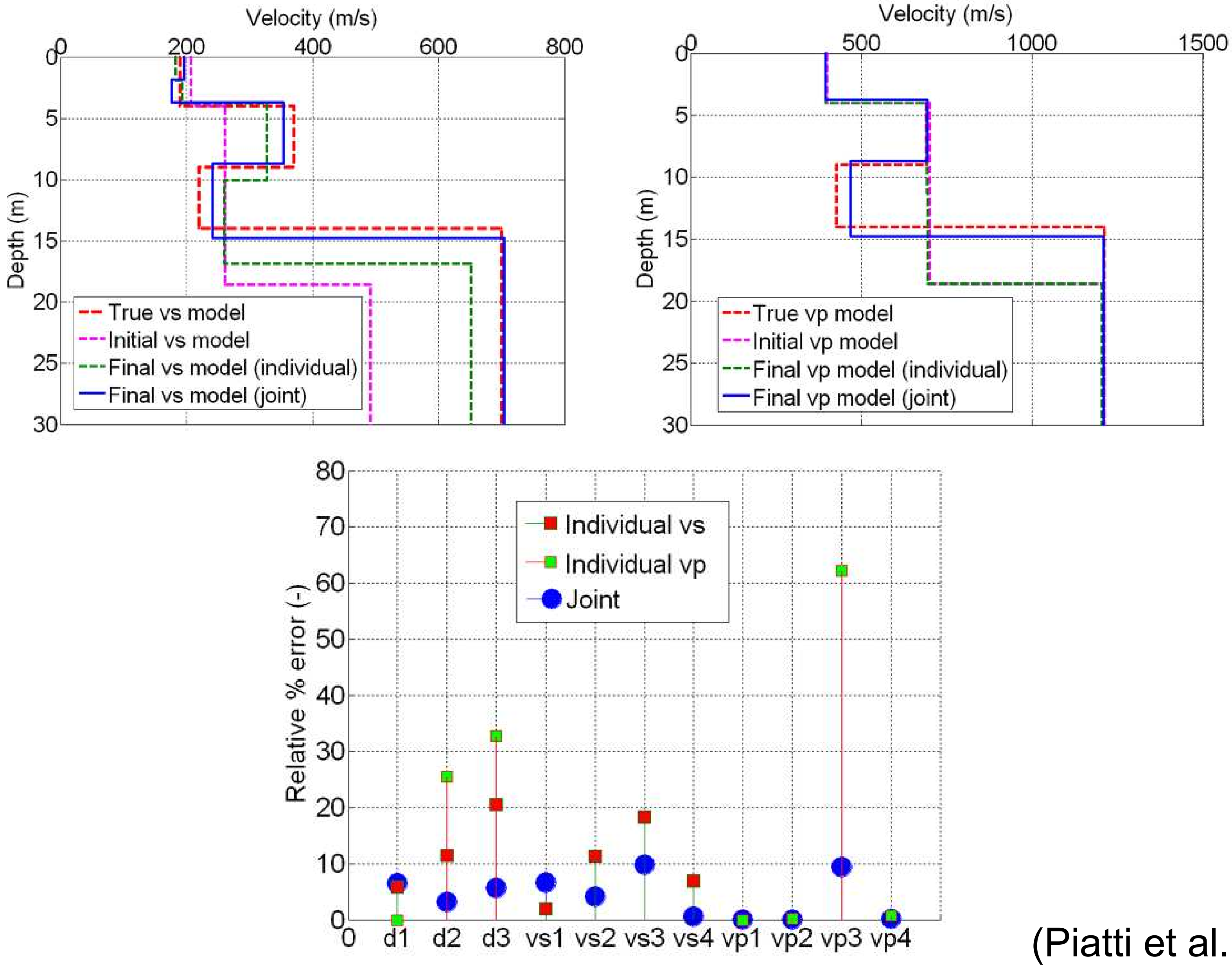
$$\mathbf{m}=[\left(\log(h_1),\ \log(h_2),\ ....,\ \log(h_n)\right)\ \left(\log(V_{S1}),\ \log(V_{S2}),\ ....,\ \log(V_{Sn+1})\right)$$
$$\left(\log(V_{P1}),\ \log(V_{P2}),\ ....,\ \log(V_{Pn+1})\right)]$$

Example on synthetic data



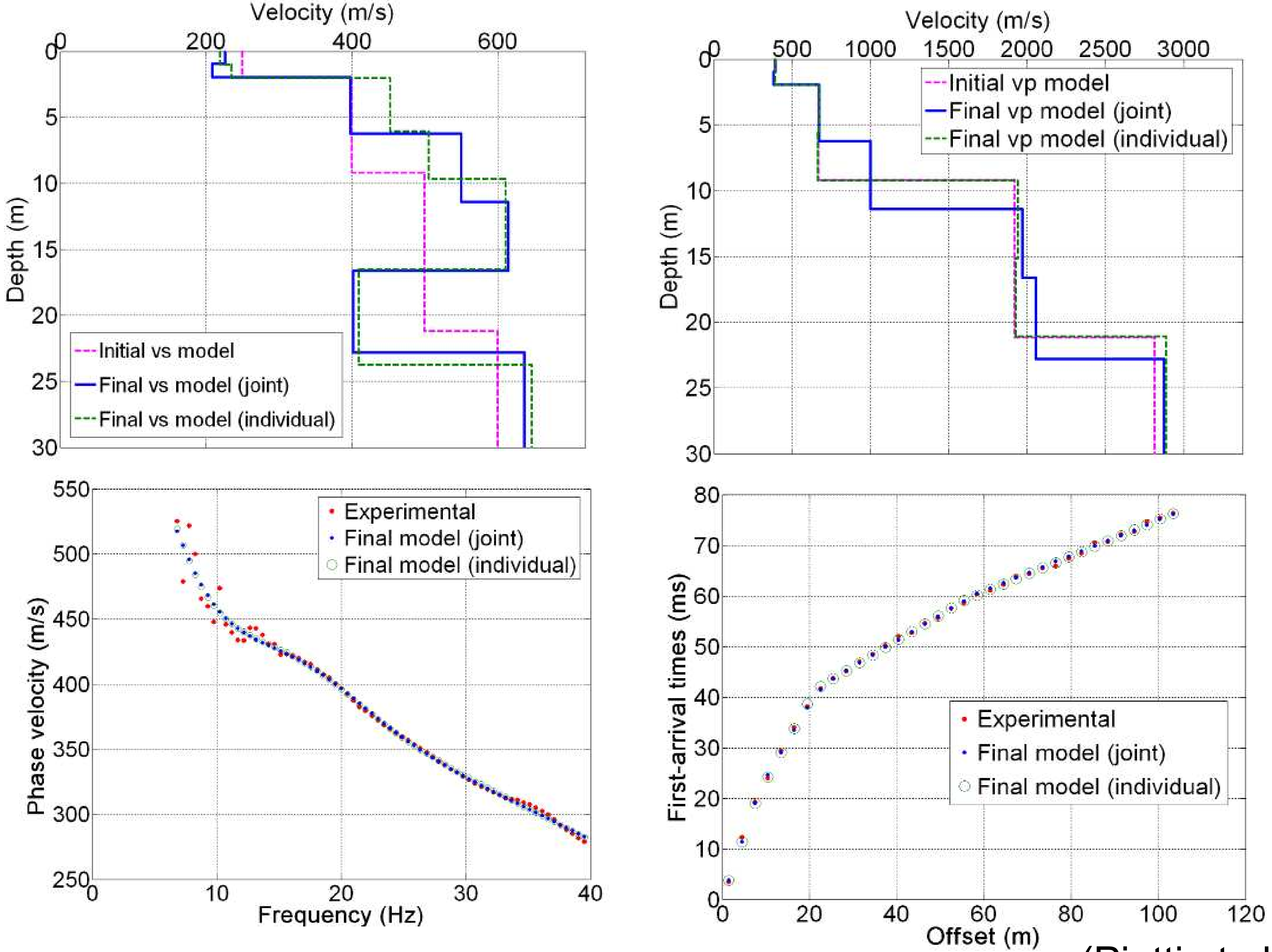
(Piatti et al., 2012b)

Example on synthetic data



(Piatti et al., 2012b)

Experimental data



(Piatti et al., 2012b)

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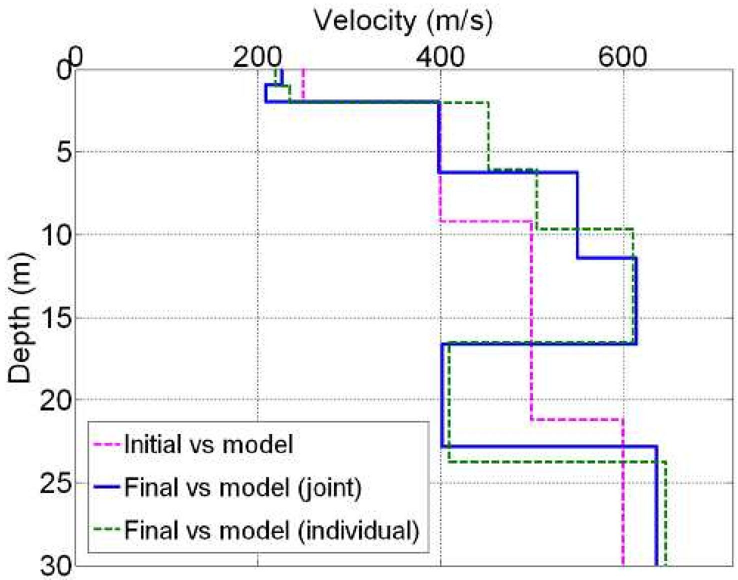
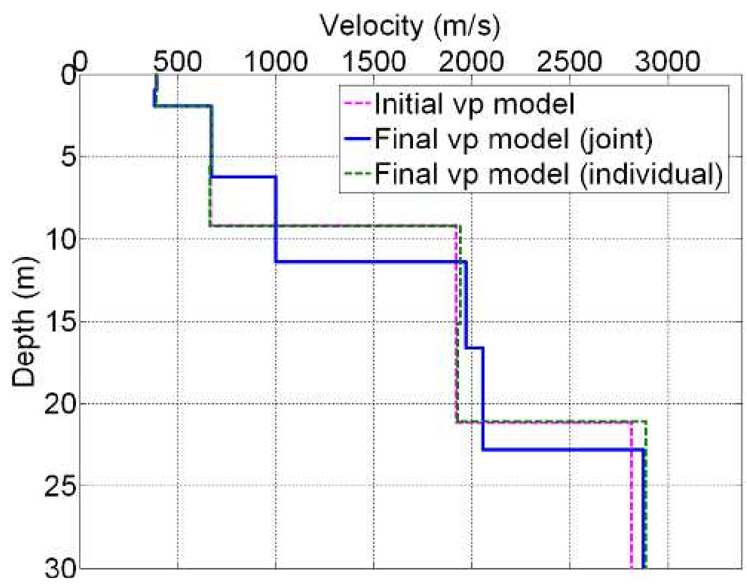
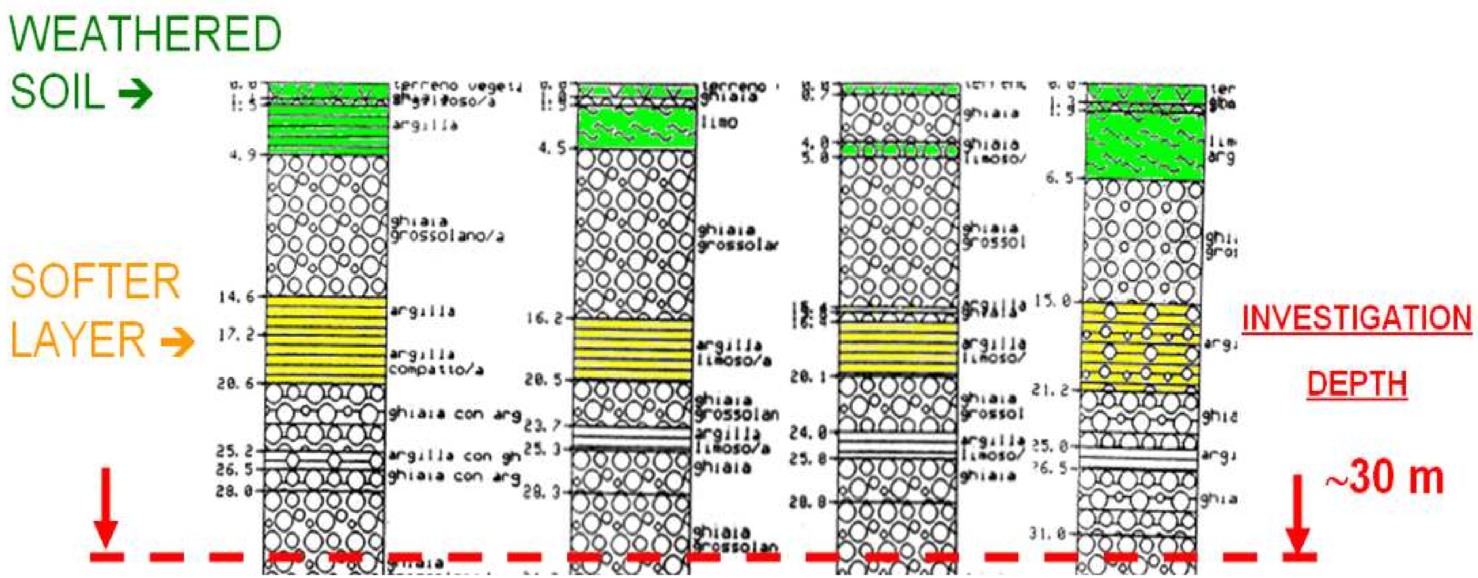






(Piatti et al., 2012b)

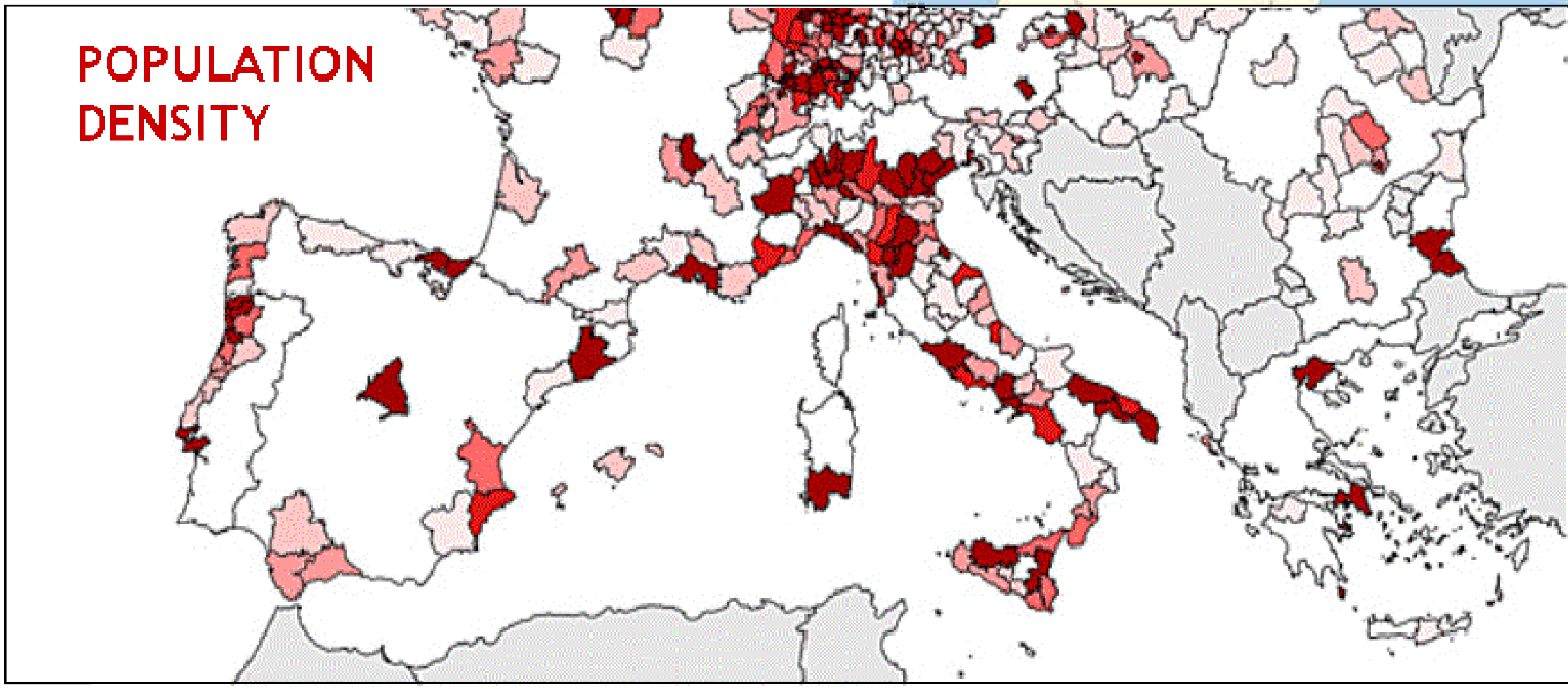
Case History #1

Combination of seismic and electrical methods for the assessment of site conditions for seepage analysis along an embankment

- Combination of several methods for reliable evaluation of cover thickness
- Joint inversion to improve accuracy

The PO river

LENGTH: 650 km
DISCHARGE
ave.= 1450 m3/s
max.= (nov 2000): 13000m3/s



Seepage potential

Floods very often start with localized seepage that can degenerate causing inundations

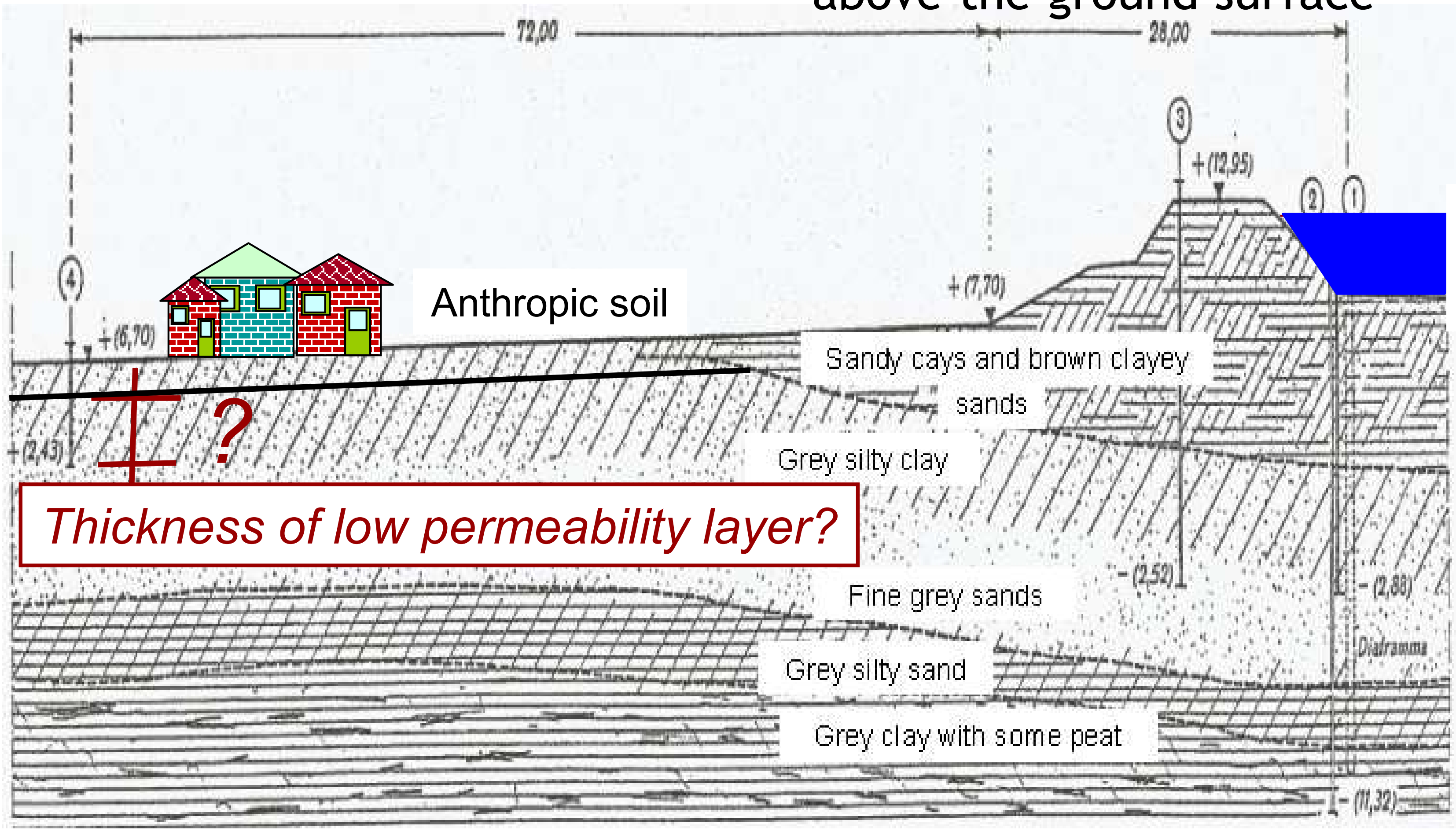
10 extreme events each 100 years

Levees for a total length over 2400 km

Seepage potential

Geology: alluvial deposits: recent sands, gravel, clay
TARGET: clayey layer: continuity, thickness

Water level can reach 10 m
above the ground surface



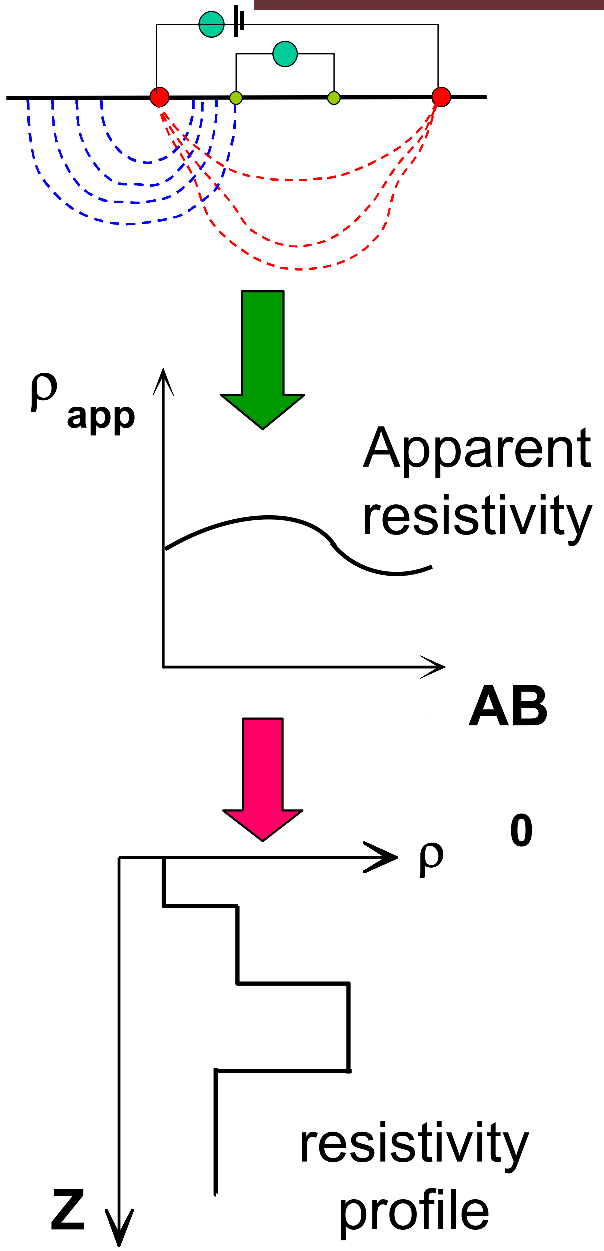
Geophysical investigation

large extension of the areas
Interest in fast geophysical tests from the surface

At a test site several methods have been tested and compared

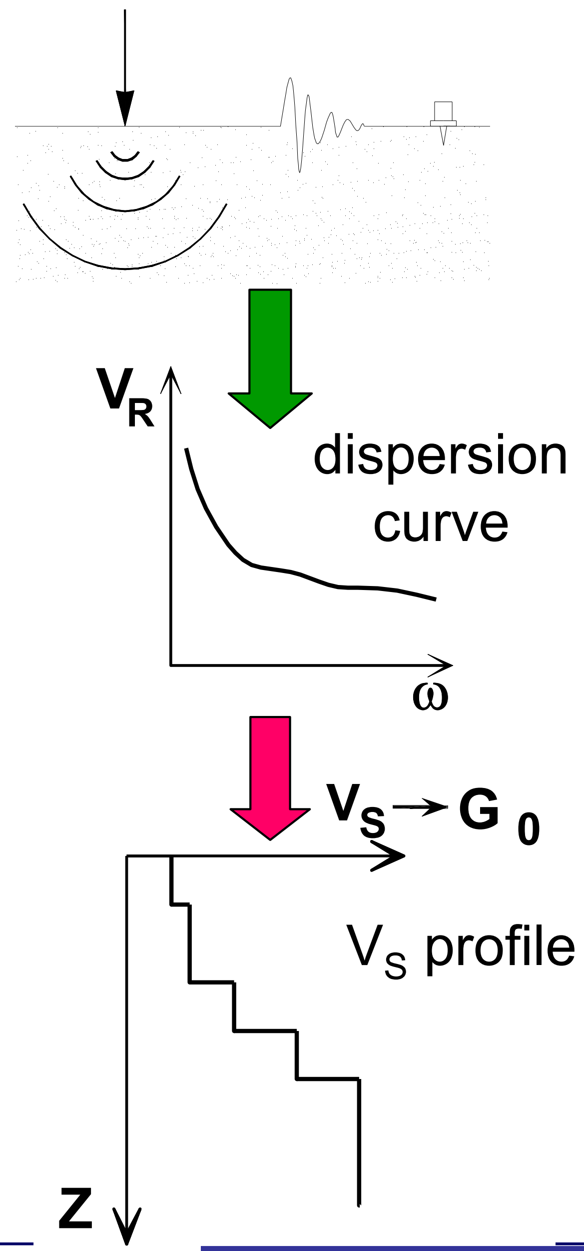
VES ERT
HEP
SWM
P_{refr} SH_{refr}

Combinations MASW + VES



Processing

Inversion

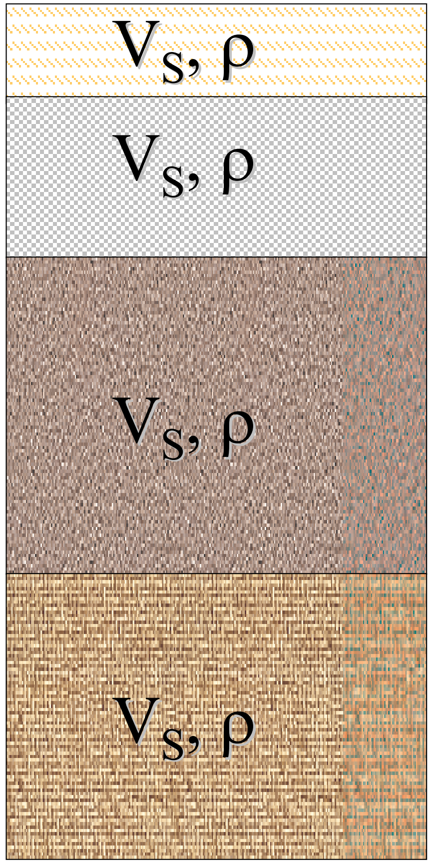


Joint inversion VES + MASW

Physical parameters: shear velocity and resistivity
Assumed parameter distribution: stack of homogeneous isotropic layers

MODEL PARAMETERS:

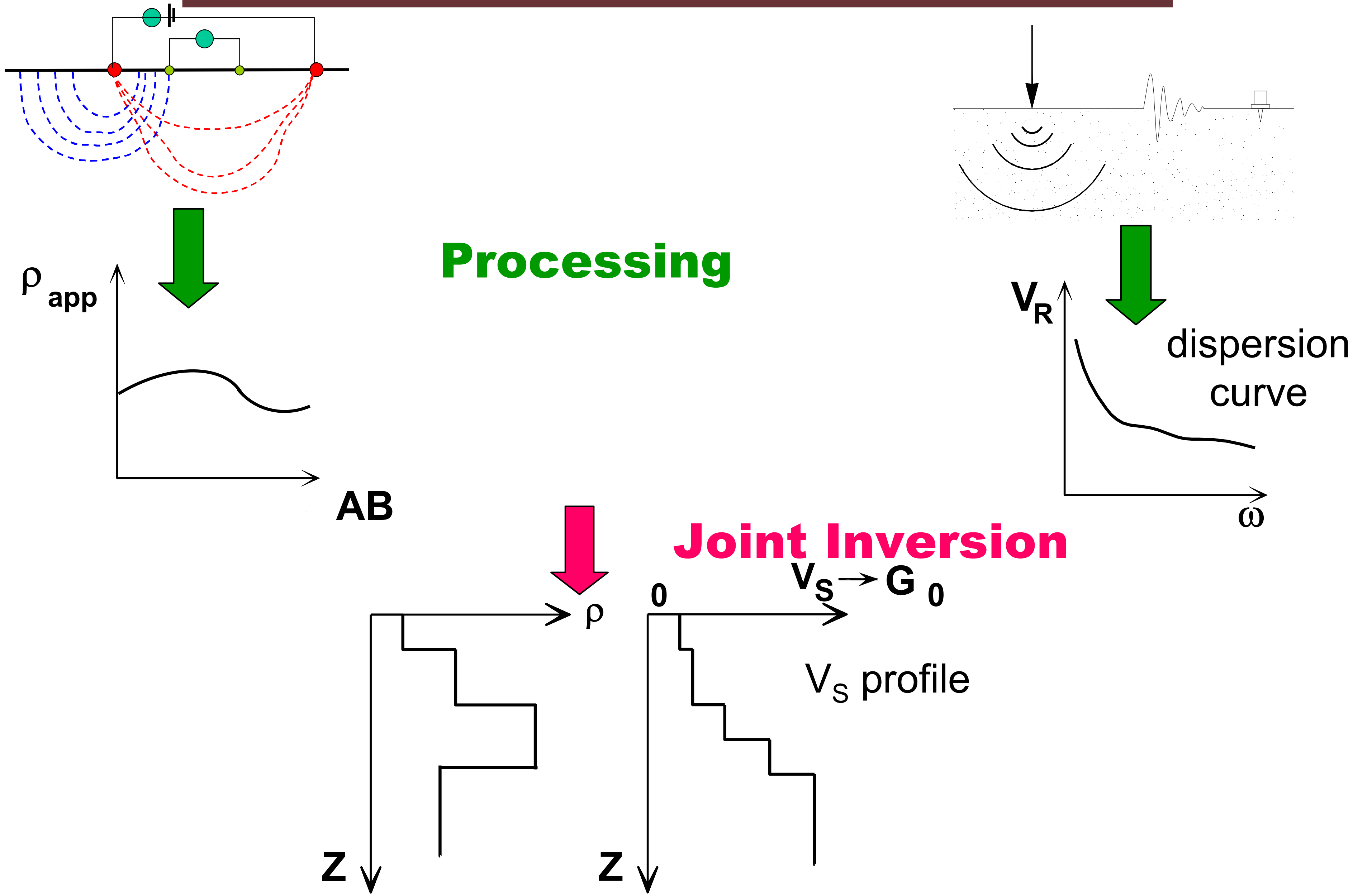
n ρ
n V_S
n-1 H



LINK BETWEEN THE TWO MODELS:
geometry, thickness of the layers
(same position of interfaces: independent variations of the two parameters, a variation of resistivity does not imply a variation of seismic shear velocity)

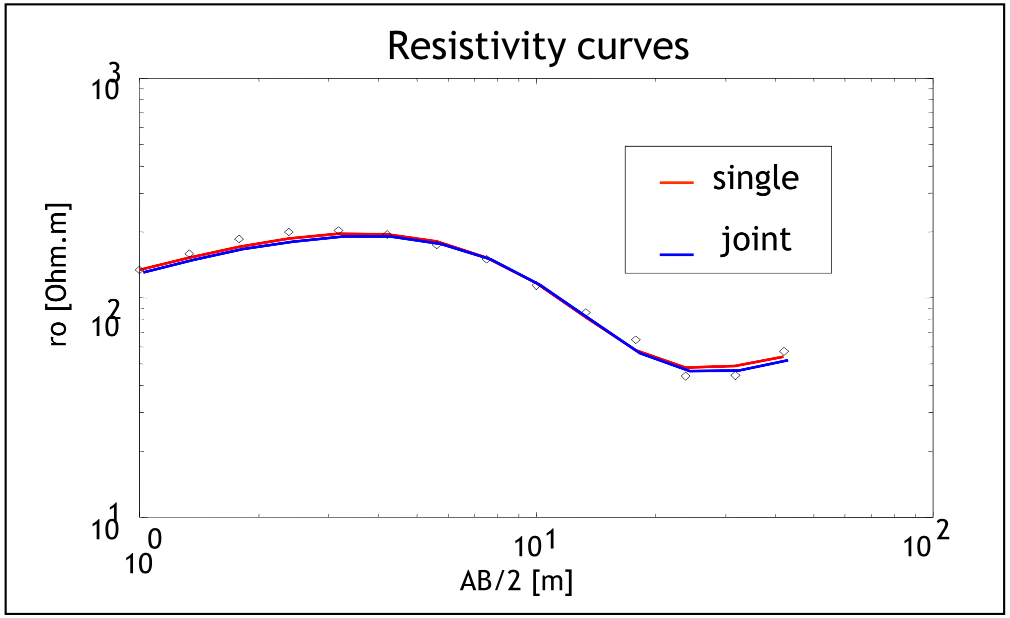
From 4n-2 to 3n-1 unkowns
with the same experimental information

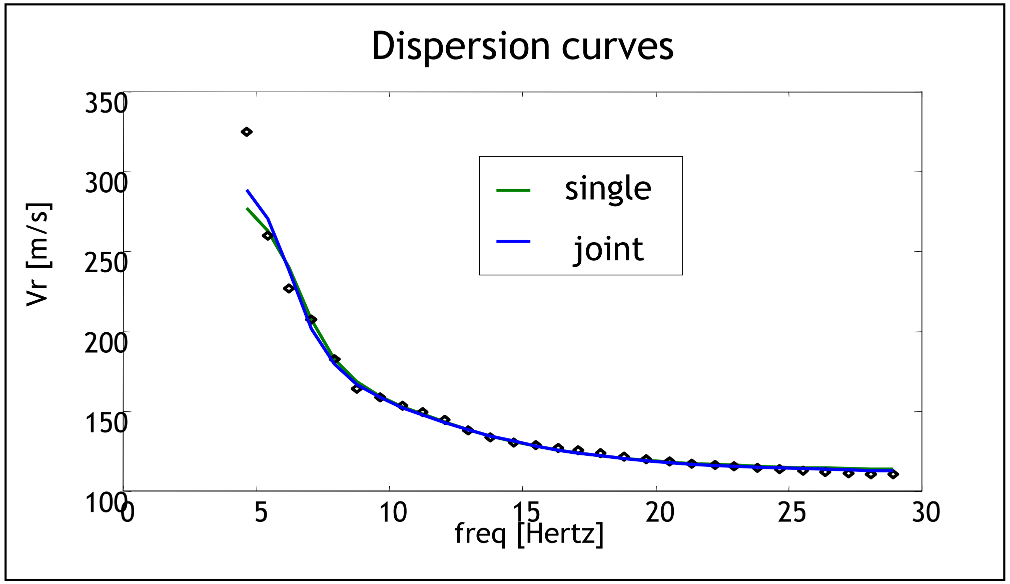
Joint inversion VES + MASW

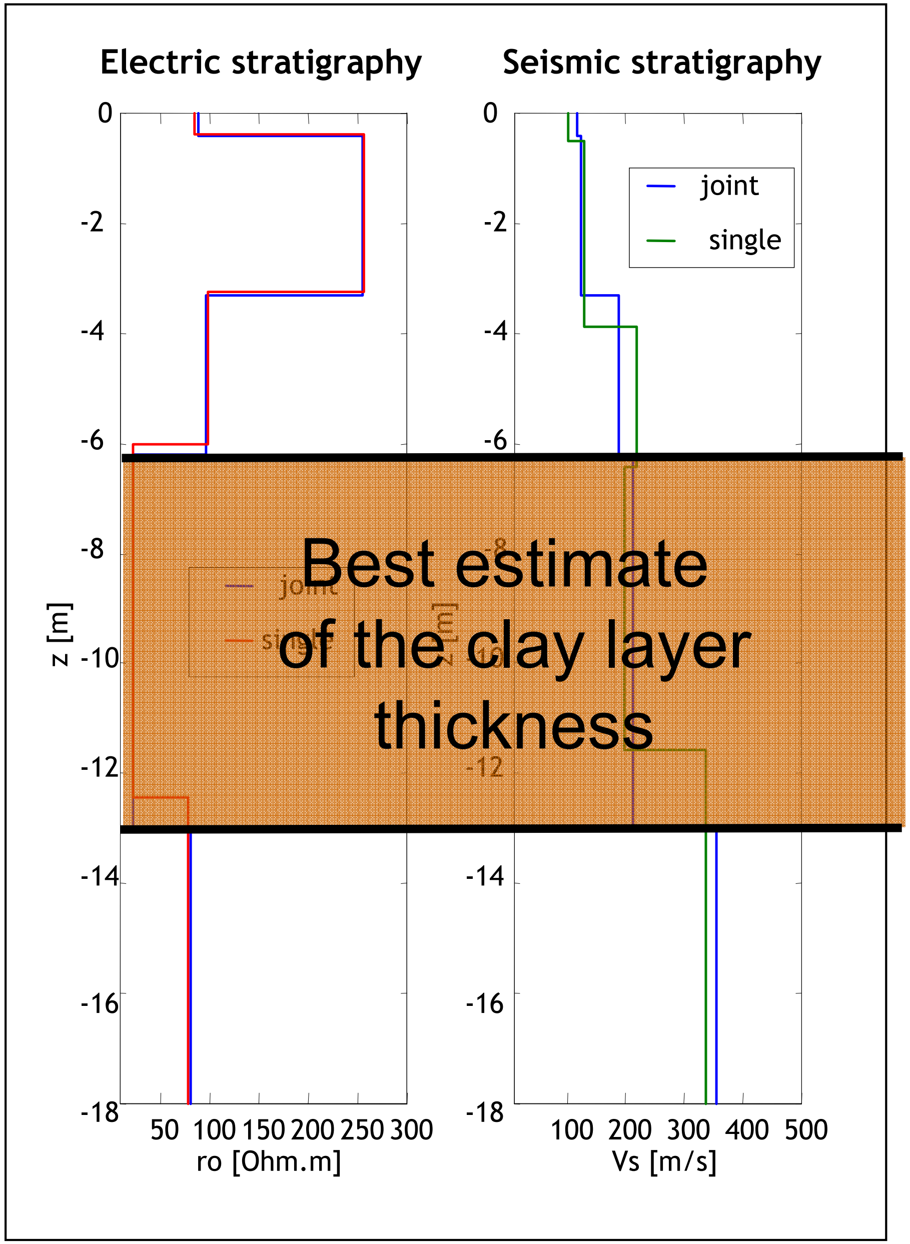


Field test results

(Comina et al., 2004)





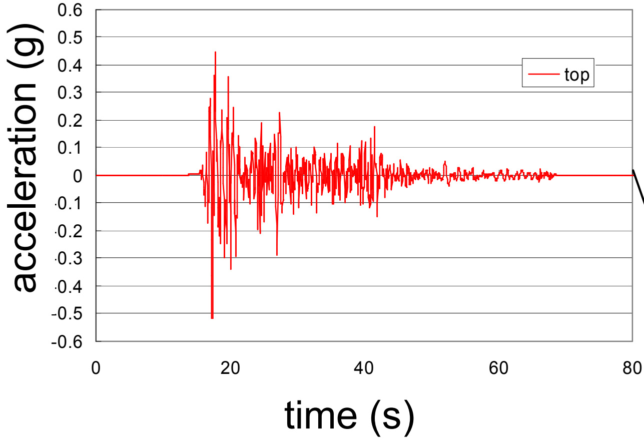


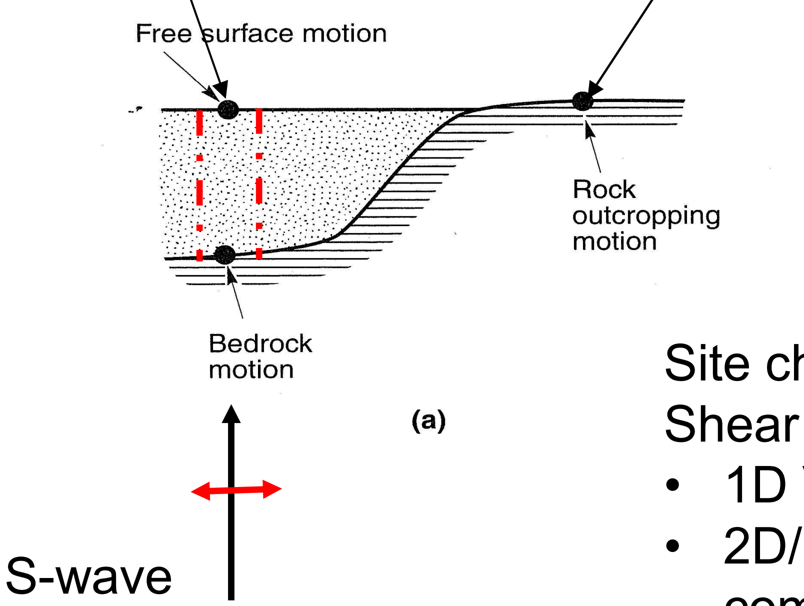
Case history #2

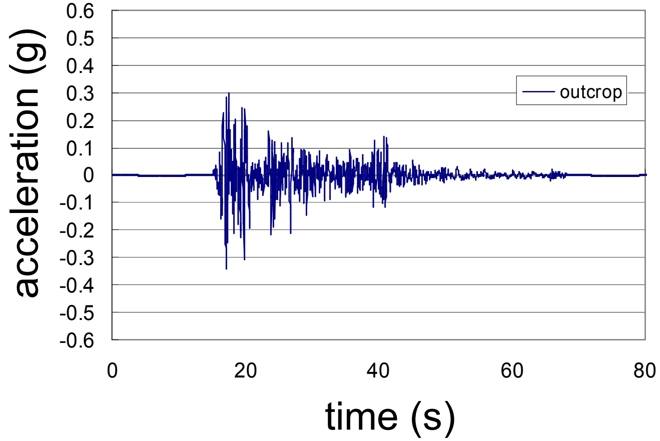
Building a shear wave velocity model for seismic site response studies

- Combination of different techniques for validation
- Exploitation of the information in the seismic dataset with different methodologies
- Integration of information

Numerical simulations of seismic site response







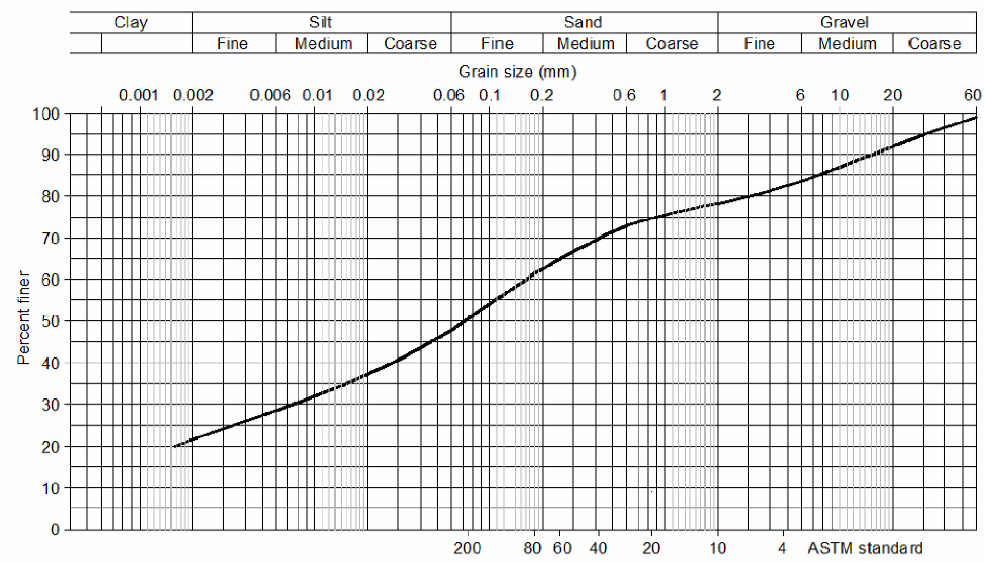
Site characterization:
Shear wave velocity model

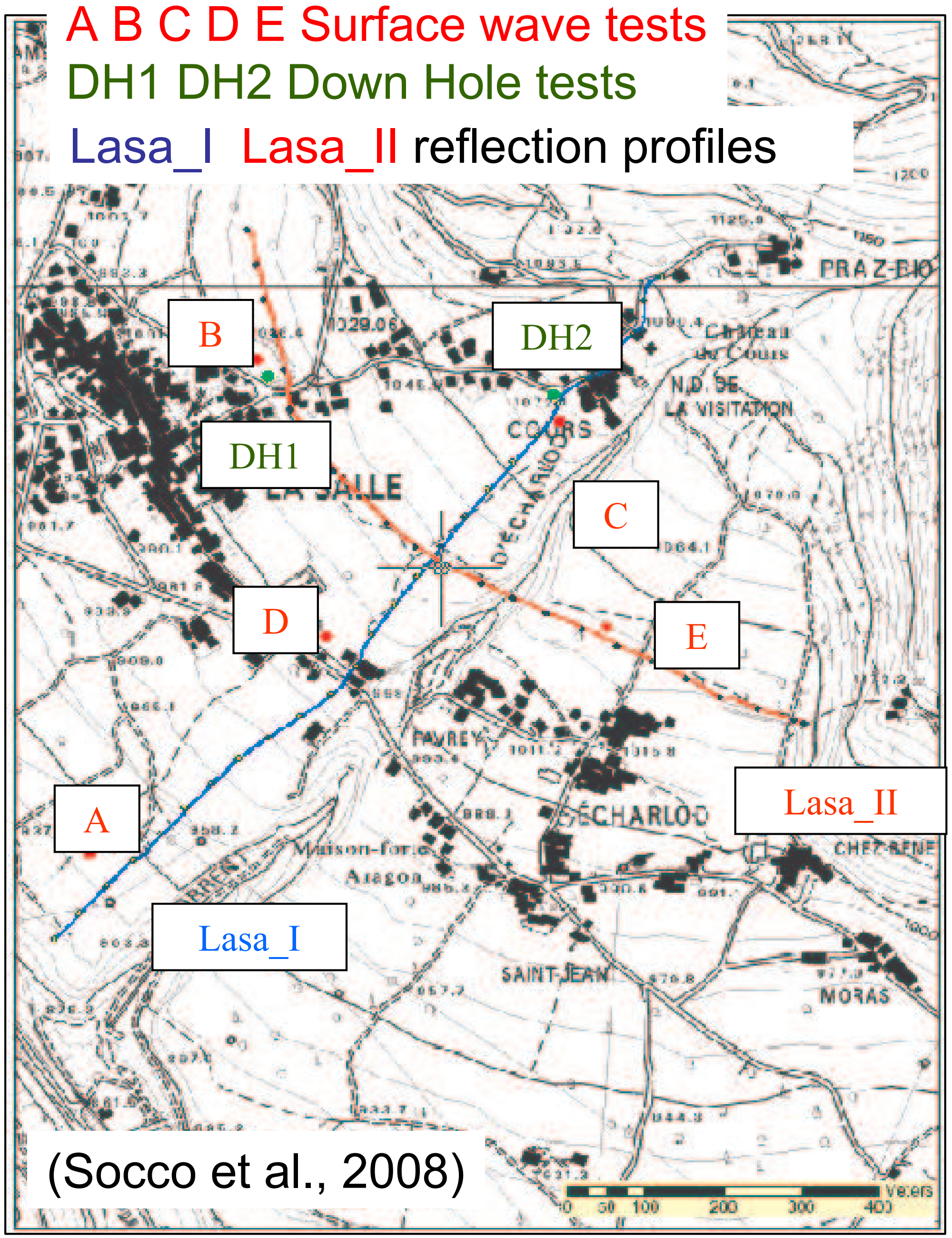
- 1D Vs profile
- 2D/3D Vs models to simulated complex situation (e.g. valley edges)

Case Study: La Salle, Italy

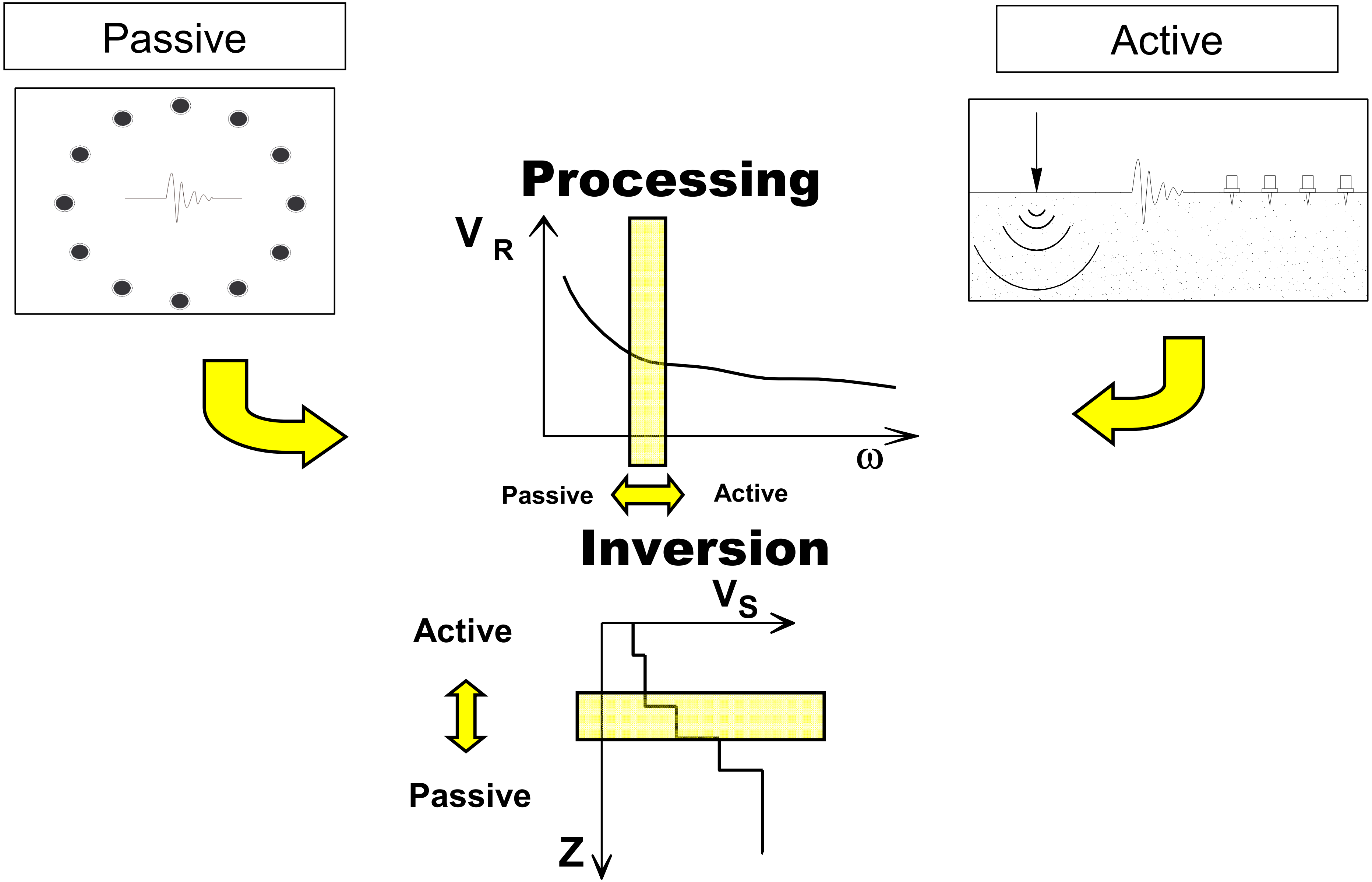
Alluvial Fan

Materials with very heterogenous composition: there are not many other option for the characterization

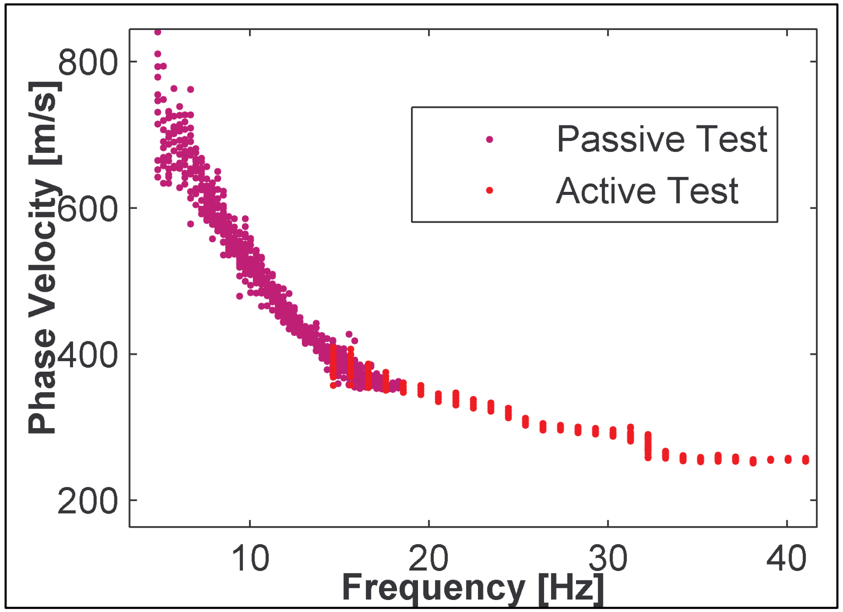


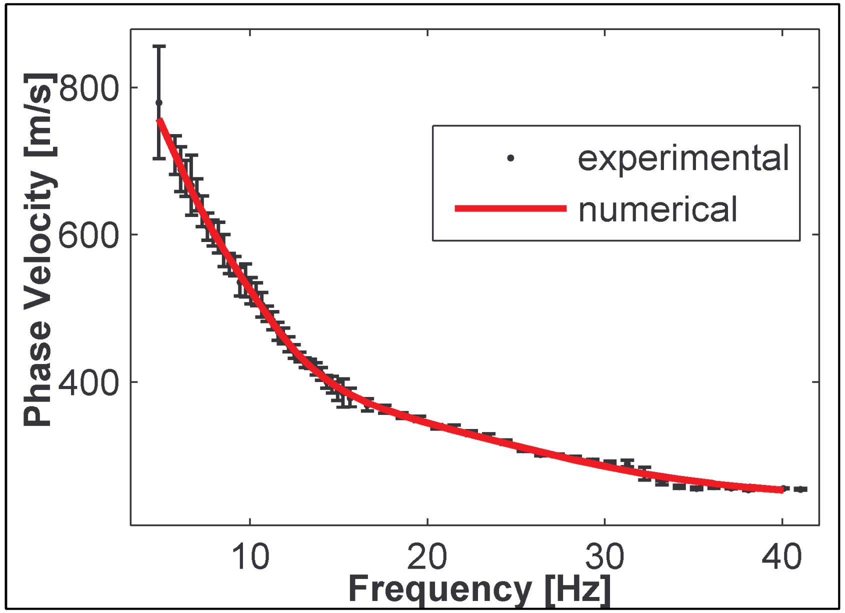


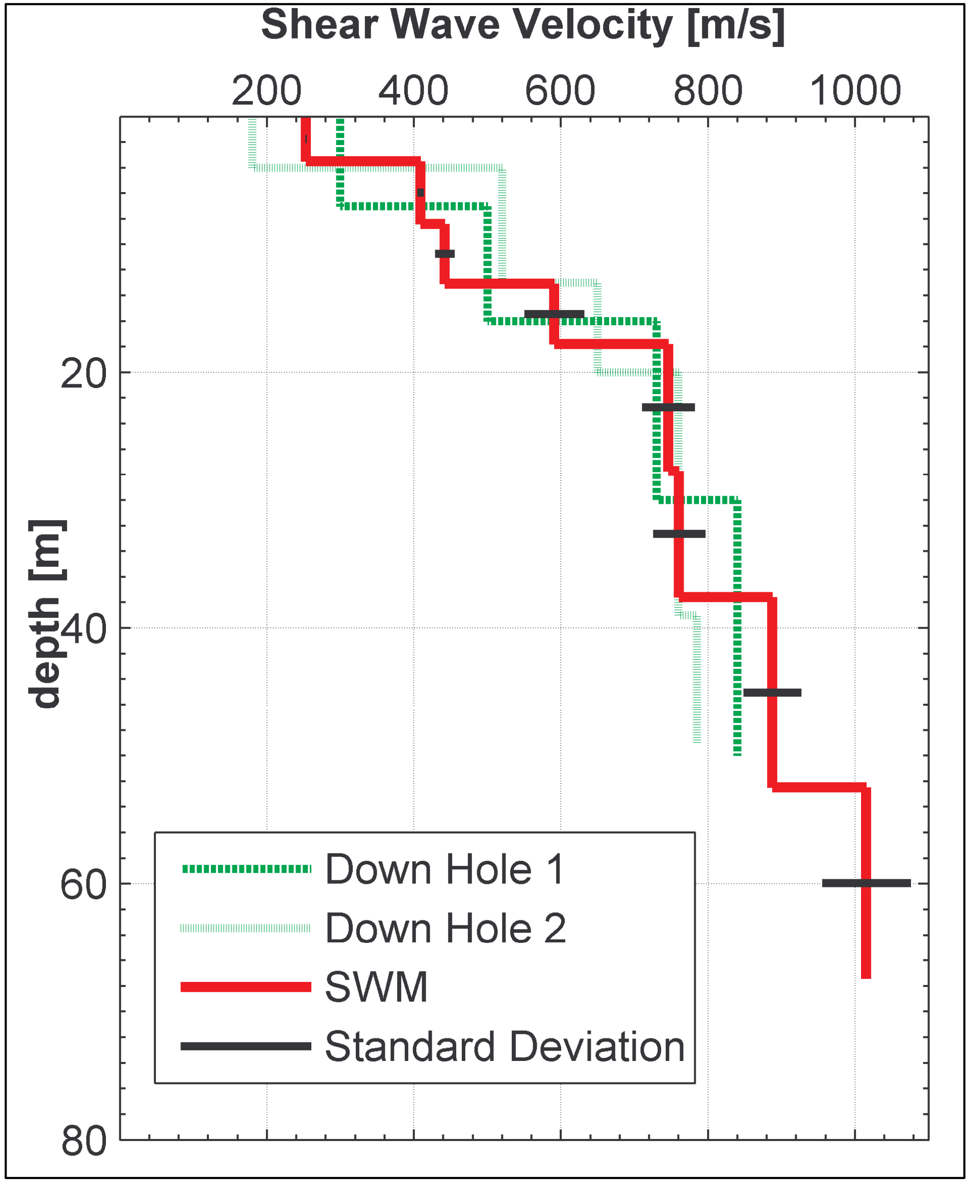
Active+Passive - SW Tests



Example: La Salle (site E)

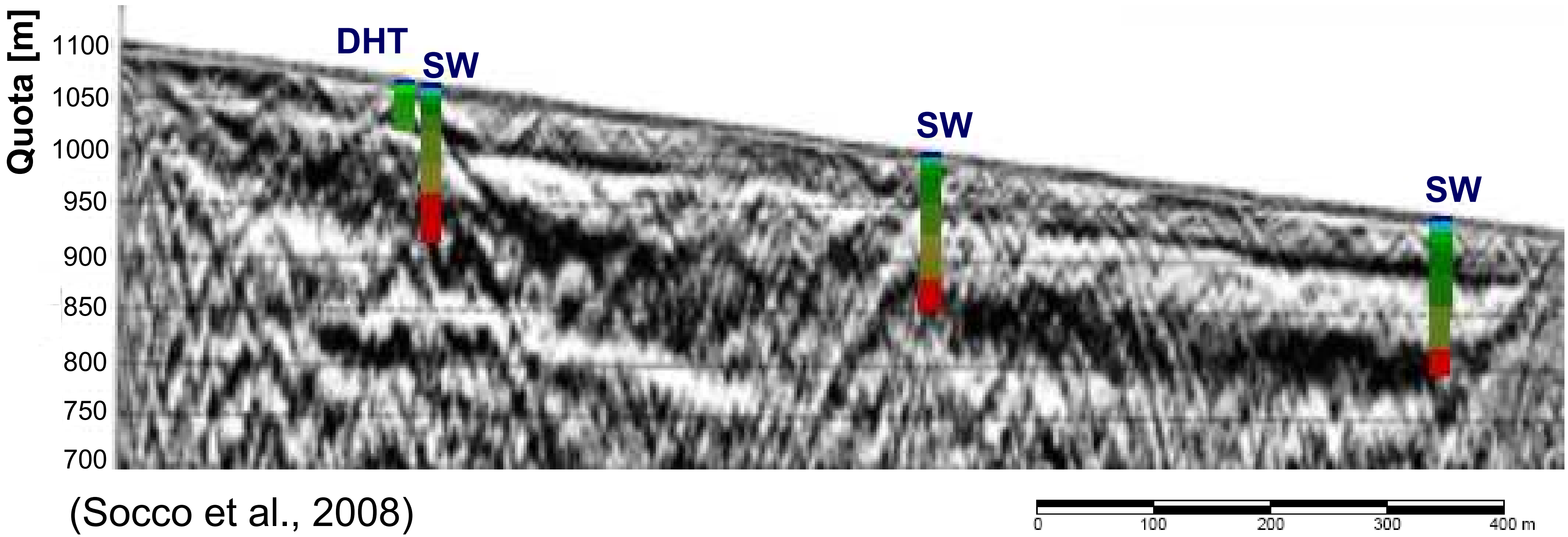




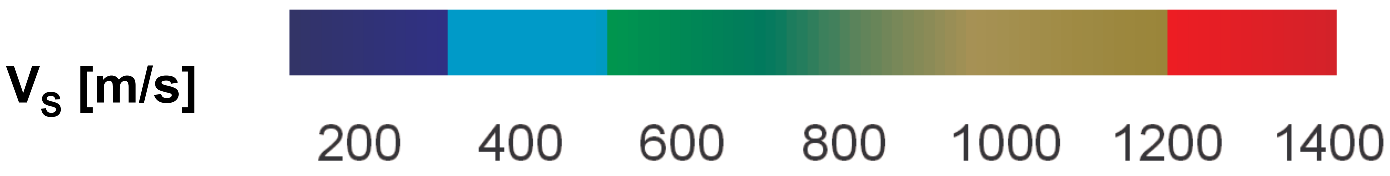


(Foti et al., 2007)

Seismic reflection vs. SWM (A+P)



(Socco et al., 2008)



Surface waves confirm that second reflection is the bedrock.

Case history #3

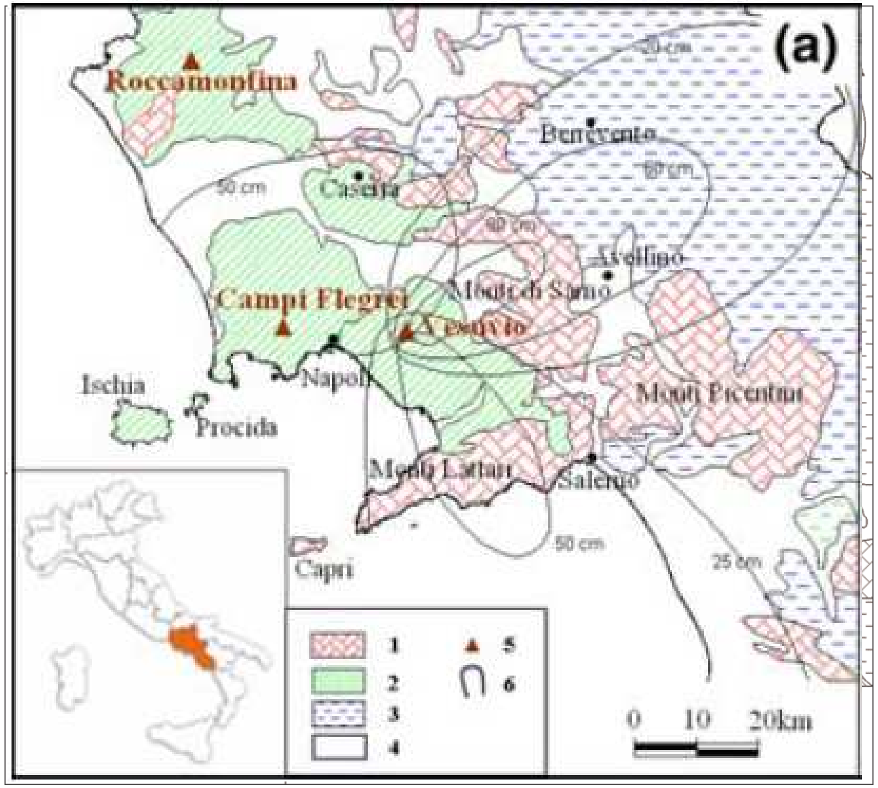
Investigation of volcanoclastic slopes

- Combination of several in situ geophysical tests to increase the reliability of the results
- Combination of laboratory and in situ testing for the assessment of saturation conditions

Flowslides of 1998 in Campania

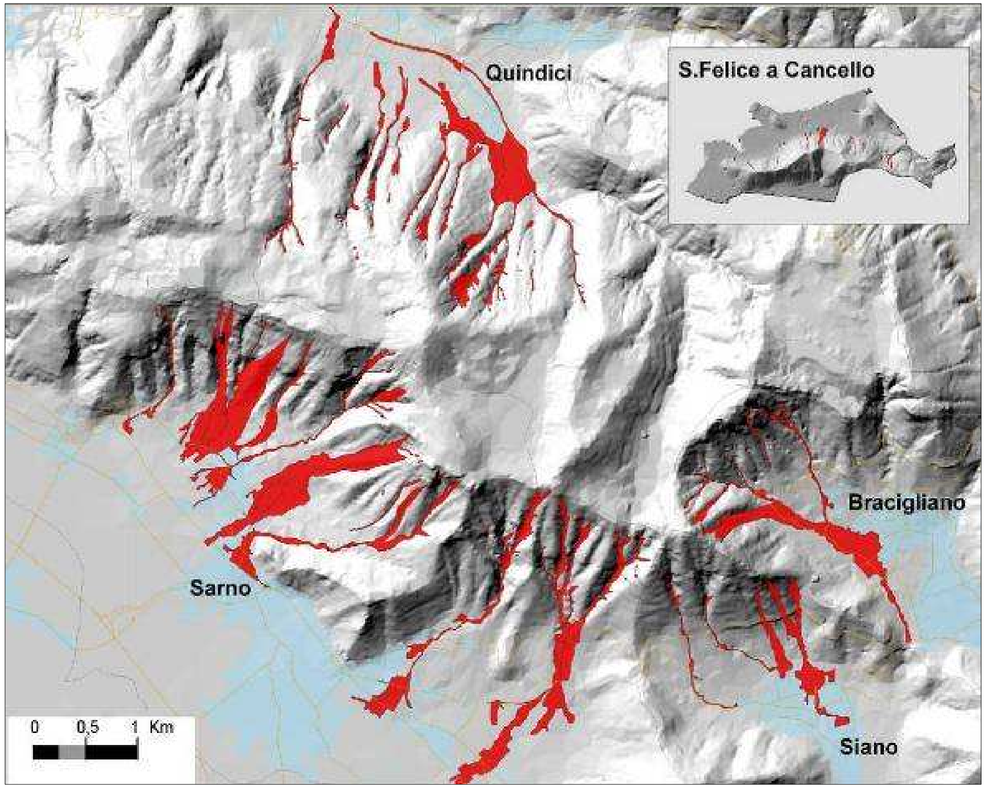
Sarno

Air-fall pyroclastic deposits



(Cascini et al., 2008)

flowslides occurred in May 1998



(Cascini et al., 2008)

Cover soils formed by volcanic ashes from the Vesuvio (few meters thick) over a carbonatic bedrock

Site characterization

Objectives

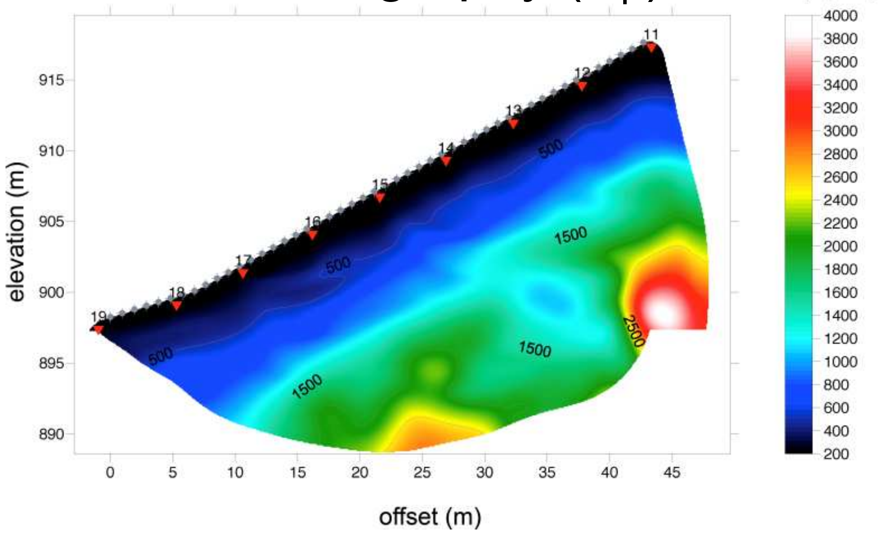
- Quantification of potential volume of the flow (for the design of mitigation infrastructures): **thickness of the soil cover**
- Prevision of onset of the flowslide: assessment and monitoring of **saturation condition of the soil cover**

Critical issues

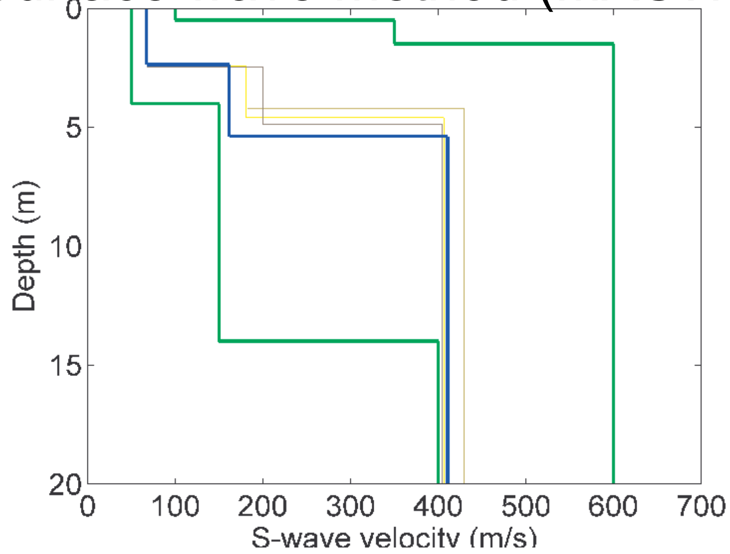
- Very difficult site logistics with steep and vegetated slopes poses strong limitations in the use of conventional site tests (boreholes and penetration testing)
- Necessity of investigating large areas

Combination of different geophysical approaches

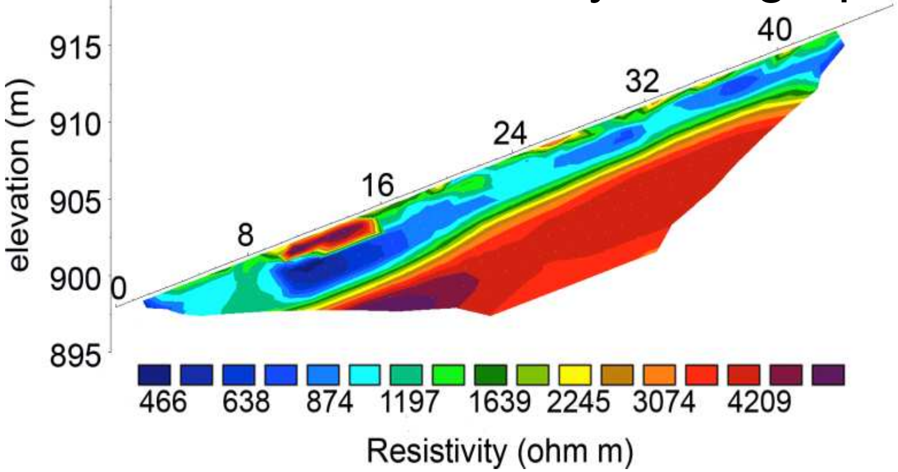
Seismic tomography (V_P)

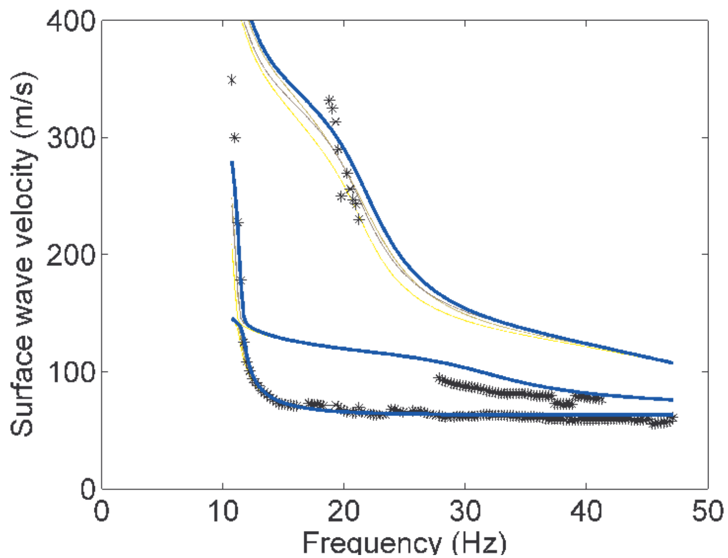


Surface wave method (MASW)



Electrical resistivity tomography



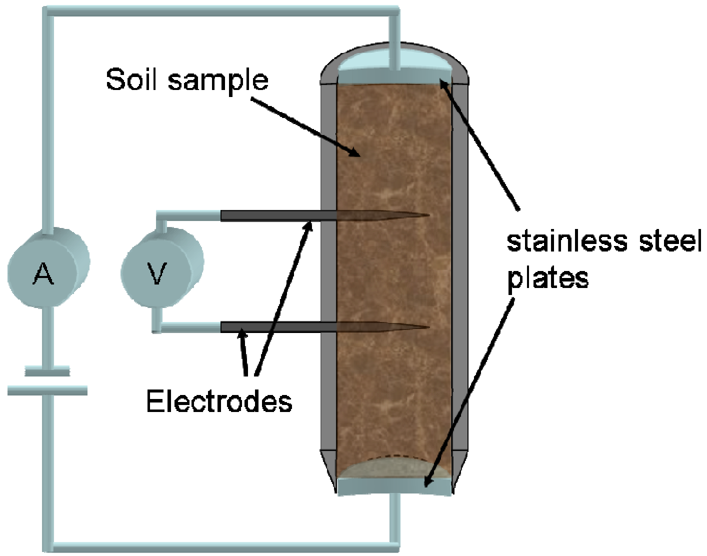


(Cosentini et al., 2012)

Comments

- Electical and seismic (V_P) tomography show that the assumption of a layered medium in MASW is reasonable
- Inversion of MASW shows the relevance of higher modes at this site: surface wave analysis is not a simple and straightforward task
- The estimated thickness of the cover material is comparable with different methods

Laboratory calibration of Archie's law for unsat materials

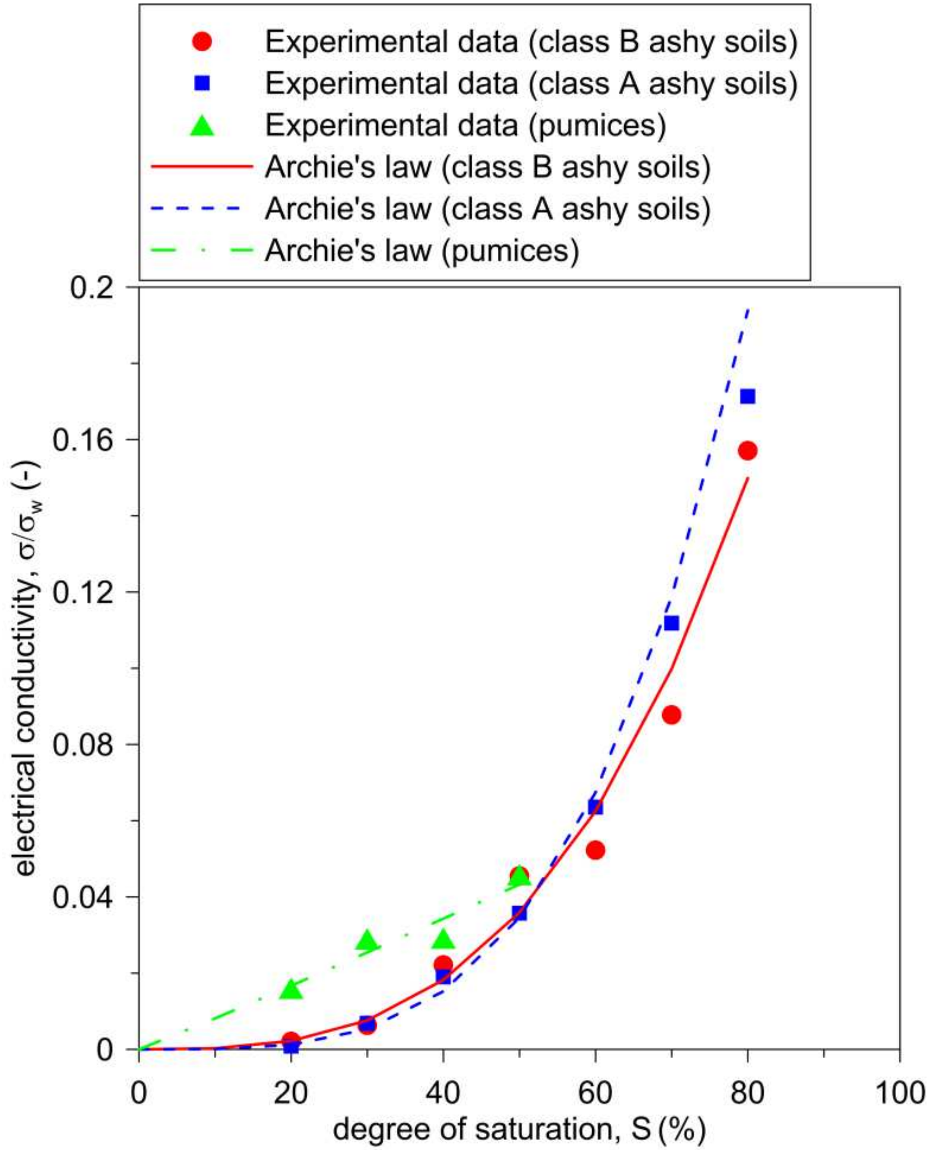


$$\sigma_t = \sigma_w \, n^m \, S_r^{\,p}$$

n: porosity

S: saturation

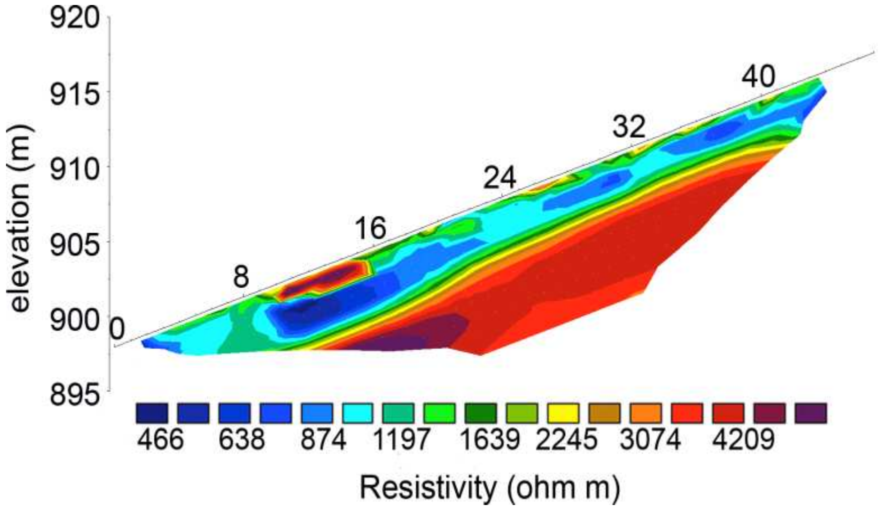
σ_w : pore fluid conductivity

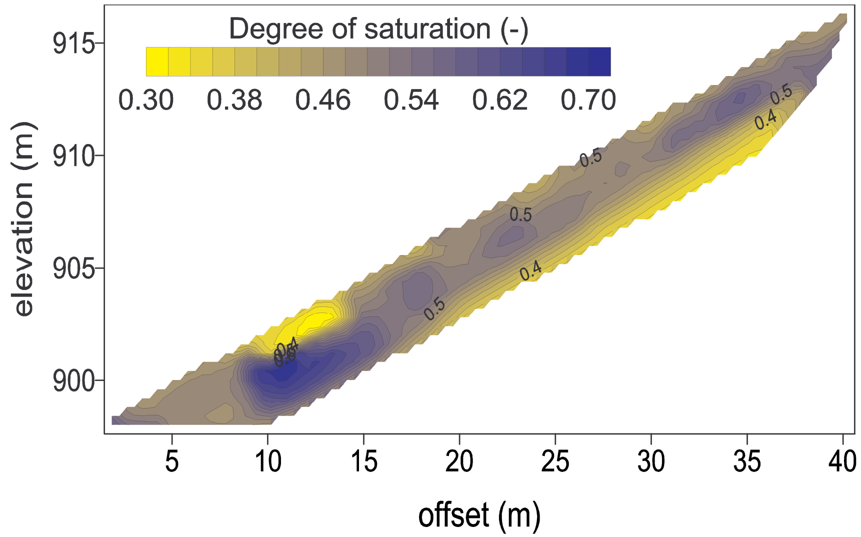


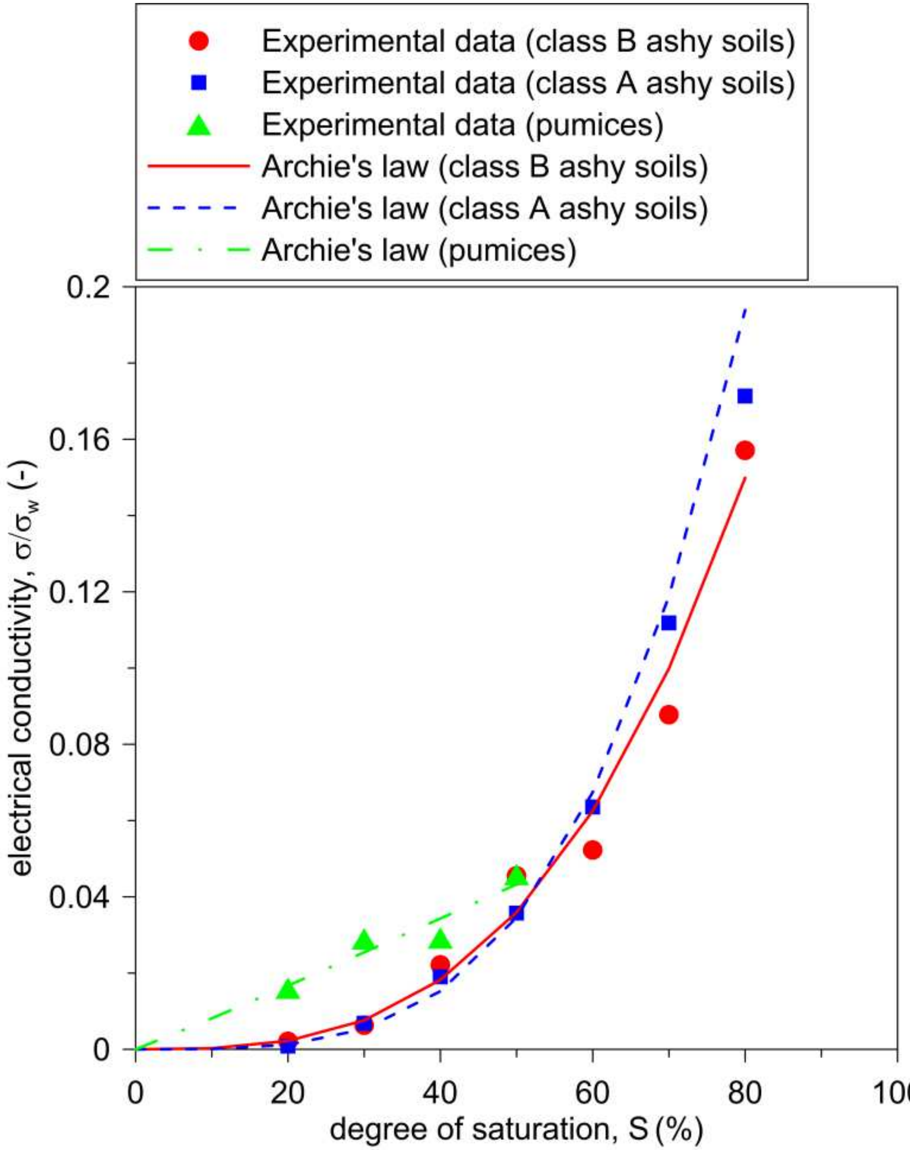
(Cosentini et al., 2012)

The two exponet *m* and *p* are found by fitting laboratory data

Mapping resistivity into degree of saturation







(Cosentini et al., 2012)

Closing remarks

- Importance of choosing the right technique for the specific application
- Integration of different techniques reduces uncertainties
- Laboratory experimental can provide a framework and calibration for quantitative interpretation of field tests

Thank you for your attention

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Dr Claudio Strobbia (now at Western-Gico - UK)

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