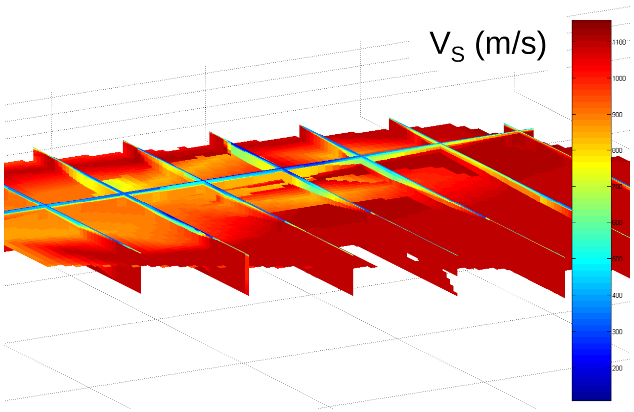
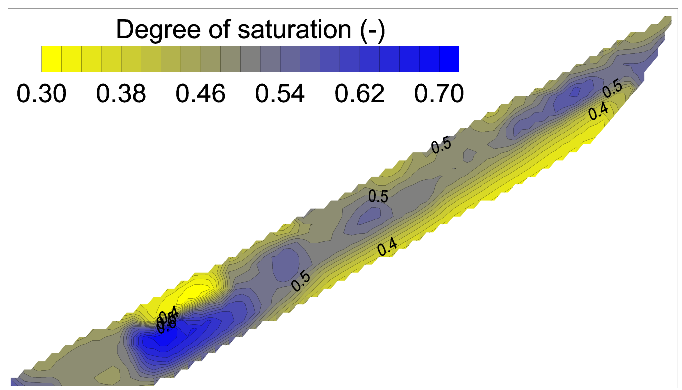
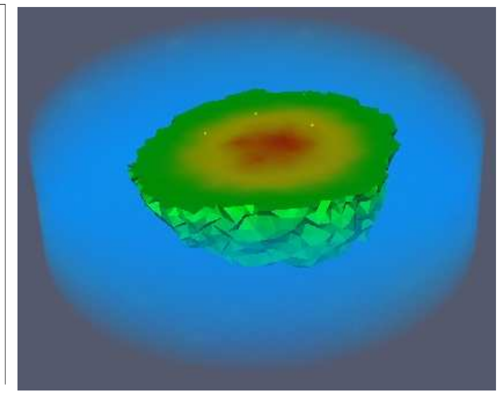
11th ISSMGE Webinar

8th of May 2013

Geophysical Methods for Geotechnical Site Characterization







Sebastiano Foti

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"Ground Property Characterization from In-Situ Tests"

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POLITECNICO DI TORINO

(ITALY)

Outline

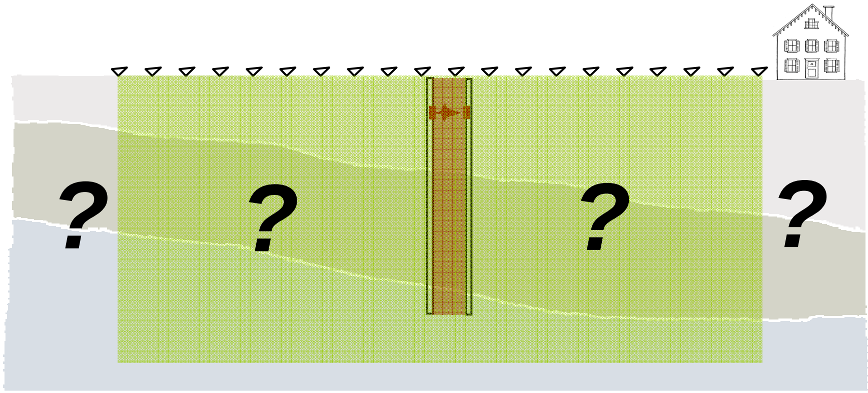
- Geophysical methods
  - Scope and potential for geotechnical and geoenvironmental characterization
  - Use of seismic velocities
  - Significance of other geophysical parameters
  - In-hole vs surface methods
- Combined use of geophysical methods
  - Different levels of integration
  - Case histories
    - Levees
    - Seismic site response
    - Landslides

Geophysical Methods

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.

They are based on the excitation of an object with an energy field (artificial or natural) and on the measurement of the object response.

The interpretation of the object response allows the object to be characterised.



Geophysical parameters

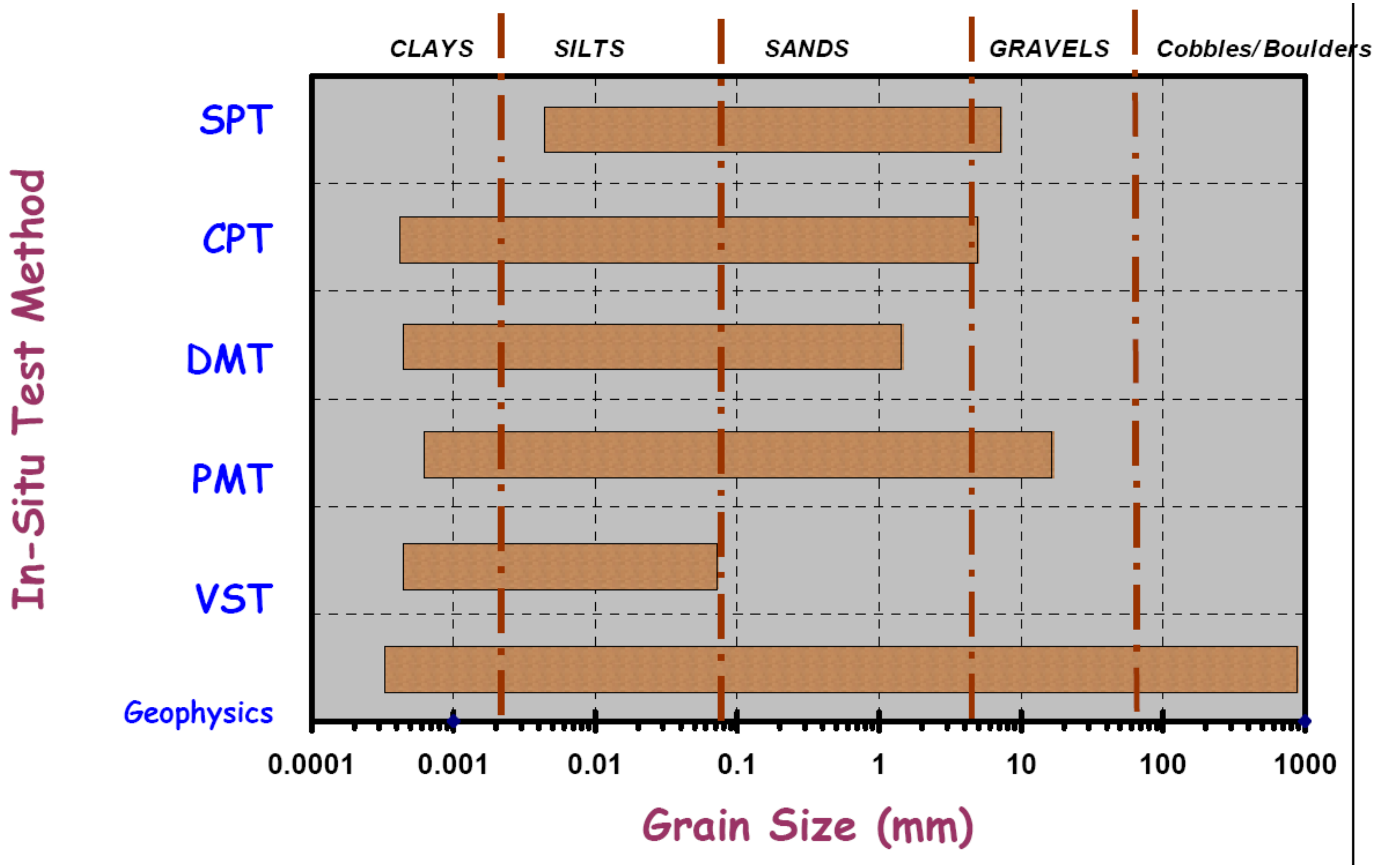
- Density
- Electrical Conductivity (or Resistivity)
- Electrical Permittivity
- Magnetic Suscettibility
- Chargeability
- Seismic velocities

Geophysical parameters

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

→ Direct relationship to mechanical parameters of the medium (Elastic Moduli)

Applicability of in situ tests



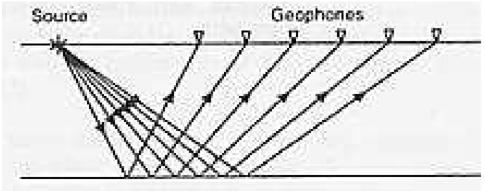
(Mayne et al, 2002)

Geotechnical and geoenvironmental site characterization

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

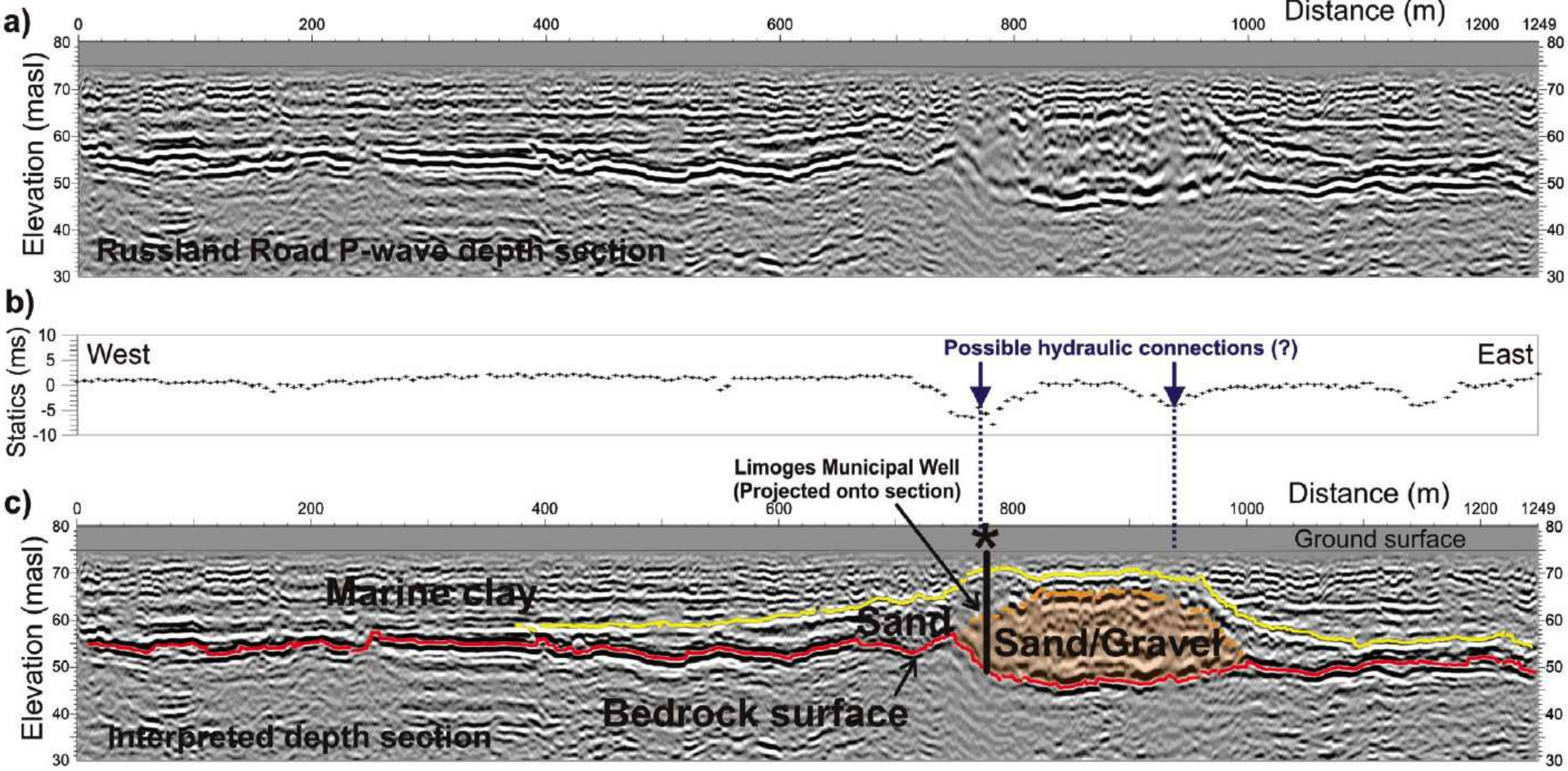
- evaluation of geometrical boundaries to model subsoil conditions (e.g. stratigraphy but also physical inclusions or hydrogeological features);
- evaluation of physical/mechanical parameters of direct use for geotechnical modeling.

Identification of stratigraphic sequence



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

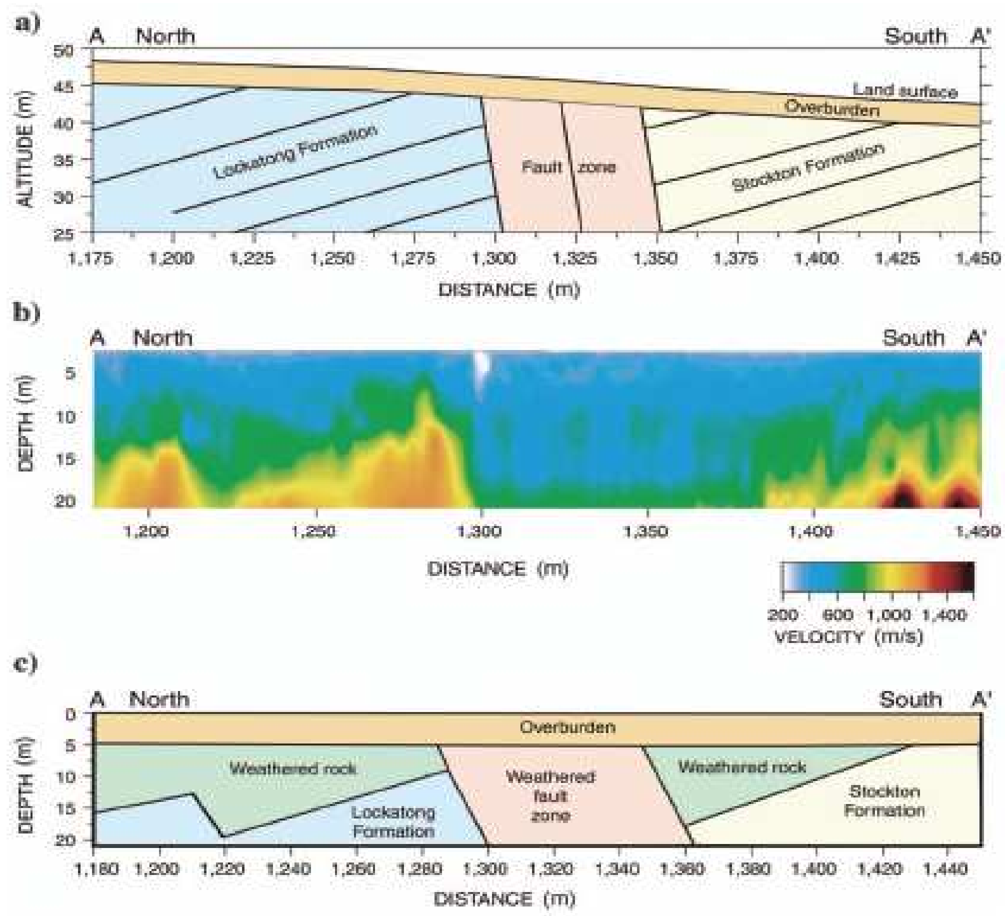
Lateral variations (shallow faults)

e.g. seismic methods: surface wave tests

Geological model (expected)

2D V_S model from surface wave analysis

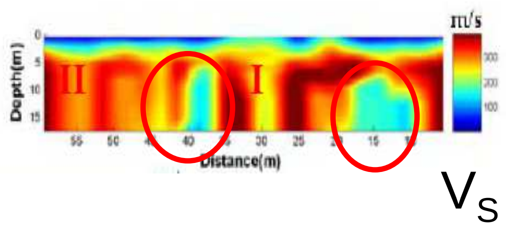
Updated geological model



[Ivanov et al., 2006]

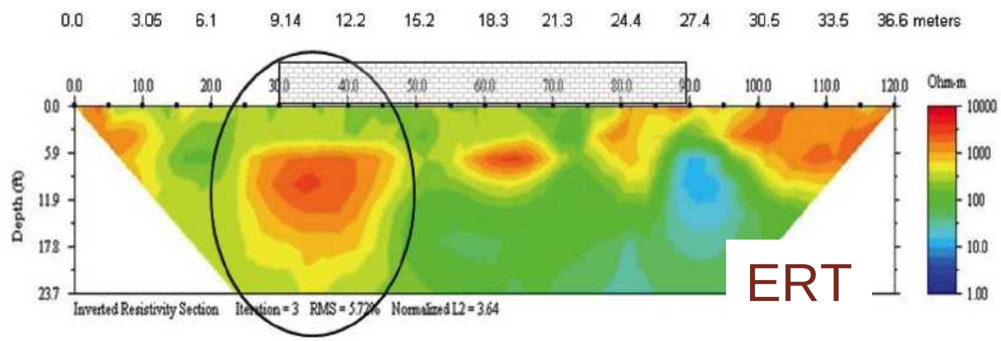
Cavity detection

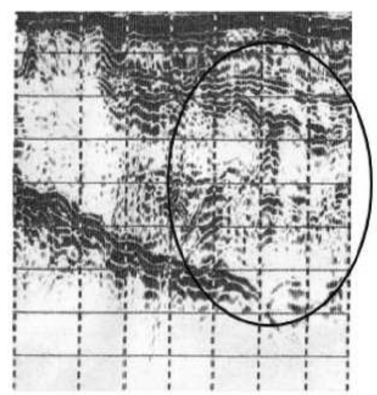
Example 1: void detection in a minerary area in canada with pseudo-2D V_S sections from surface wave analysis



Xu et al., 2008

Example 2: (ERT) Electrical Resistivity Tomography and (GPR) Ground Penetrating Radar surveys reveal a sinkhole beneath a house

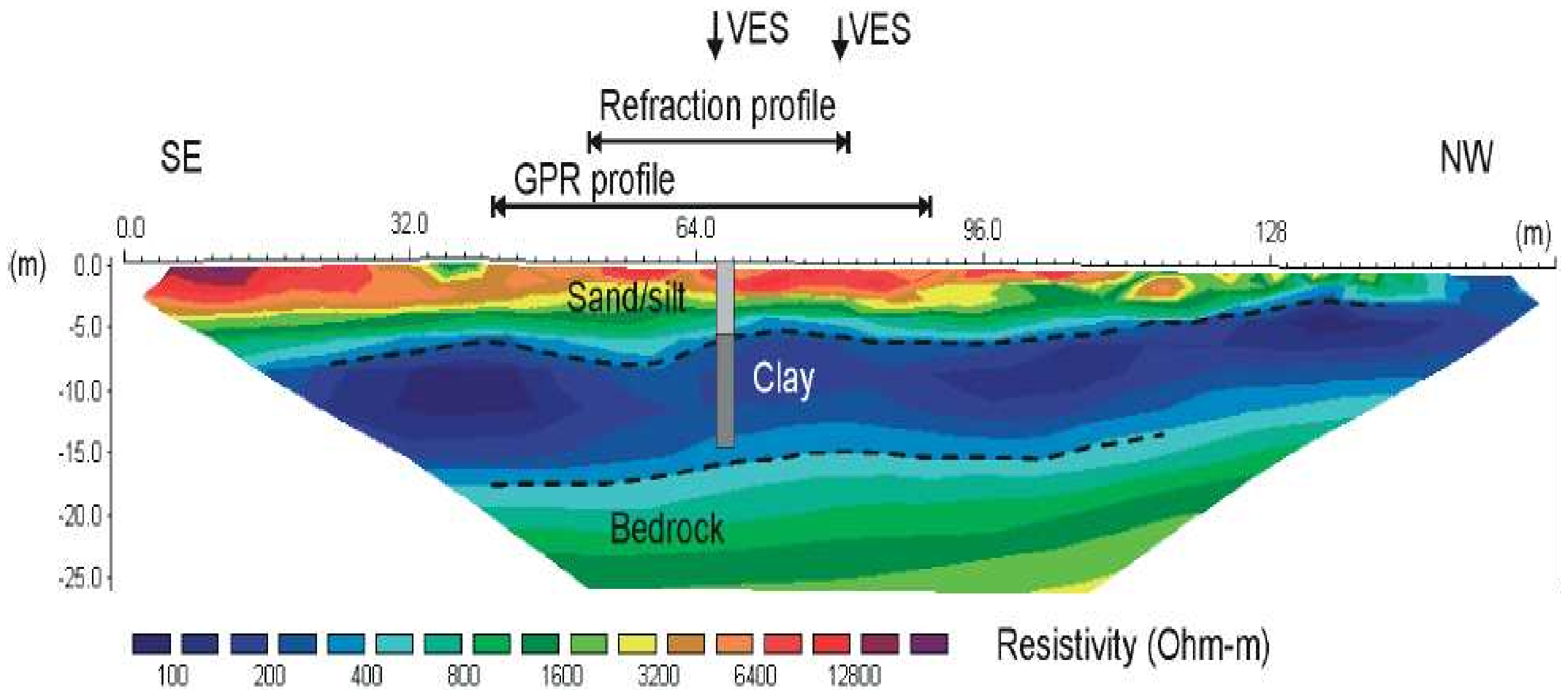




Dobecki and Upchurch, 2006

Identification of stratigraphic sequence / local litography

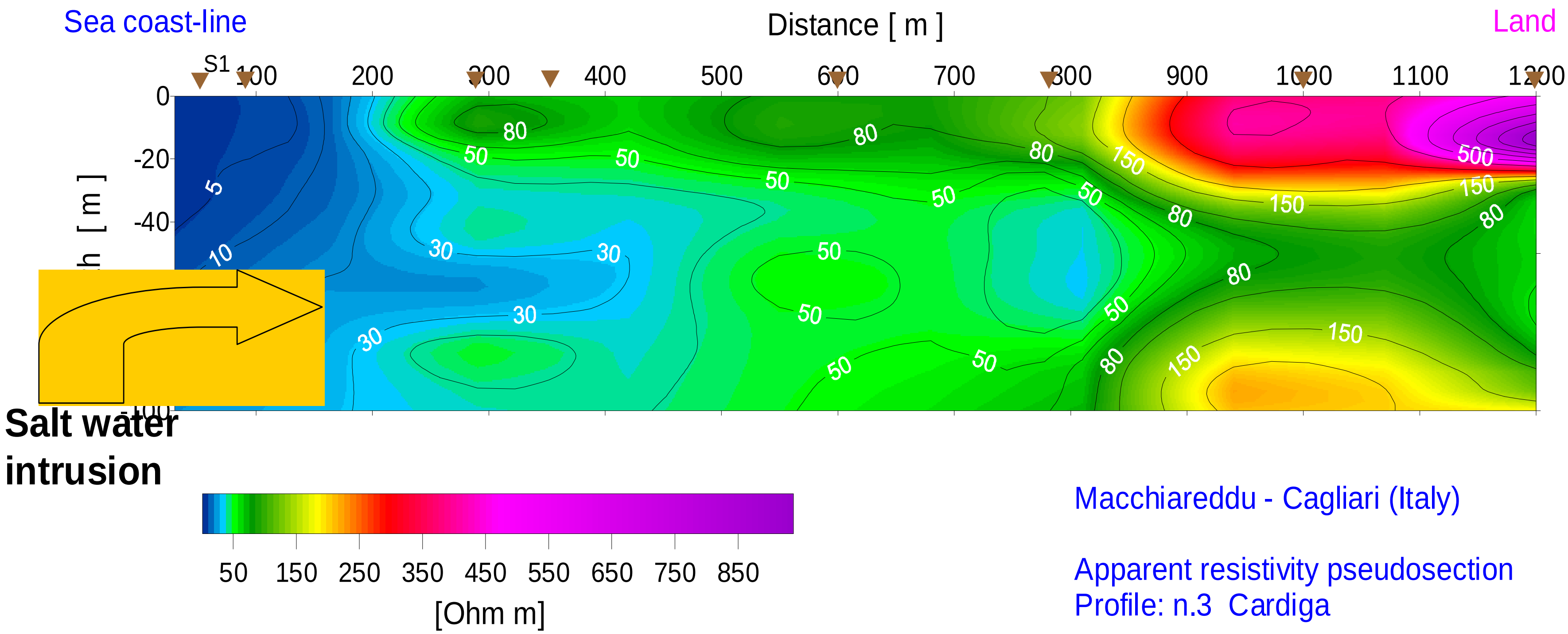
Non-seismic methods: e.g. electrical methods to identify clays below sands



Turesson and Lind, 2005

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

Hydro - geophysics



2D rendering of time domain EM vertical 1D profiles for salt water intrusion in coastal aquifer.

Courtesy of Alberto Godio

Pollutants and waste detection

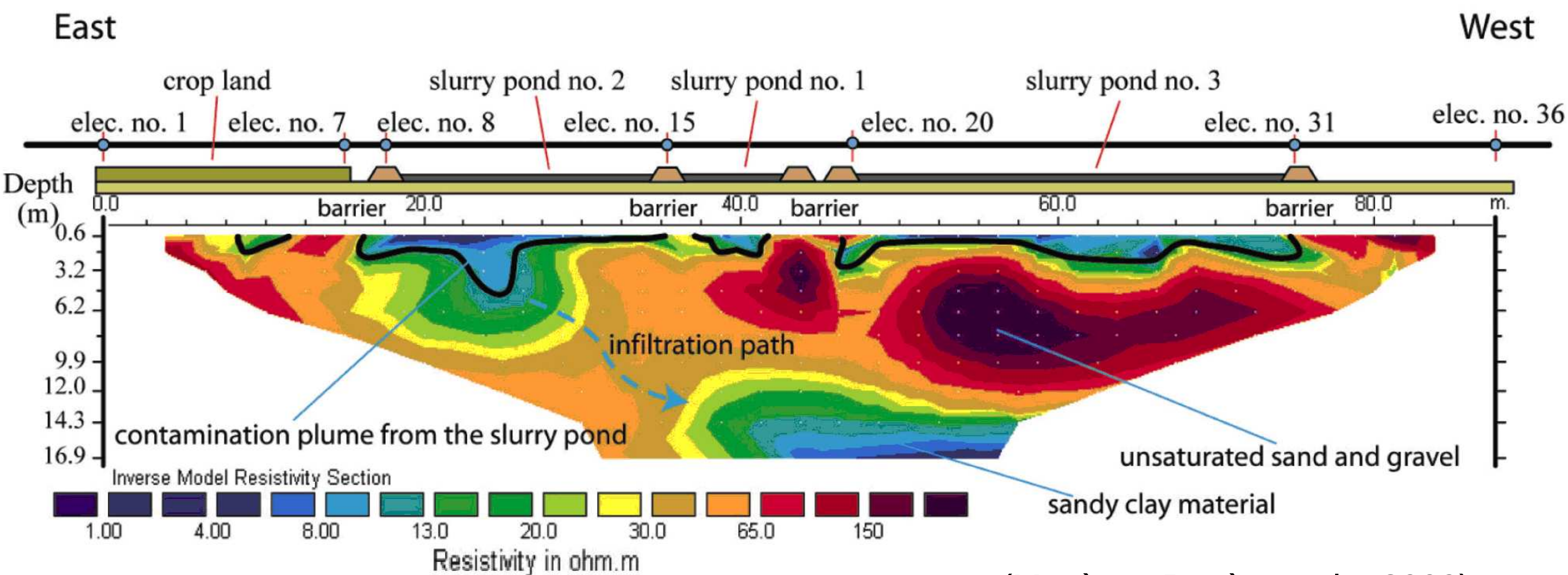
Courtesy of Valentina Socco

Pollutants and waste detection

Courtesy of Valentina Socco

Hydrogeological / environmental applications

Electrical Resistivity Tomography (ERT)

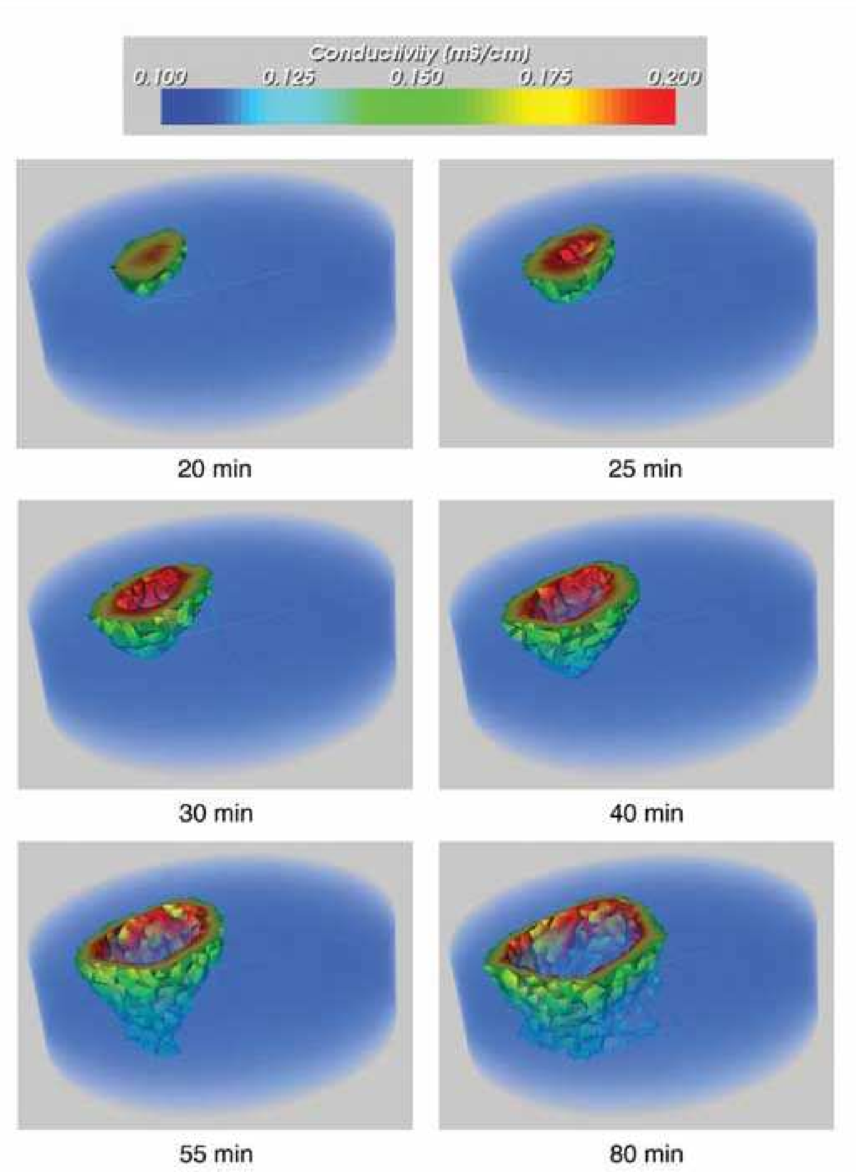


(Martìnez-Pagàn et al., 2009)

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).

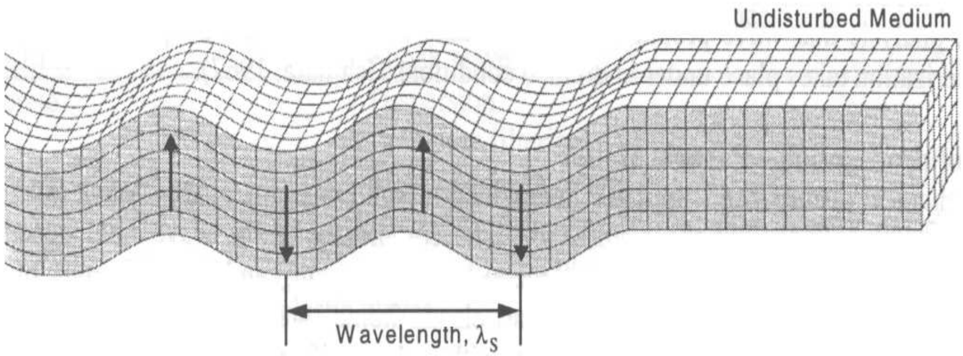
Geotechnical and geoenvironmental site characterization

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

- 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.

Seismic methods

Shear wave propagation

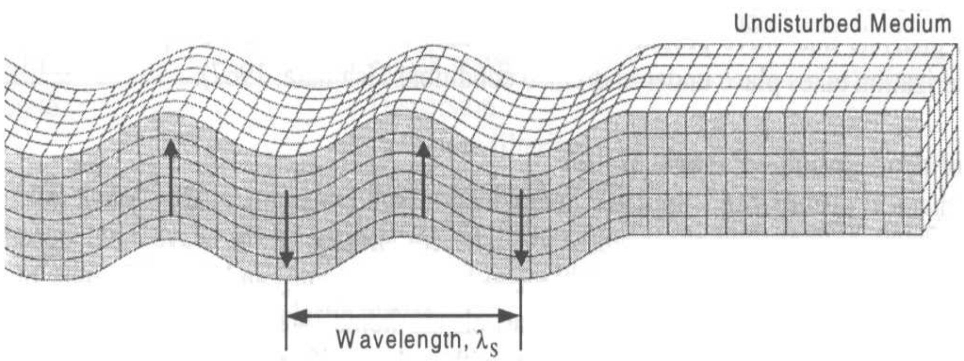


In a linear elastic medium

$$G = \rho V_S^2$$

Seismic methods

Shear wave propagation

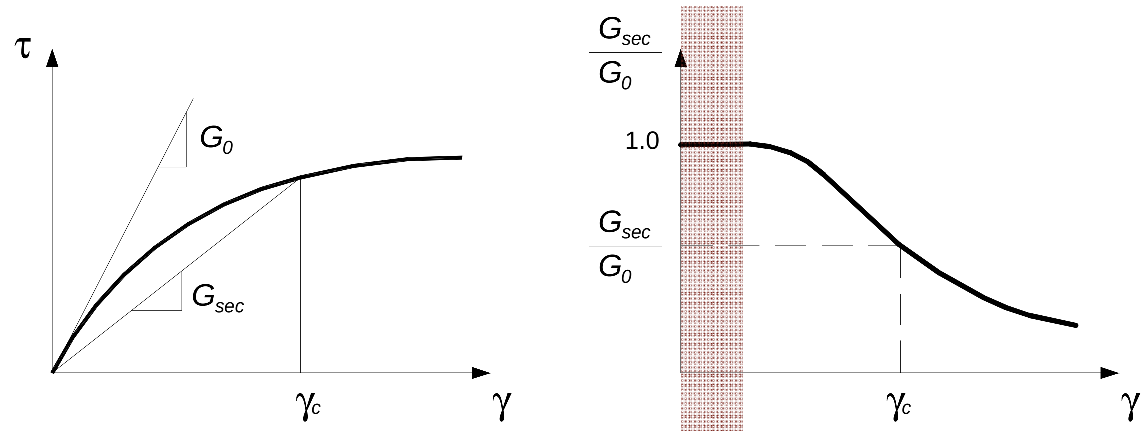


In a linear elastic medium

$$G = \rho V_S^2$$

In soils

$$G_0 = \rho V_S^2$$

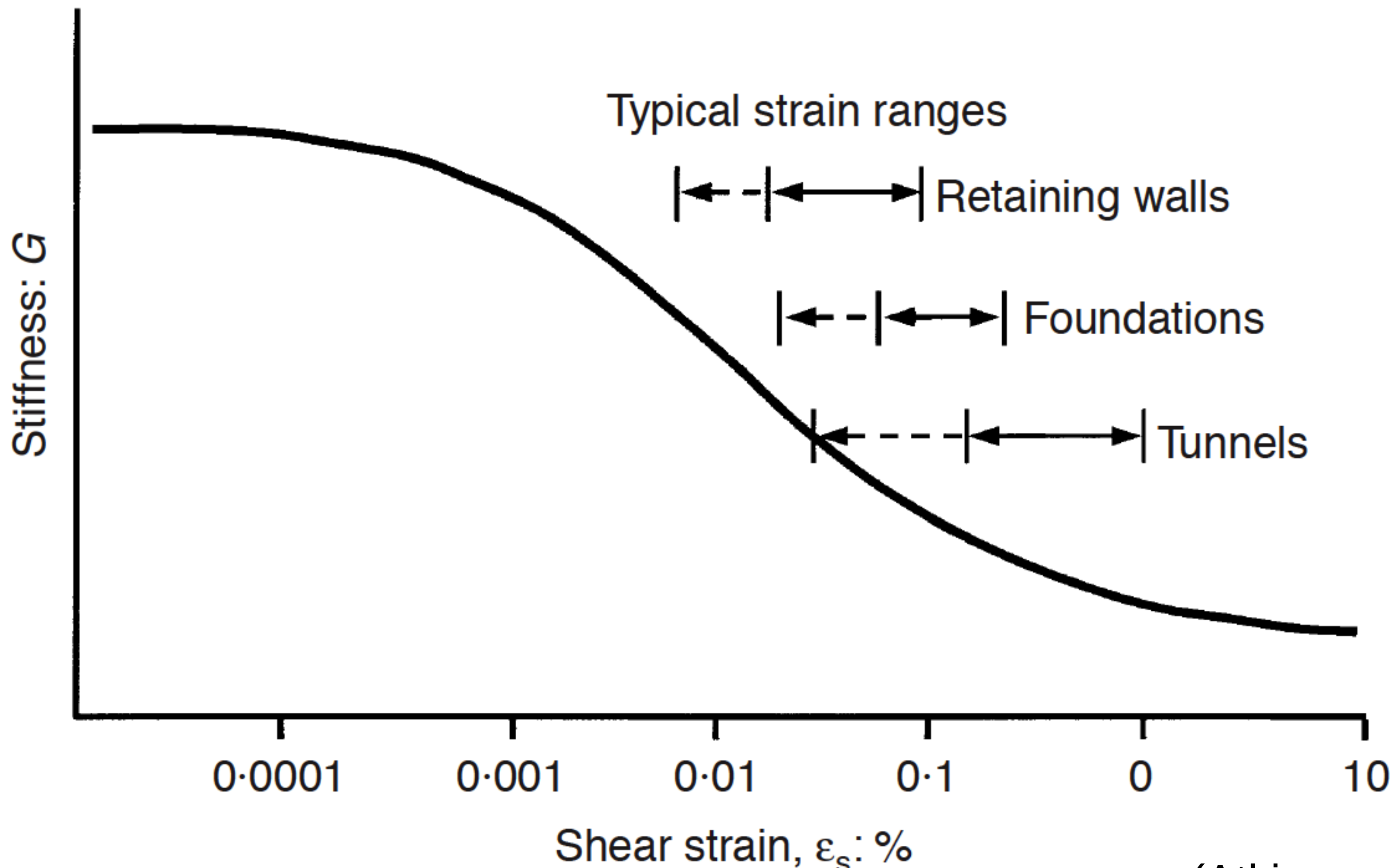


Strain range of geophysical test

Role of G0 in geotechnical engineering

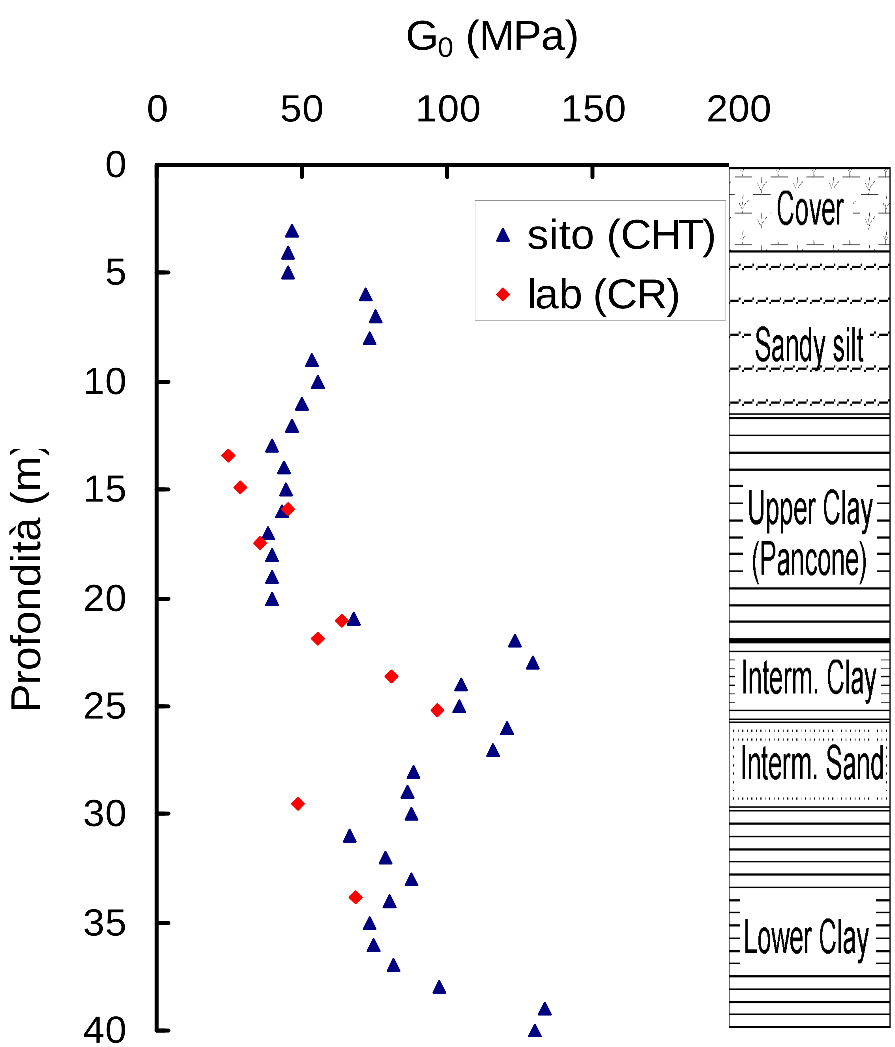
- Evaluation of seismic site response
- Foundation vibrations
- Dynamic soil structure interaction
- Vibrations (e.g. railroads, industrial activities, …)
- Liquefaction suscettivity assessment
- Monitoring of ground improvement projects
- Correlation to operative values of G at medium strains
- Numerical simulations with advanced constitutive laws
- Evaluation of disturbance of soil samples

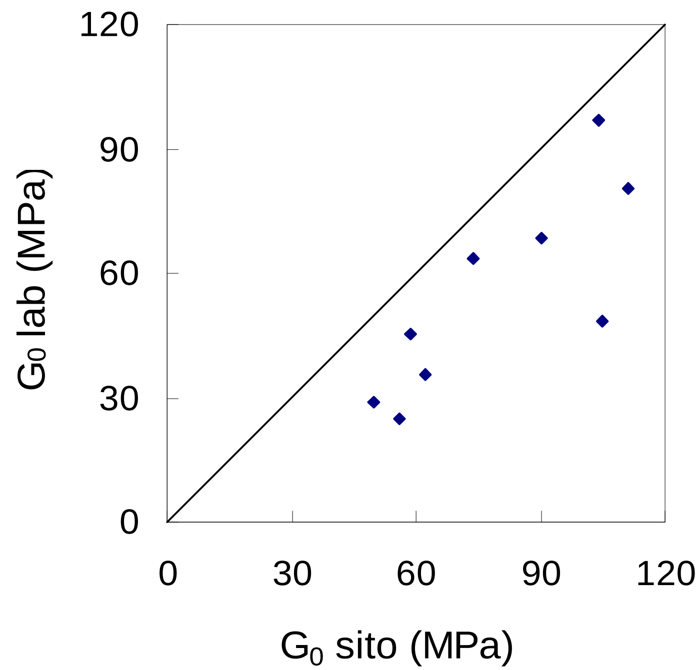
Typical strain ranges for geotechnical problems



(Atkinson, 2000)

Site vs Lab (Pisa)

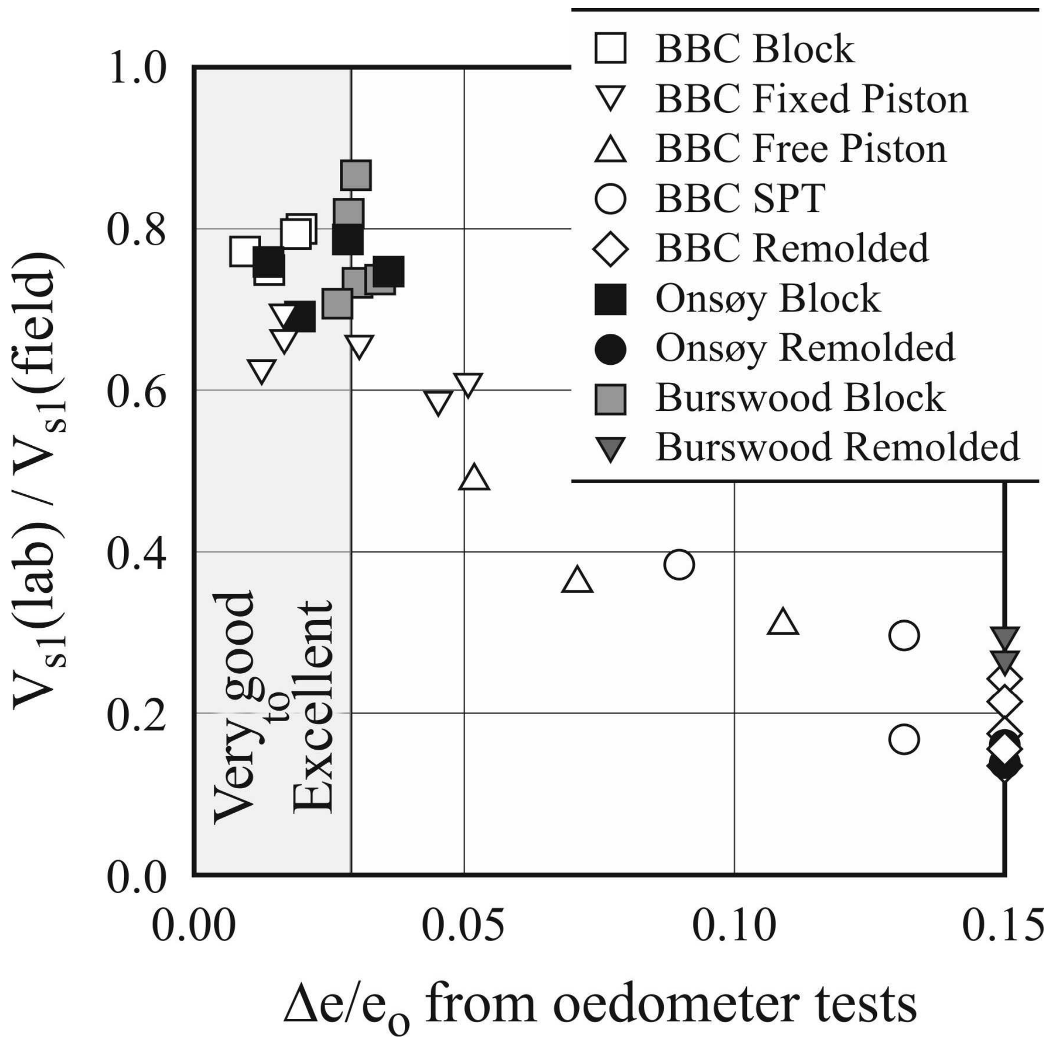




$$G_0 = \rho V_S^2$$

(Cross-Hole Test)

Assessment of sample quality



The ratio
V_S(lab) / V_S(field)
Gives an indication of sample quality

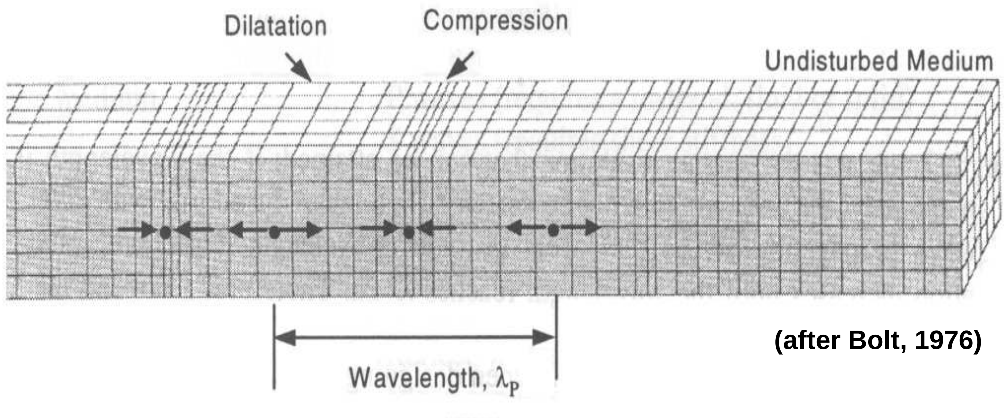
it can be used also for coarse grained soils

DeGroot et al (2011).

Body Waves

Compressional wave

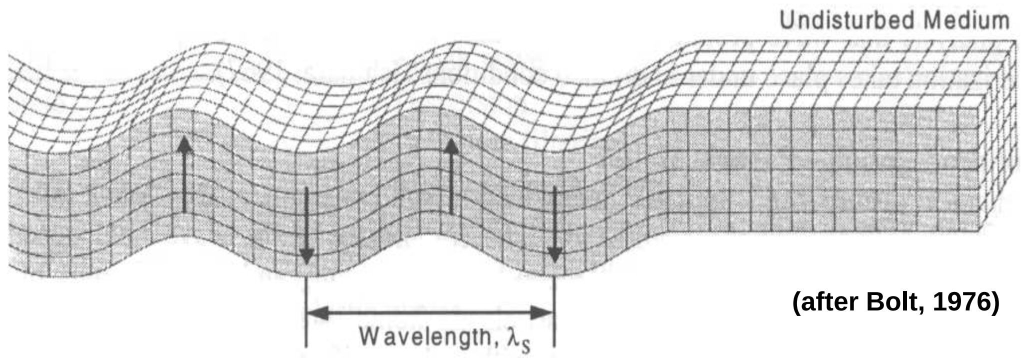
$$V_P = \sqrt{\frac{M}{\rho}}$$



(after Bolt, 1976)

Shear wave

$$V_S = \sqrt{\frac{G}{\rho}}$$



(after Bolt, 1976)

Vertically polarized SV
or
Horizontally polarized SH

Direction of Propagation

In a linear elastic isotropic homogeneous medium

$$V_P = \sqrt{\frac{M}{\rho}}$$

$$V_S = \sqrt{\frac{G}{\rho}}$$

V_S: shear wave velocity

V_P: dilational wave velocity

ρ: density

G: shear modulus

M: laterally constrained modulus

(oedometric conditions)

Note: In saturated soils V_P is strongly influenced by the compressibility of the pore fluid (water)

Biot Theory

Macroscopic approach: the medium is modeled as a binary continuum arising from the superposition of a fluid and a solid phase occupying simultaneously the same regions of space. The porosity is the link between the two.

Hypothesis:

- isotropic, linear elastic soil skeleton
- a non-dissipative compressible fluid saturates all voids
- no relative motion between the solid and the fluid phases (valid for low frequency range)

Writing the equations of motion for the porous media and applying the Helmholtz decomposition, it is possible to show the existence of two different compressional waves and of a unique shear waves.
The fastest compressional wave is called of the first kind or P-wave, the slowest is called of the second kind or Biot wave.

Biot solution

Under the hypothesis of grain incompressibility, the velocity of propagation of body waves in porous media can be written as:

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

$$V_S = \sqrt{\frac{G}{\rho}}$$

$$where \quad \rho = (1-n)\cdot\rho^S + n\cdot\rho^F$$

ρ^S grain density

ρ^F water density

K^F water bulk modulus

K^{SK} soil skeleton bulk modulus

G shear modulus

n porosity

ν^{SK} Poisson ratio of the (evacuated) soil skeleton

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

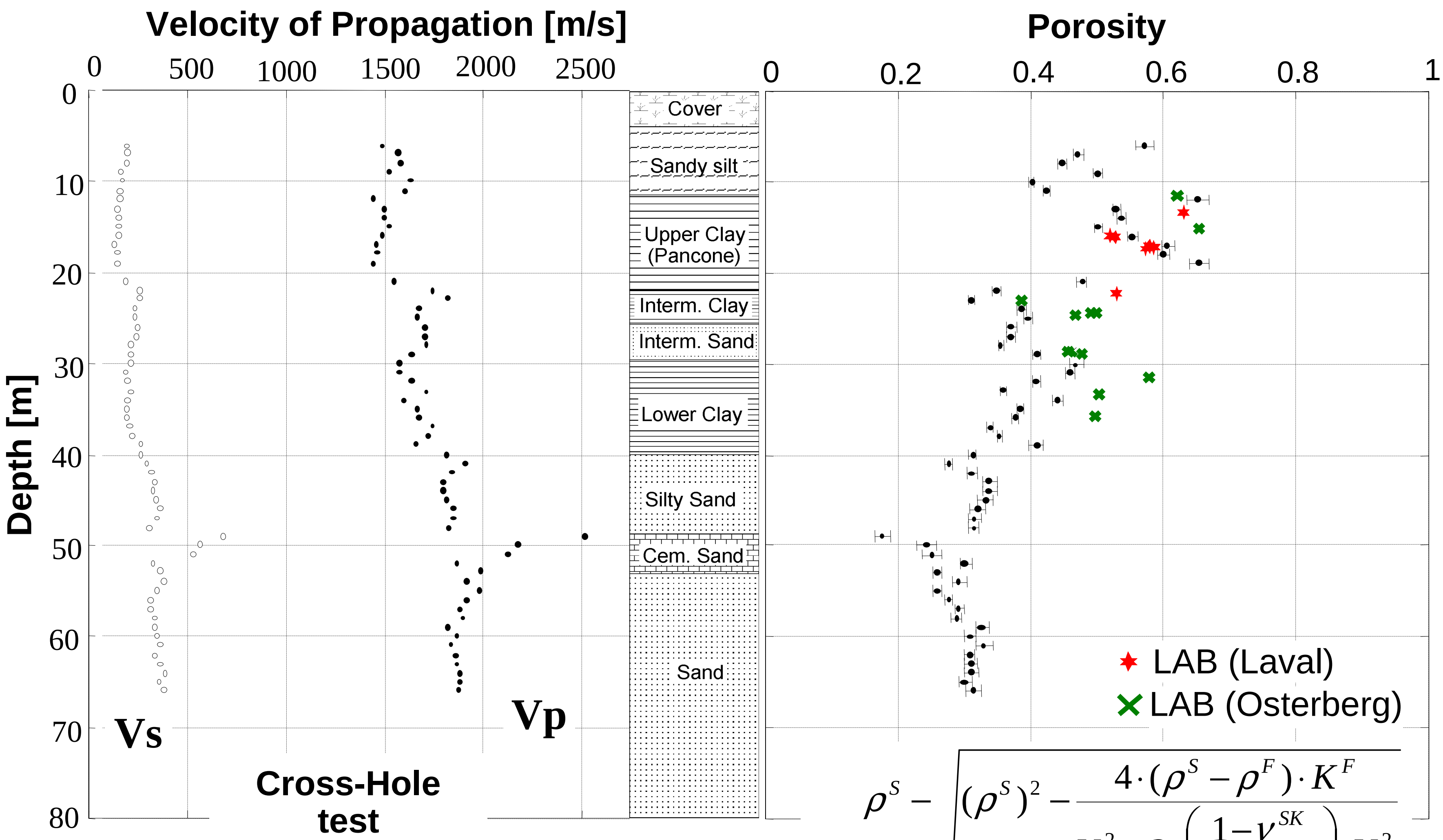
ρ^S, ρ^F, K^F: standard values

V_P & V_S: measured

ν^{SK} : range 0.1÷0.4

Soil porosity from seismic velocities

Leaning Tower of Pisa site

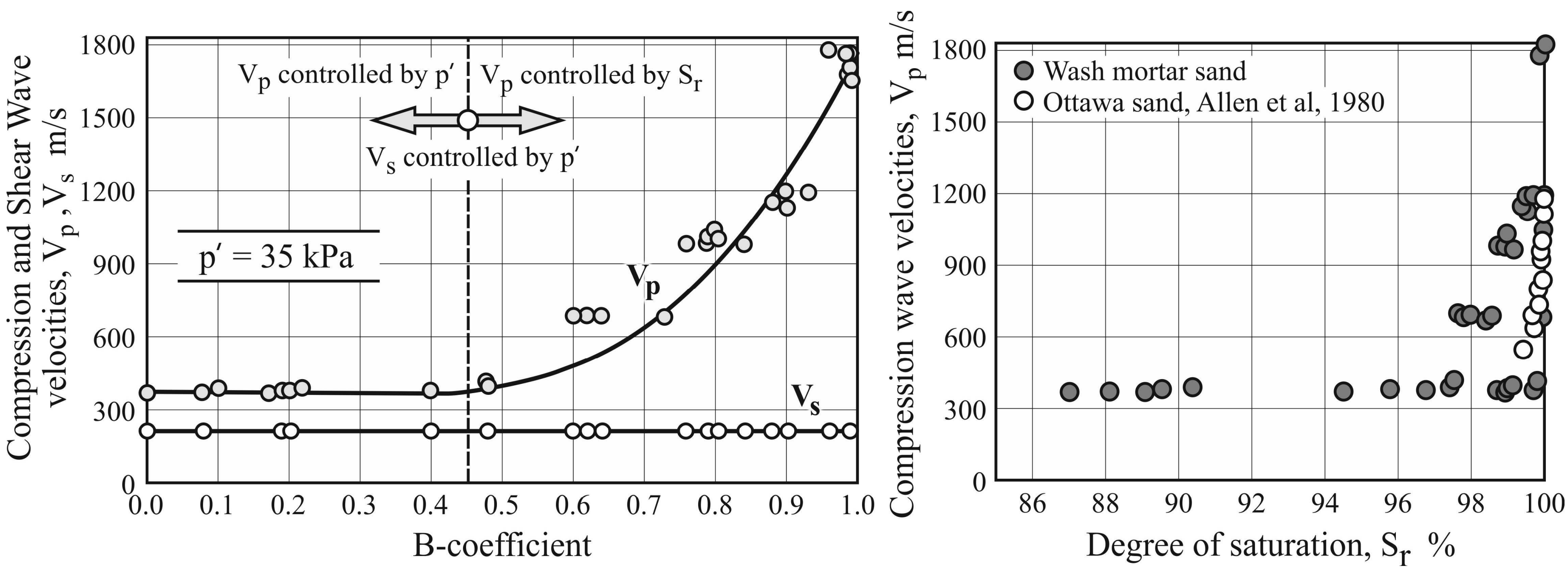


$$n = \frac{\rho^S - \sqrt{(\rho^S)^2 - \dfrac{4\cdot(\rho^S-\rho^F)\cdot K^F}{V_P^2 - 2\cdot\left(\dfrac{1-\nu^{SK}}{1-2\nu^{SK}}\right)\cdot V_S^2}}}{2\cdot(\rho^S-\rho^F)}$$

(Foti et al., 2002)

Degree of saturation

Also very limited desaturation has a strong effect on the V_P

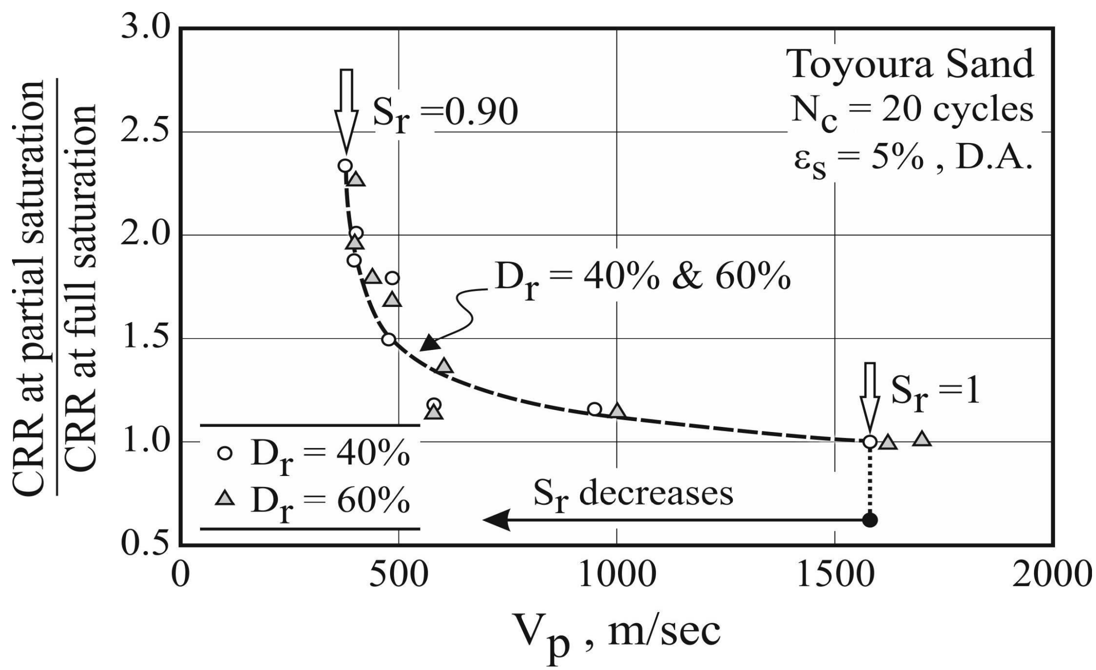


Valle-Molina (2006)

Influence of degree of salutarion on liquefaction resistance

saturation degree strongly affect liquefaction resistance

→ V_P can be used to monitor saturation and esclude liquefaction

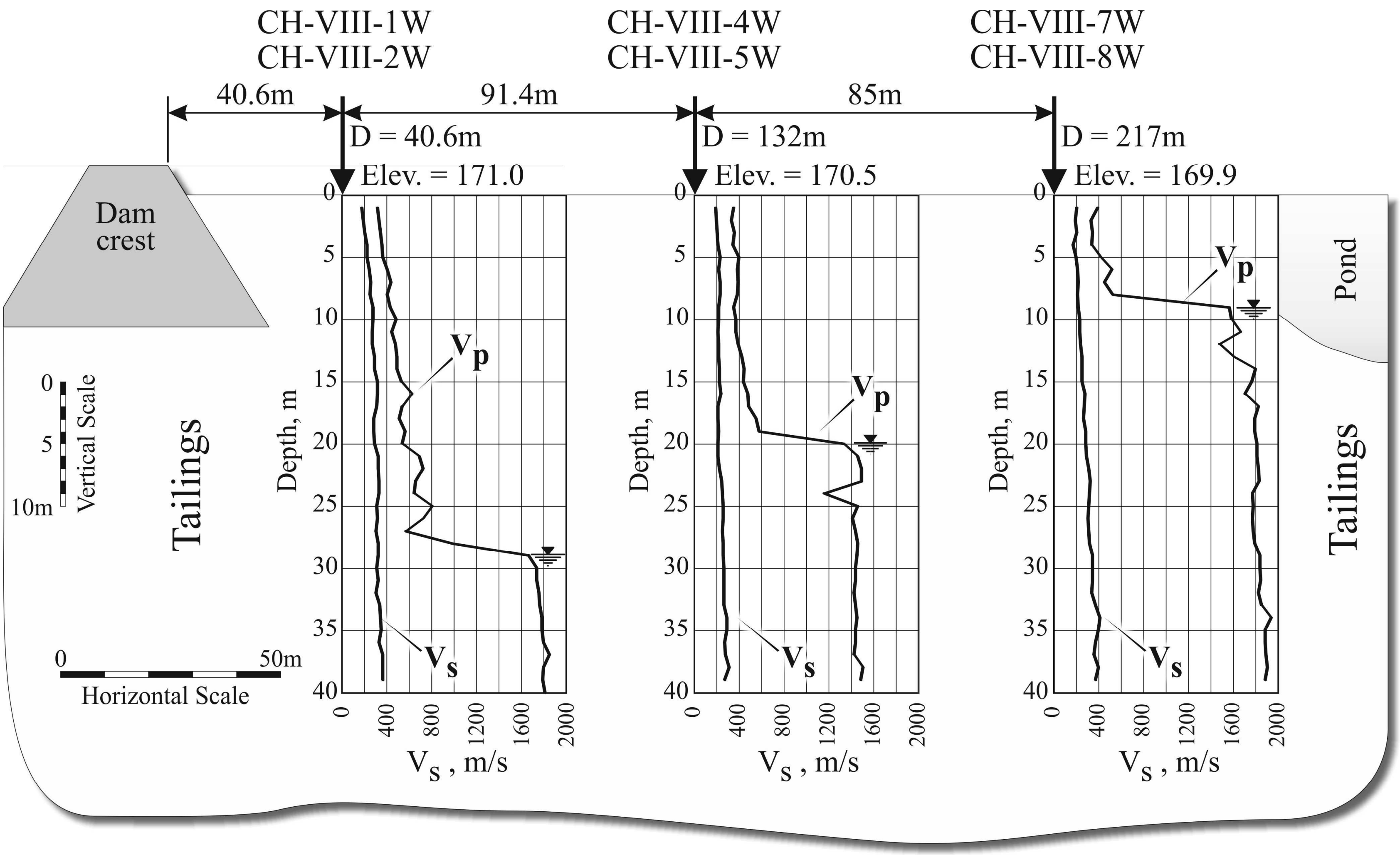


Tsukamoto et al (2006)

Example: Zelasny Most tailing dam

West dam

Jamiolkowski, 2012



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);
- mineralogy and specific surface of the solid grains;
- porosity and fabric

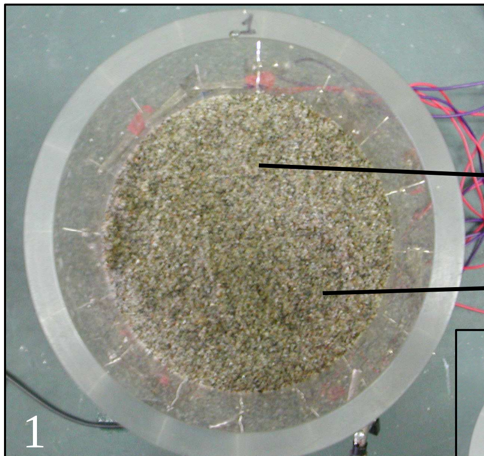
σ_w : pore fluid conductivity

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

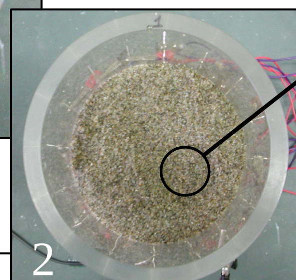
Polito – 2D ERT (Borsic et al., 2005)

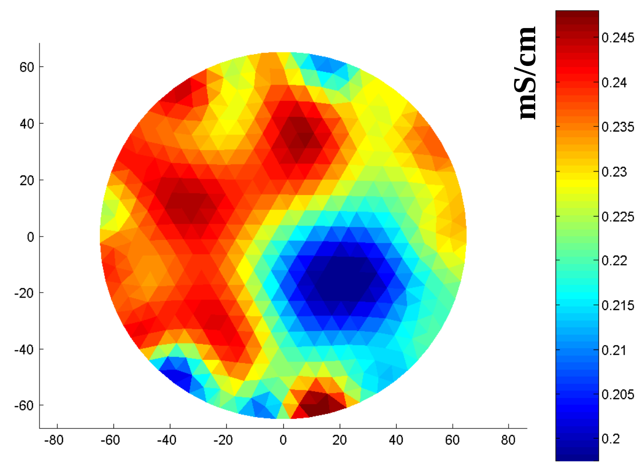
Identification of zones with different compaction levels in sand



Coarse Matrix
n ≈ **0.48**

Dense Inclusion
n ≈ **0.43**





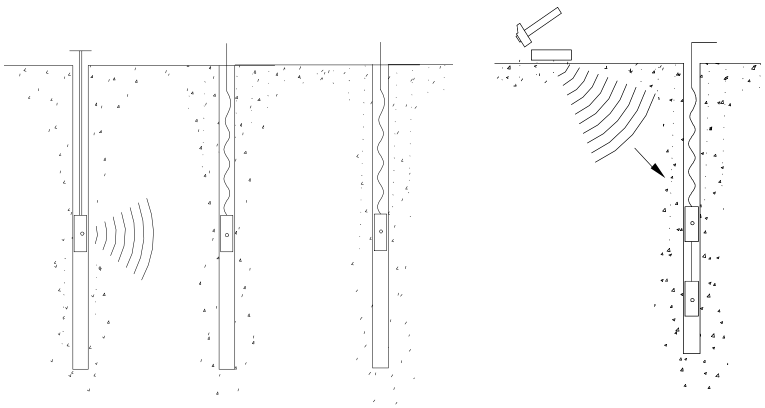
3. Tomographic reconstruction

Estimated values with Bruggeman equation

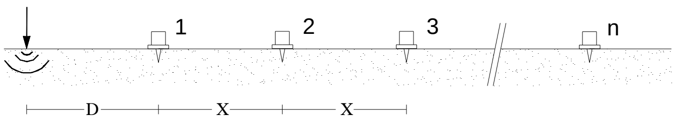
Matrix n ≈ **0.46**

Inclusion n ≈ **0.42**

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



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

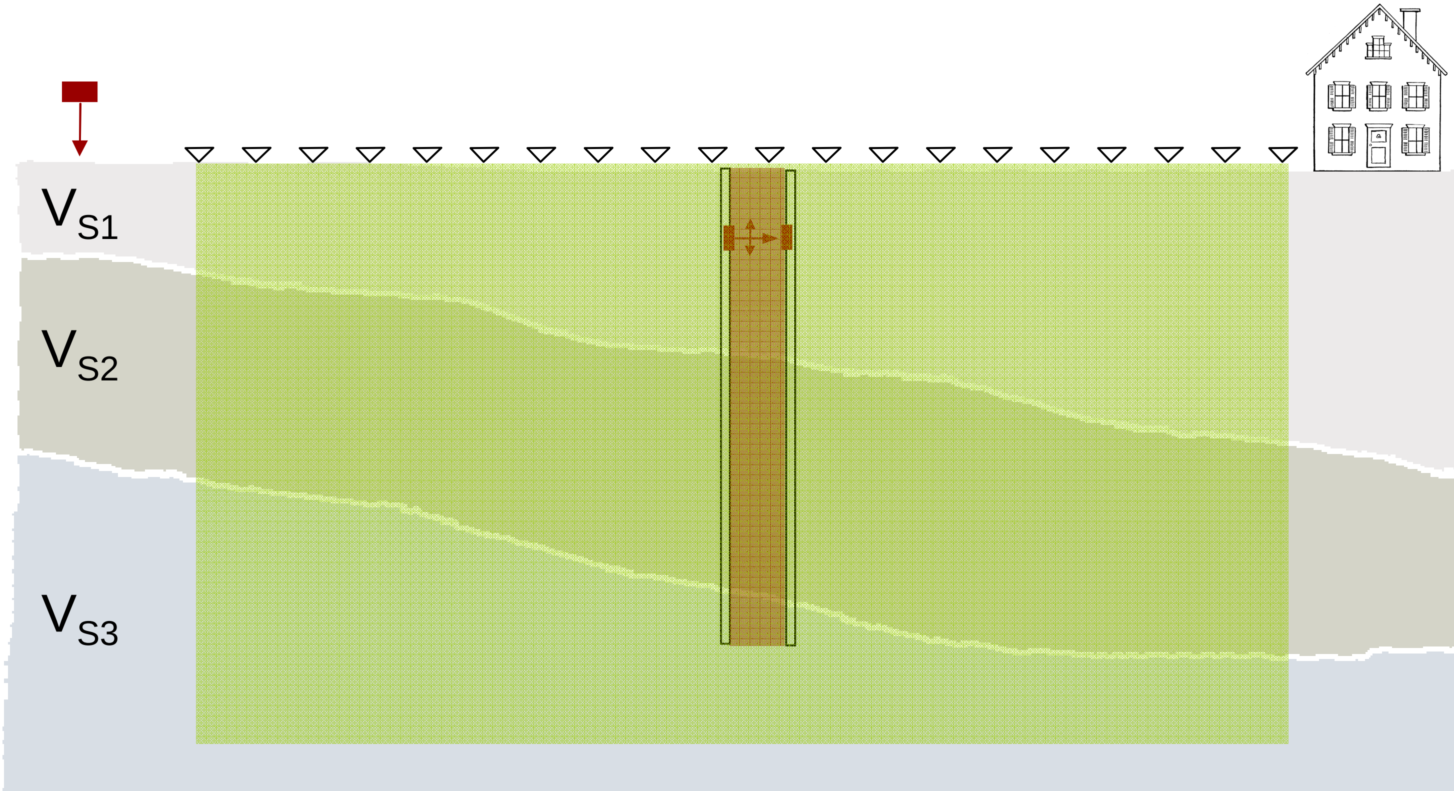


Surface Waves Methods SWM
(SASW, MASW, microtremors)
Seismic Refraction
(P-waves or SH-waves)
Seismic Reflection
(P-waves or SH-waves)

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

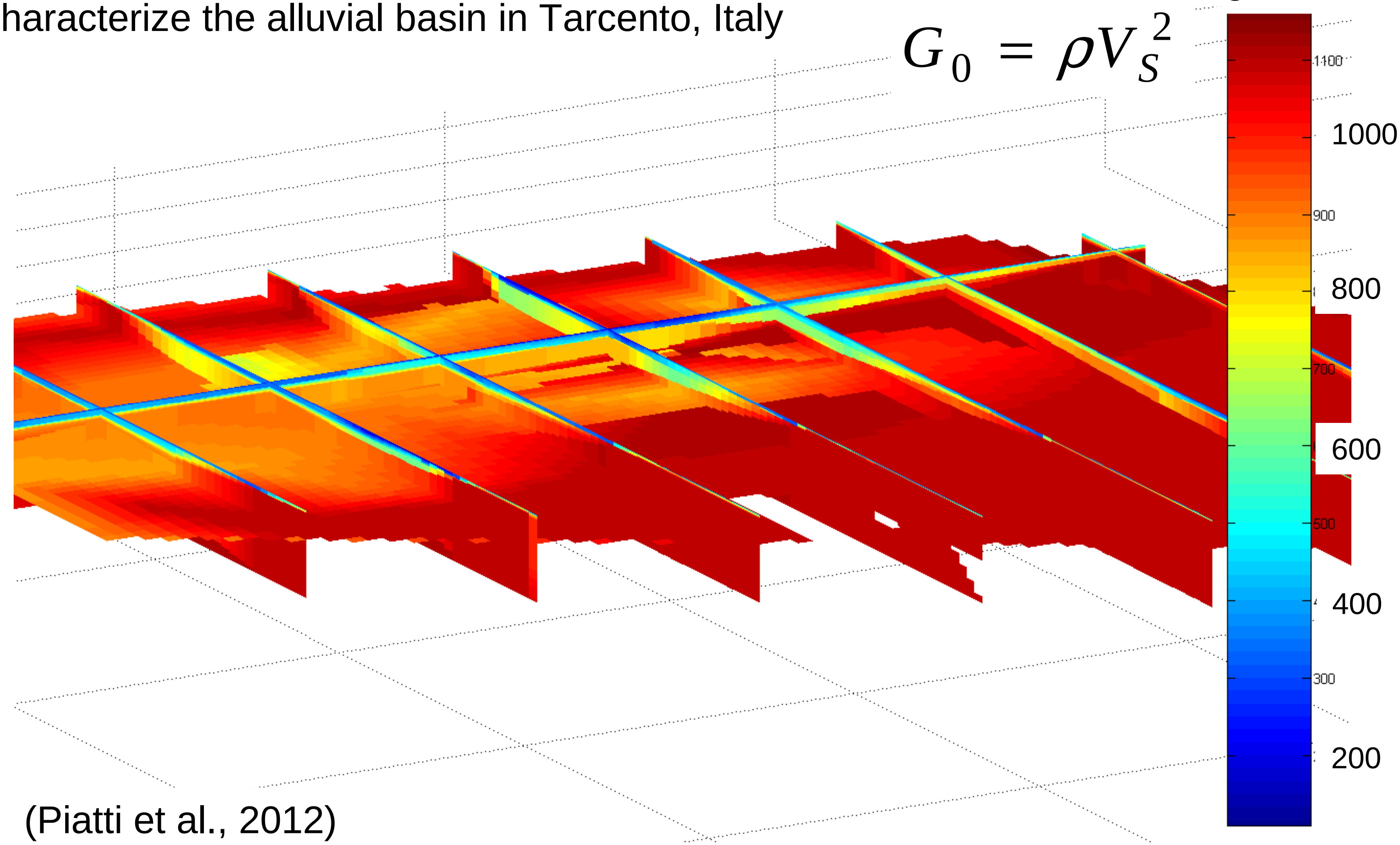
In-hole vs surface methods



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)

Flexibility of Surface Methods

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

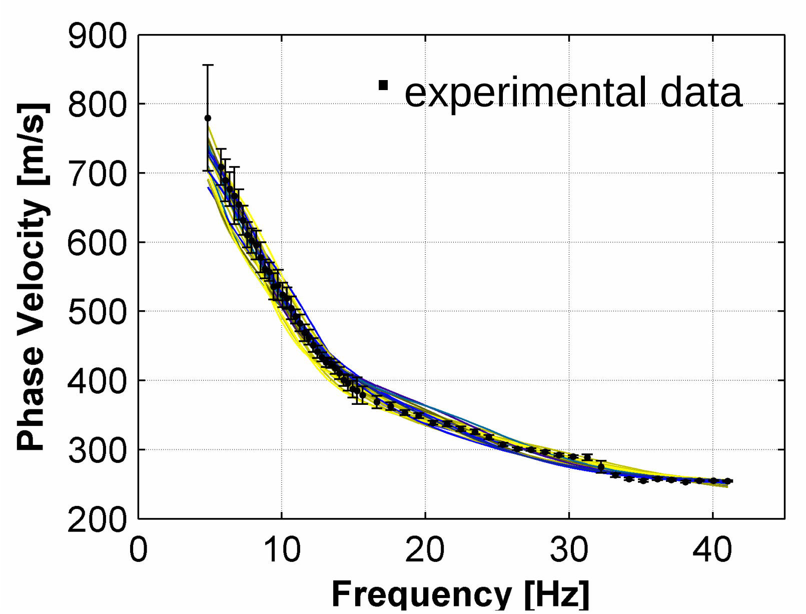
(solution of the inverse problem)

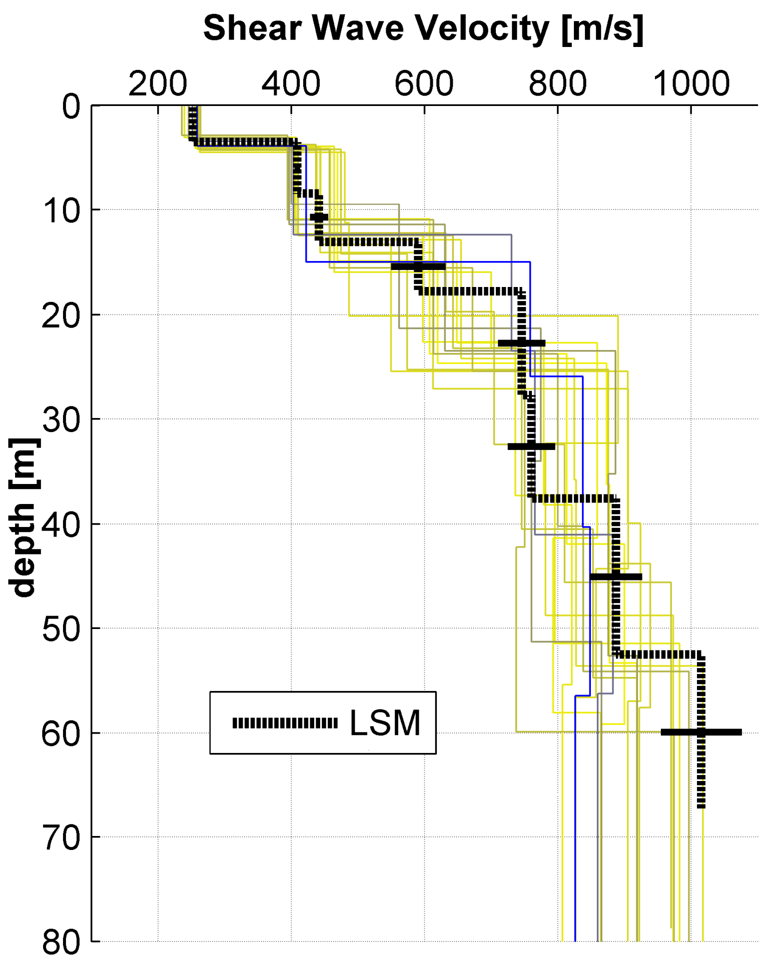
Solution non-uniqueness

(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)

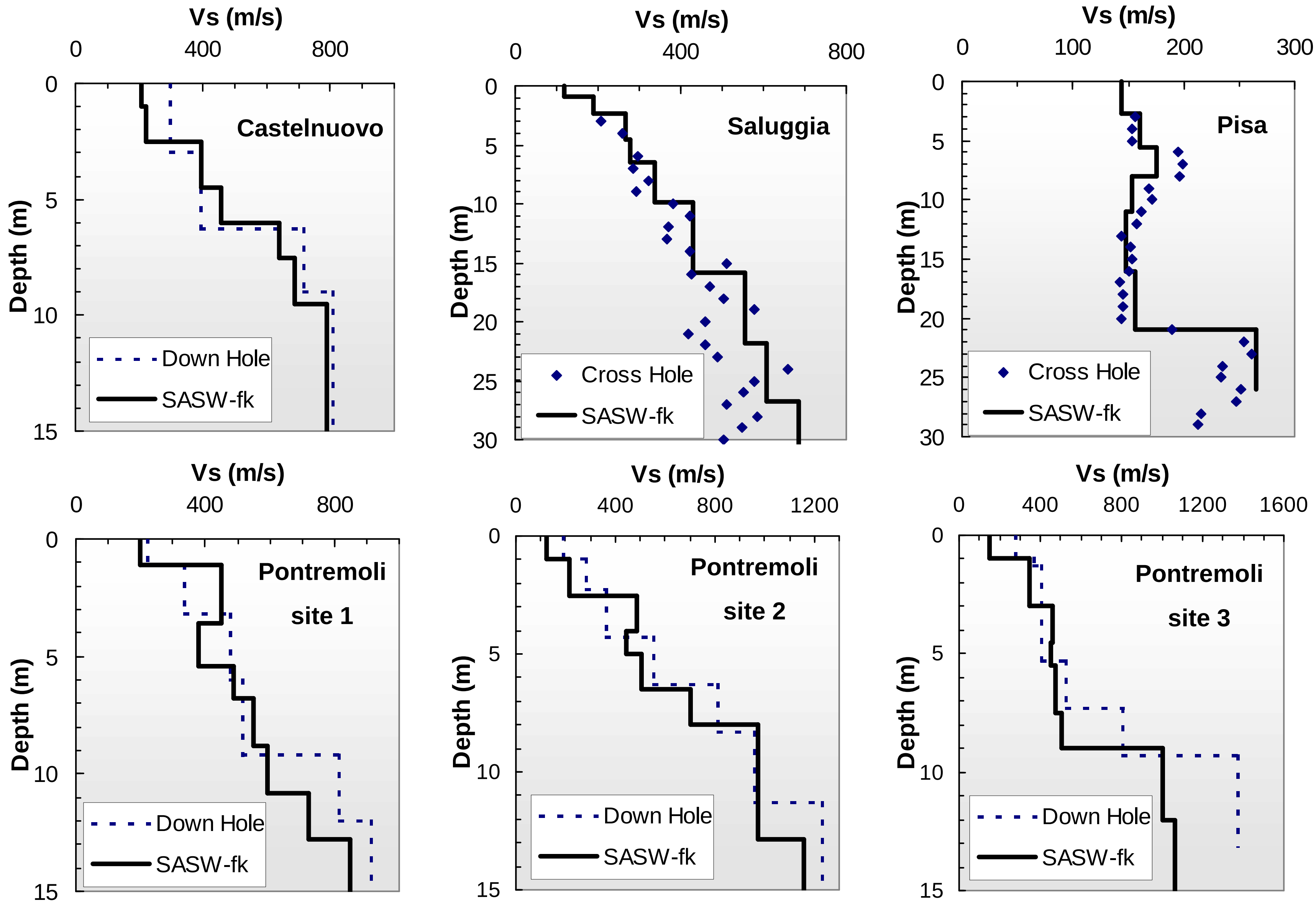
Additional information can help in constraining the solution

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



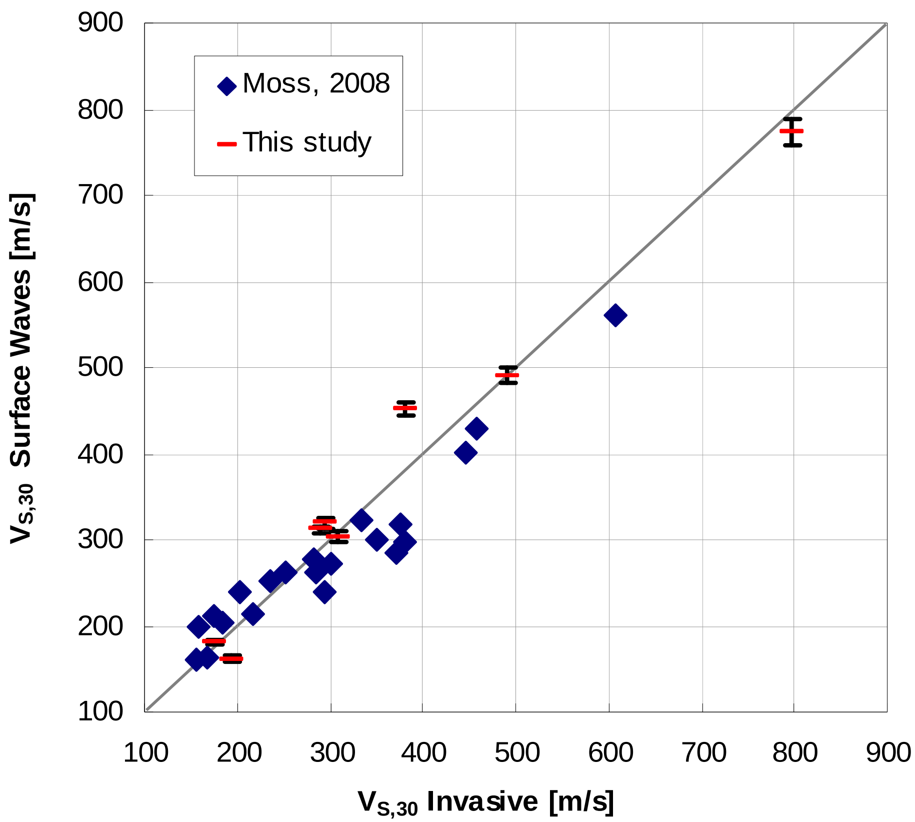
Level 1: SASW vs Invasive Methods

UBC – EC8

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

EC8
Seismic subsoil classification

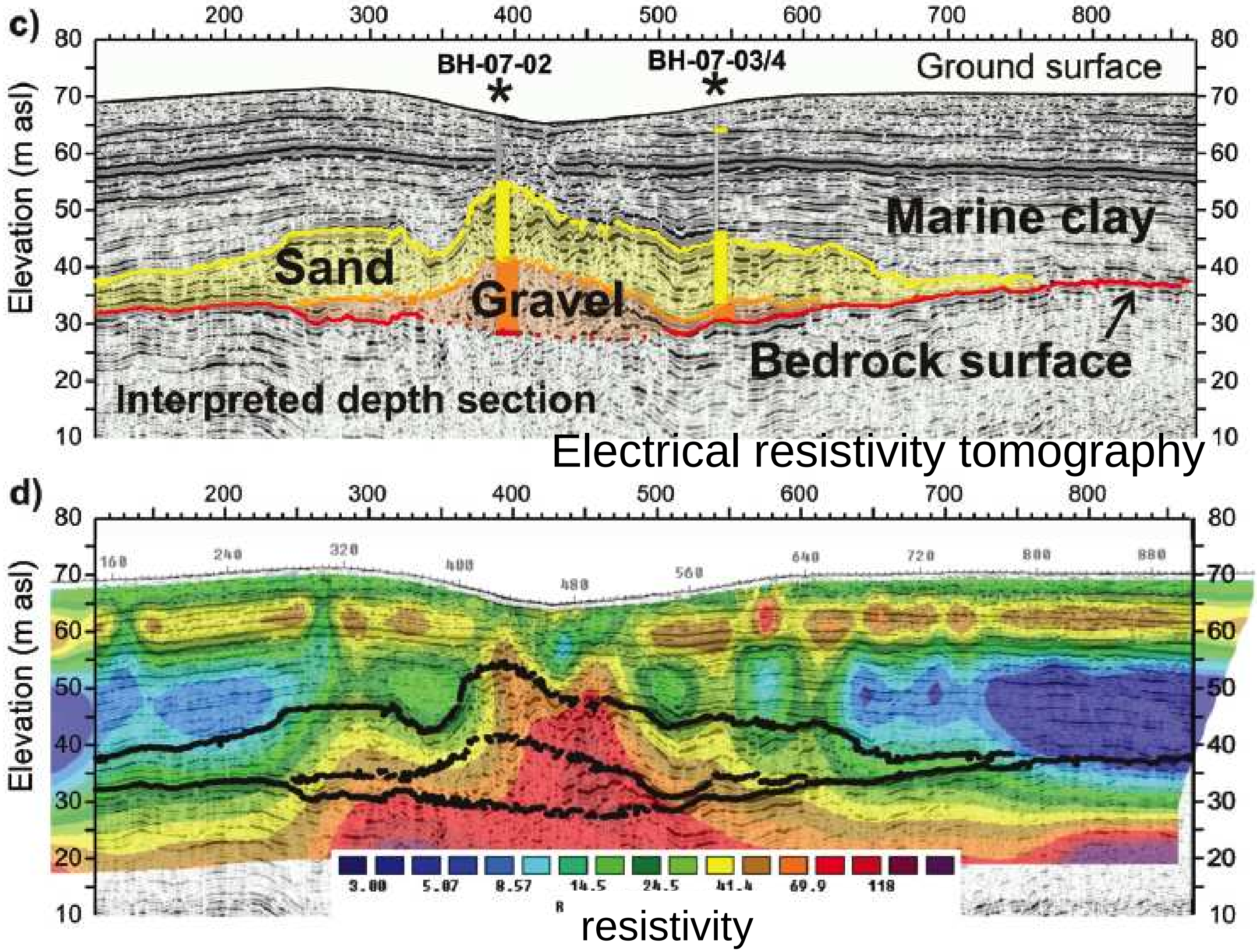
Soil class	$V_{s,30}$
A	> 800
B	360 - 800
C	180 - 360
D	< 180
E (C, D su A)	



(Comina et al., 2011)

Level 2: Data integration and data fusion

SH-wave seismic reflection



Pugin et al., 2009

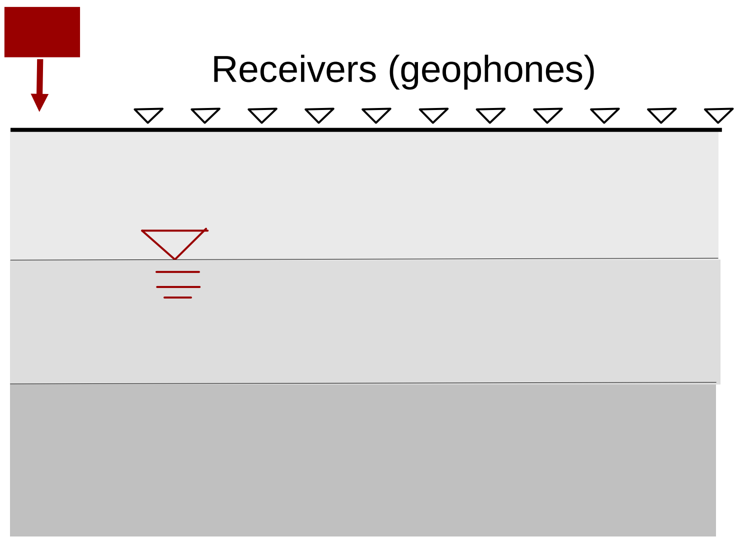
Combined use

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

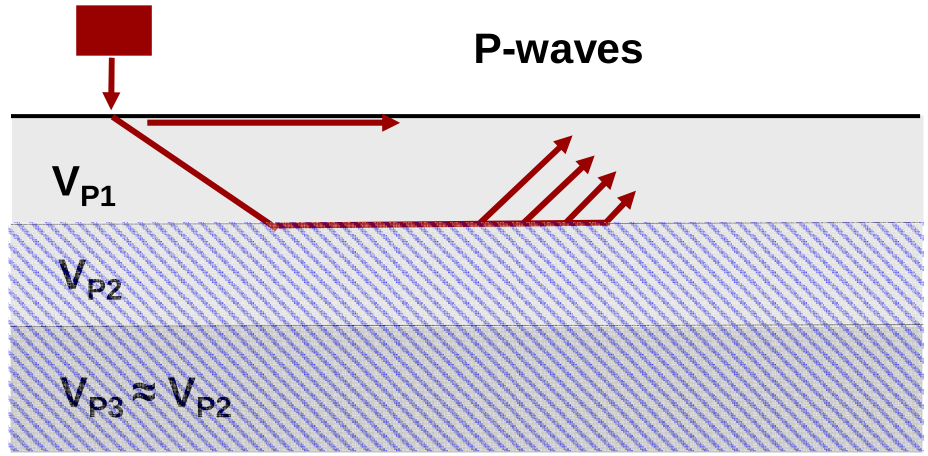
} Example: synergies of seismic refraction and surface wave analysis (SWM)

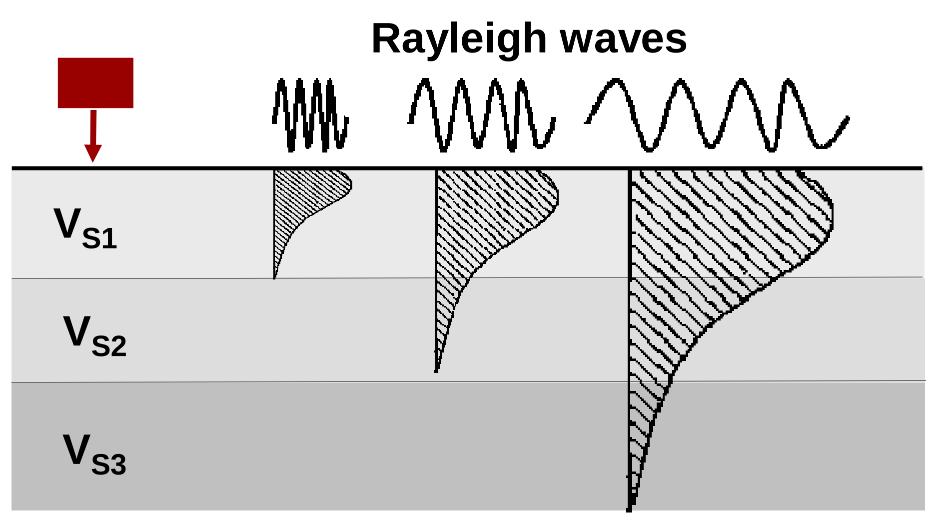
Example of synergy: SW + V_P refraction

Same testing setup and equipment

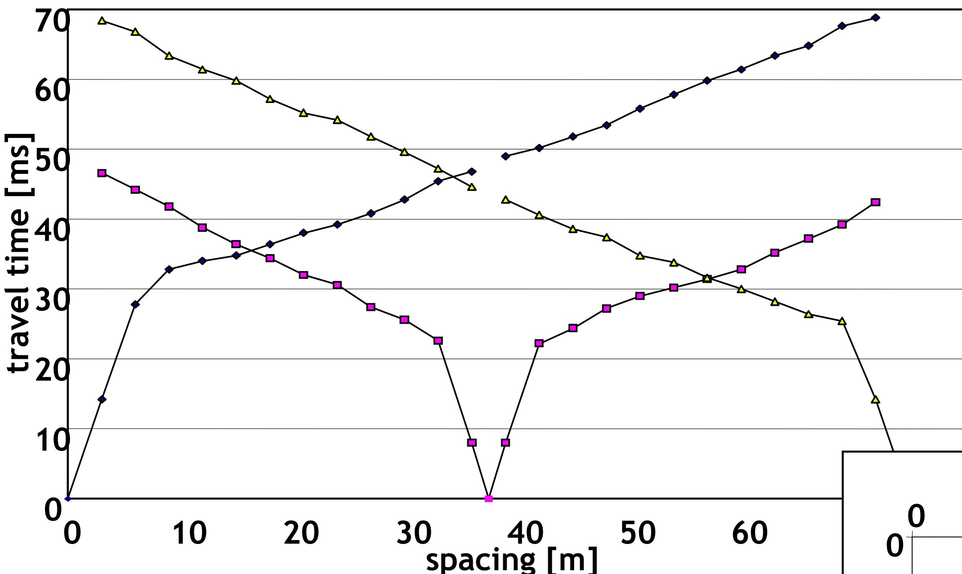


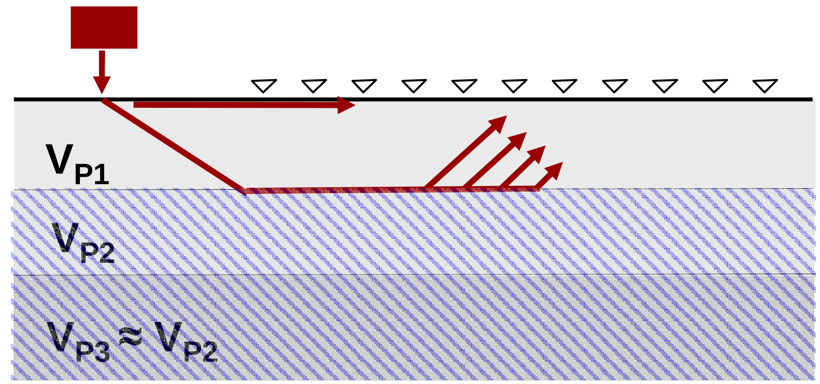
Experimental data contain both surface waves and direct/refracted P waves





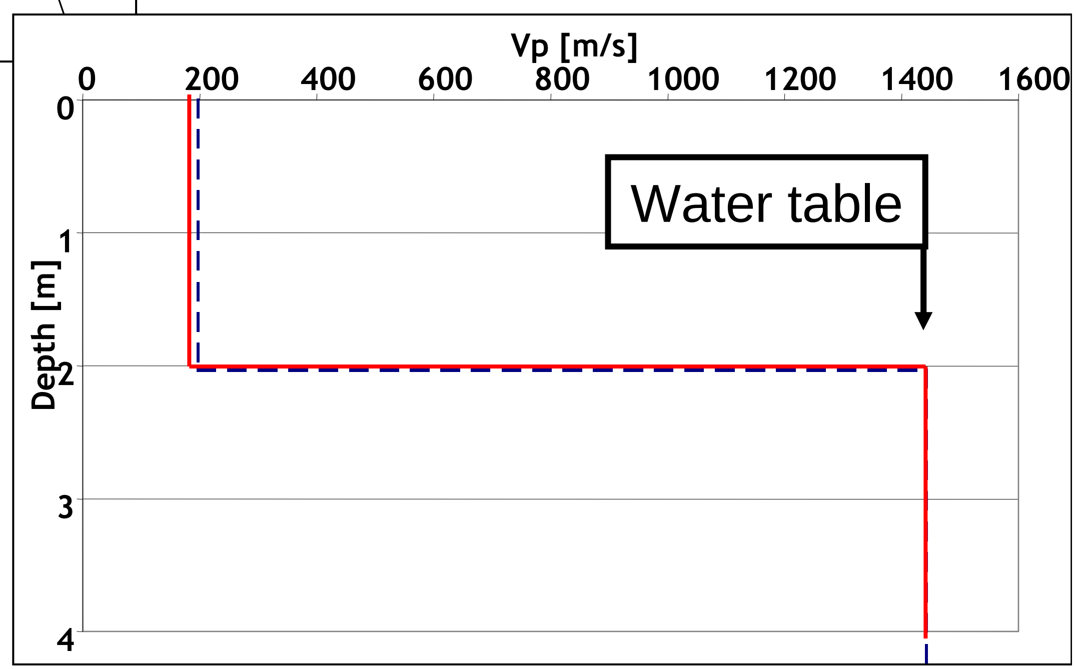
P-WAVE REFRACTION



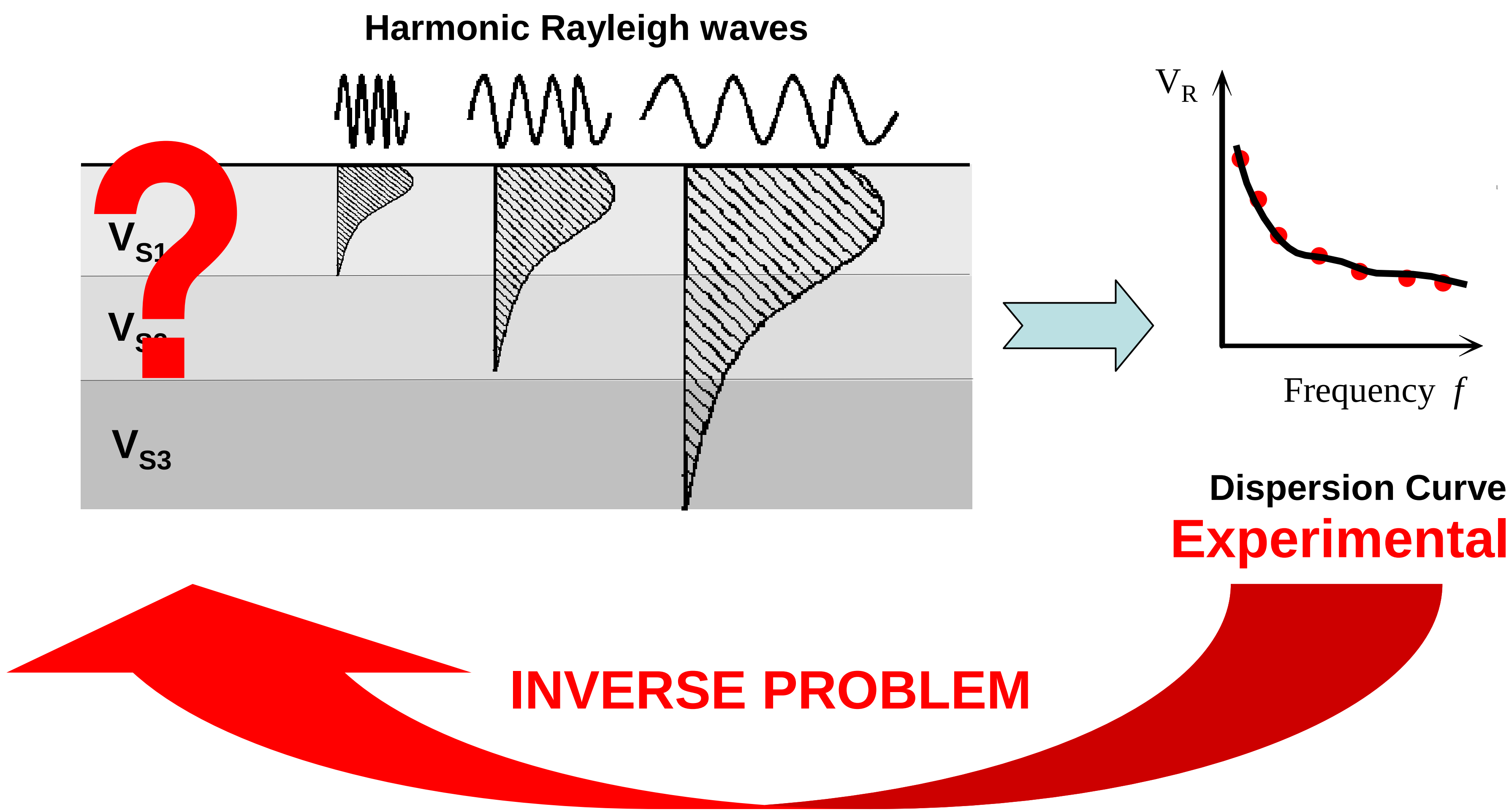


$$V_P = \sqrt{\frac{(K^{SK} + \frac{4}{3} \cdot G) + \frac{K^F}{n}}{(1-n) \cdot \rho^S + n \cdot \rho^F}}$$

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



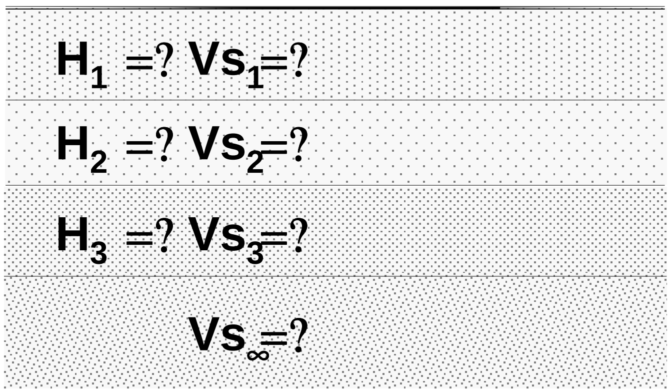
SWM concept


Harmonic Rayleigh waves
V_{S1}
V_{S2}
V_{S3}
V_R
Frequency f
Dispersion Curve
Experimental
INVERSE PROBLEM

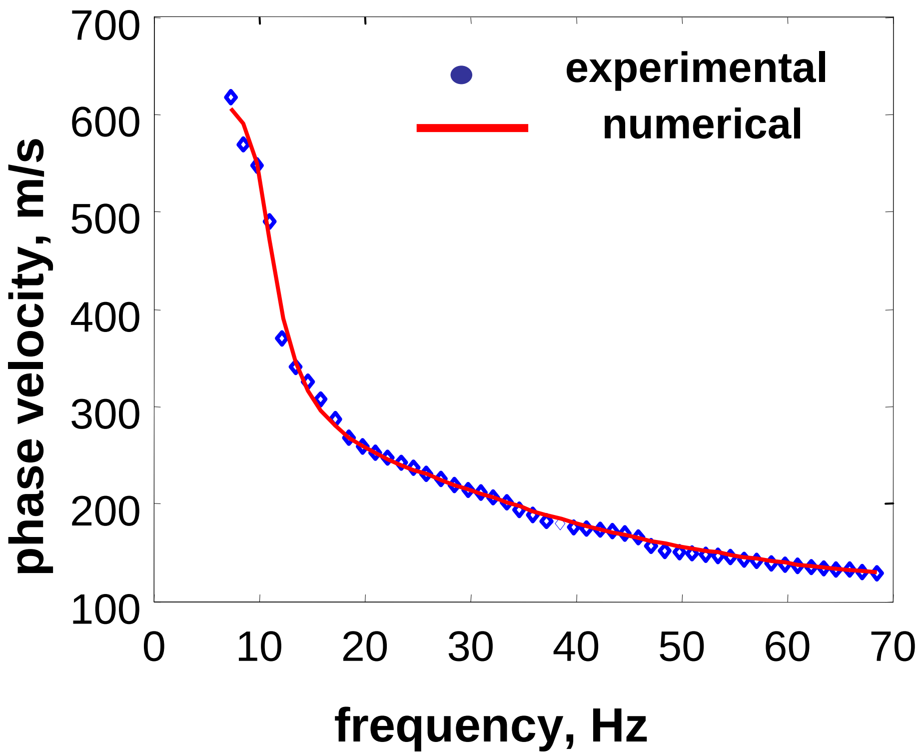
The inverse problem

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

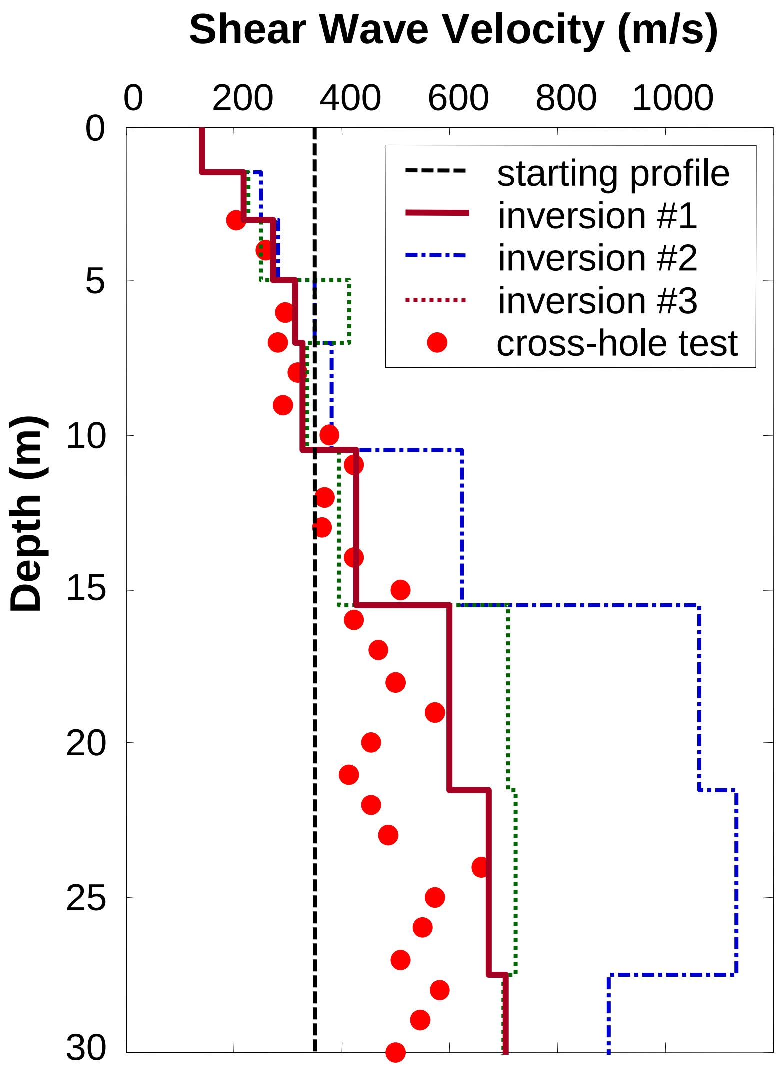


Critical aspect: illposedness of mathematical inverse problems

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

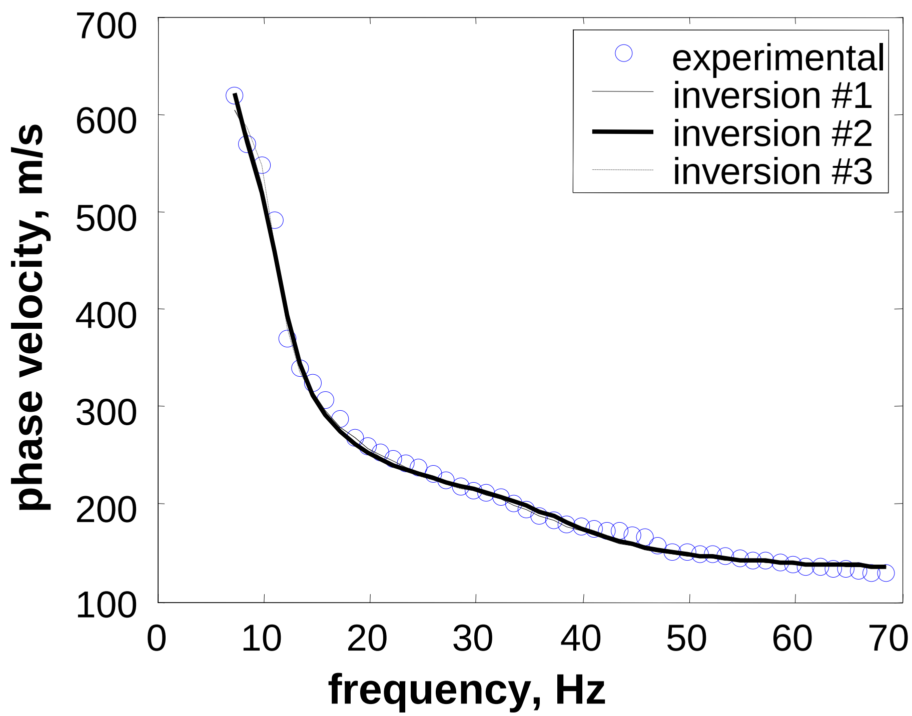
Experimental Data



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

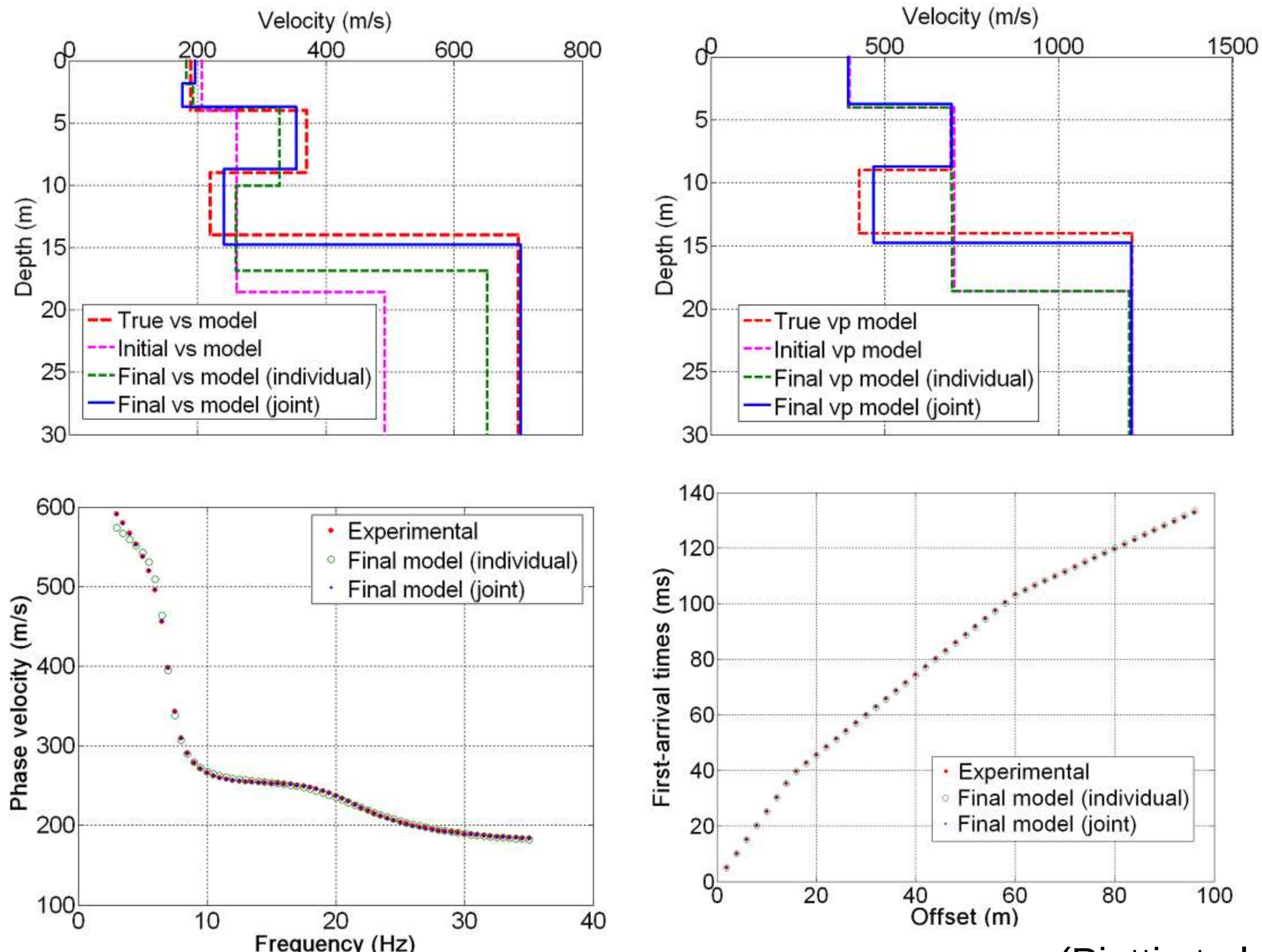
$$L=\left(\frac{1}{N+M+A}\left[\left(\mathbf{d}_{\mathbf{obs}}-\mathbf{g}(\mathbf{m})\right)^{T}\mathbf{C}_{\mathbf{obs}}^{-1}\left(\mathbf{d}_{\mathbf{obs}}-\mathbf{g}(\mathbf{m})\right)\right]\right.$$

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

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

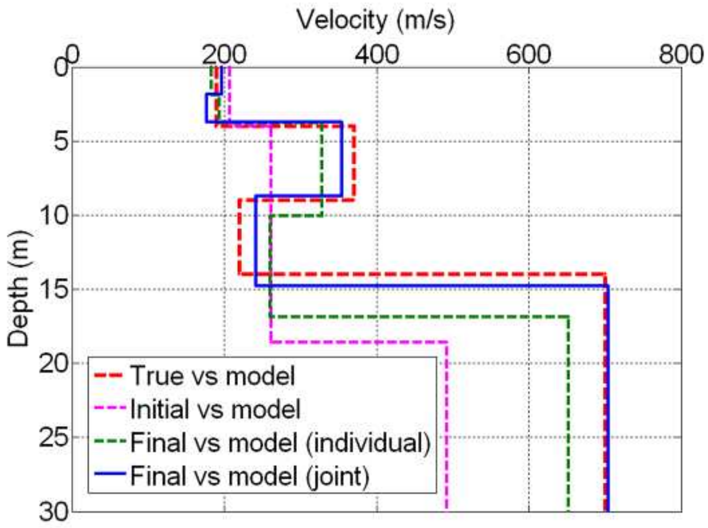
$$\mathbf{m}=[\left(\log(h_1),\ \log(h_2),\ ....,\ \log(h_n)\right)\ \left(\log(V_{S1}),\ \log(V_{S2}),\ ....,\ \log(V_{Sn+1})\right)\ \left(\log(V_{P1}),\ \log(V_{P2}),\ ....,\ \log(V_{Pn+1})\right)]$$

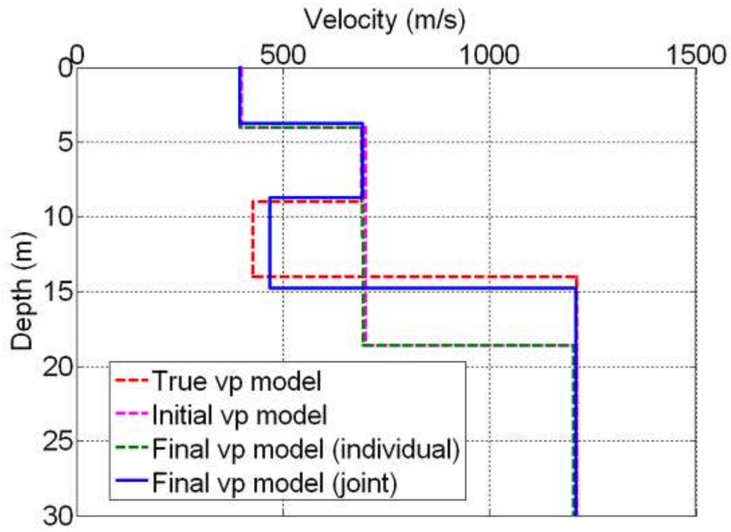
Example on synthetic data

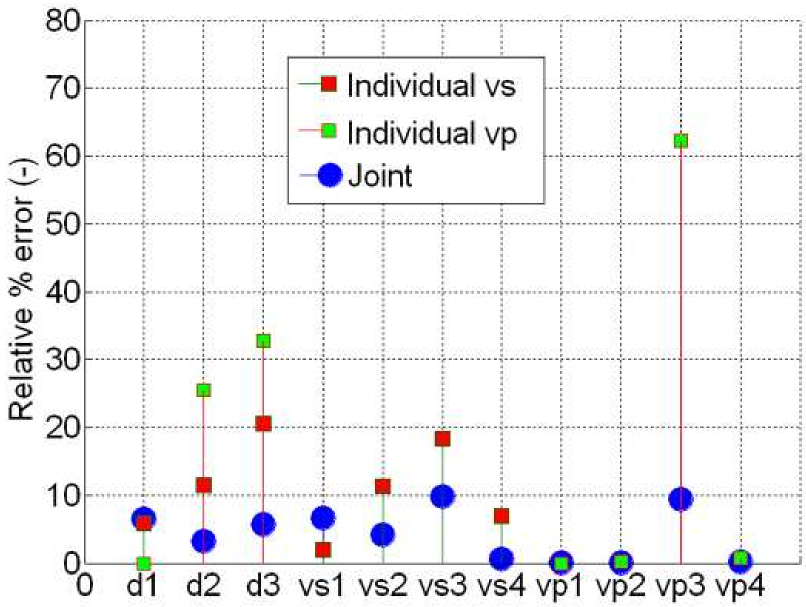


(Piatti et al., 2012b)

Example on synthetic data

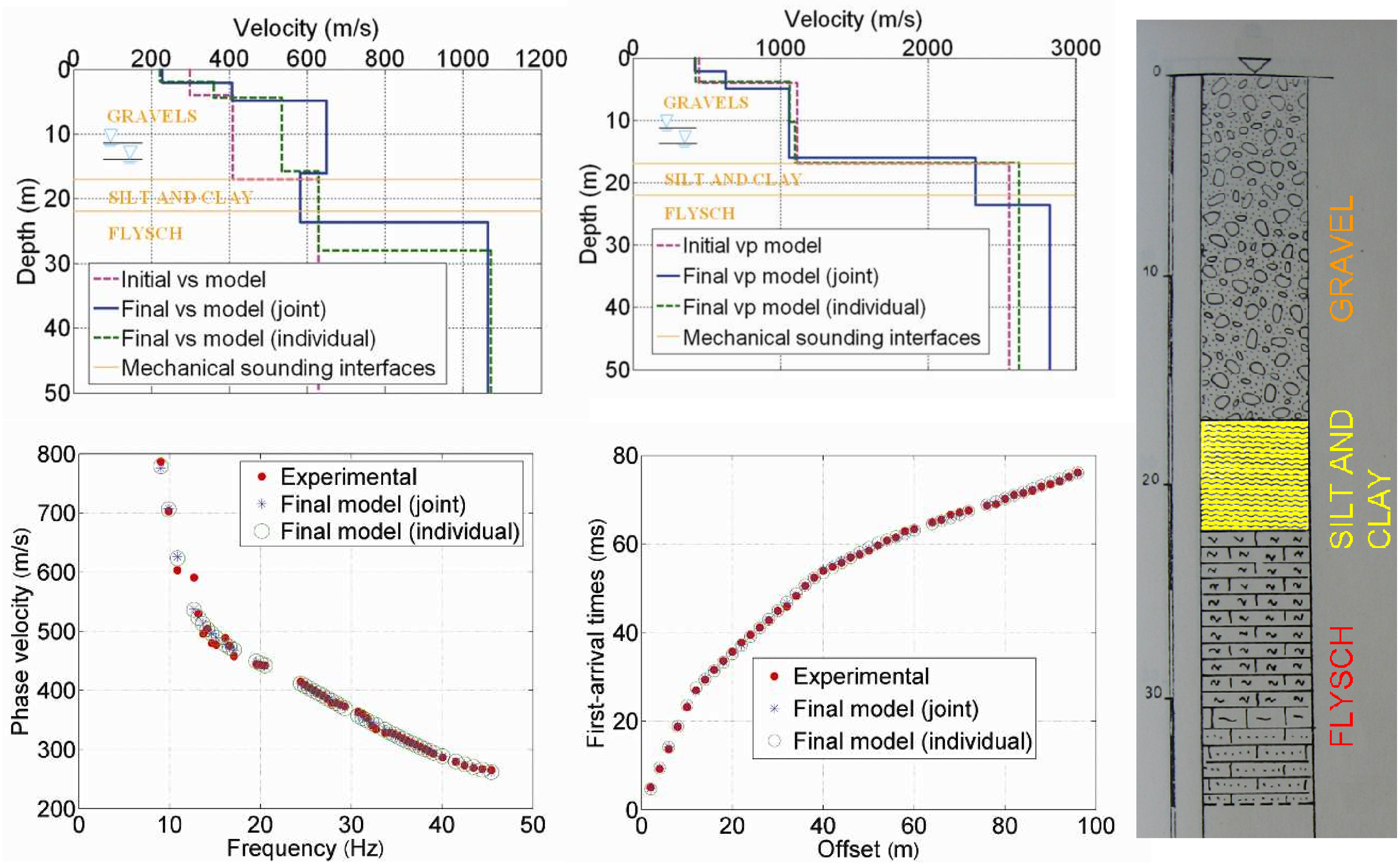






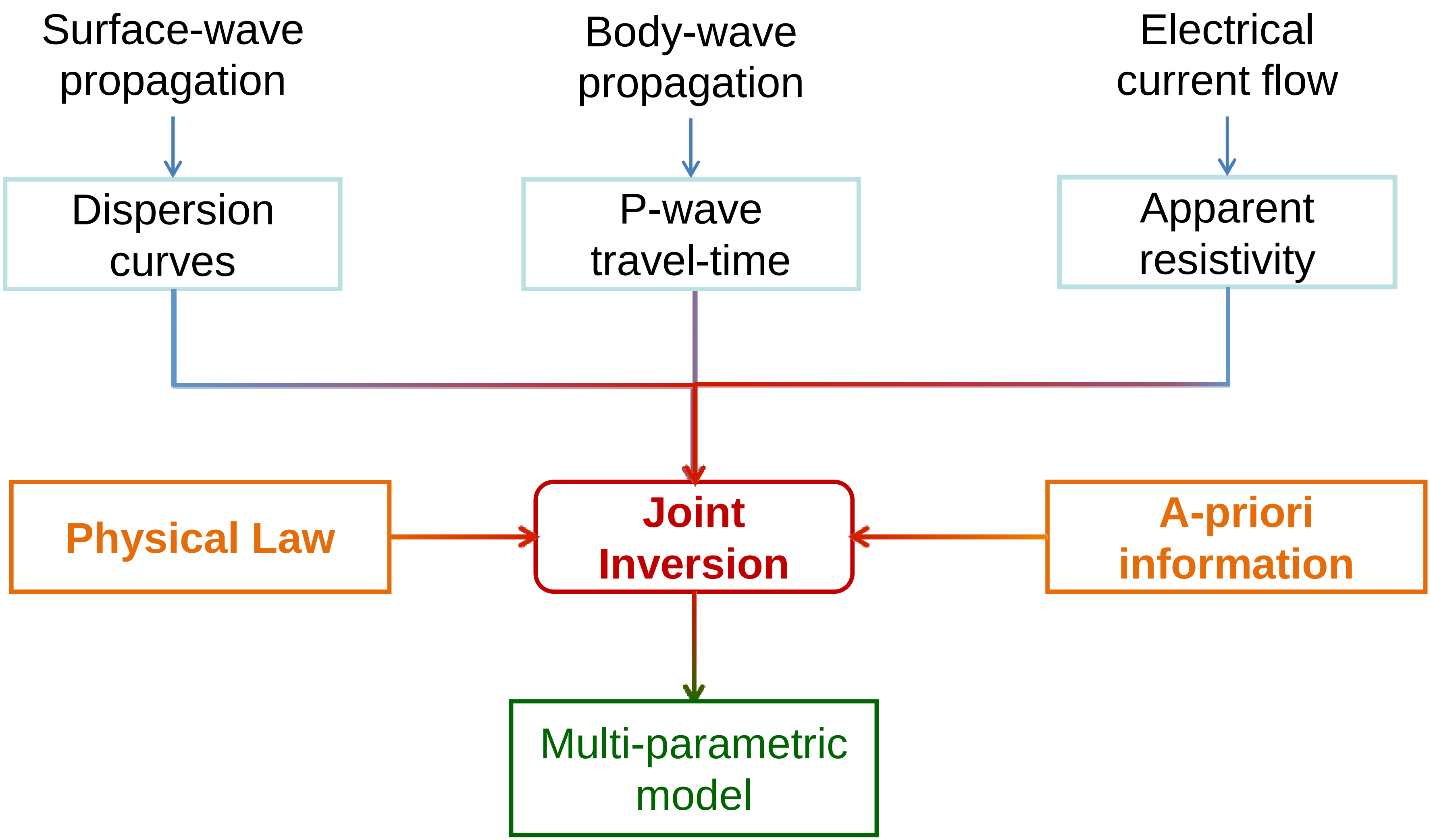
(Piatti et al., 2012b)

Experimental data



Joint inversion algorithm

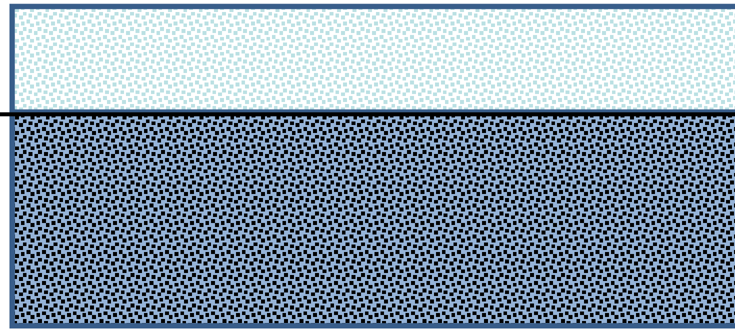
joint-inversion algorithm for a set of experimental data related to different physical phenomena and in order to obtain an internally consistent multi-parametric layered model



Physical link among model parameters

- **Poisson's ratio**

$$\upsilon_{sk} = f(V_P, V_S)$$



UNSATURATED

SATURATED

- **Porosity *n***

Density ρ → $\rho = f(\rho_S, \rho_W, \boldsymbol{n})$

Foti et al., 2002

$$\boldsymbol{n} = f(\rho_S, \rho_W, \upsilon_{sk}, V_P, V_S)$$

- **S-wave velocity V_S**
- **P-wave velocity V_P**

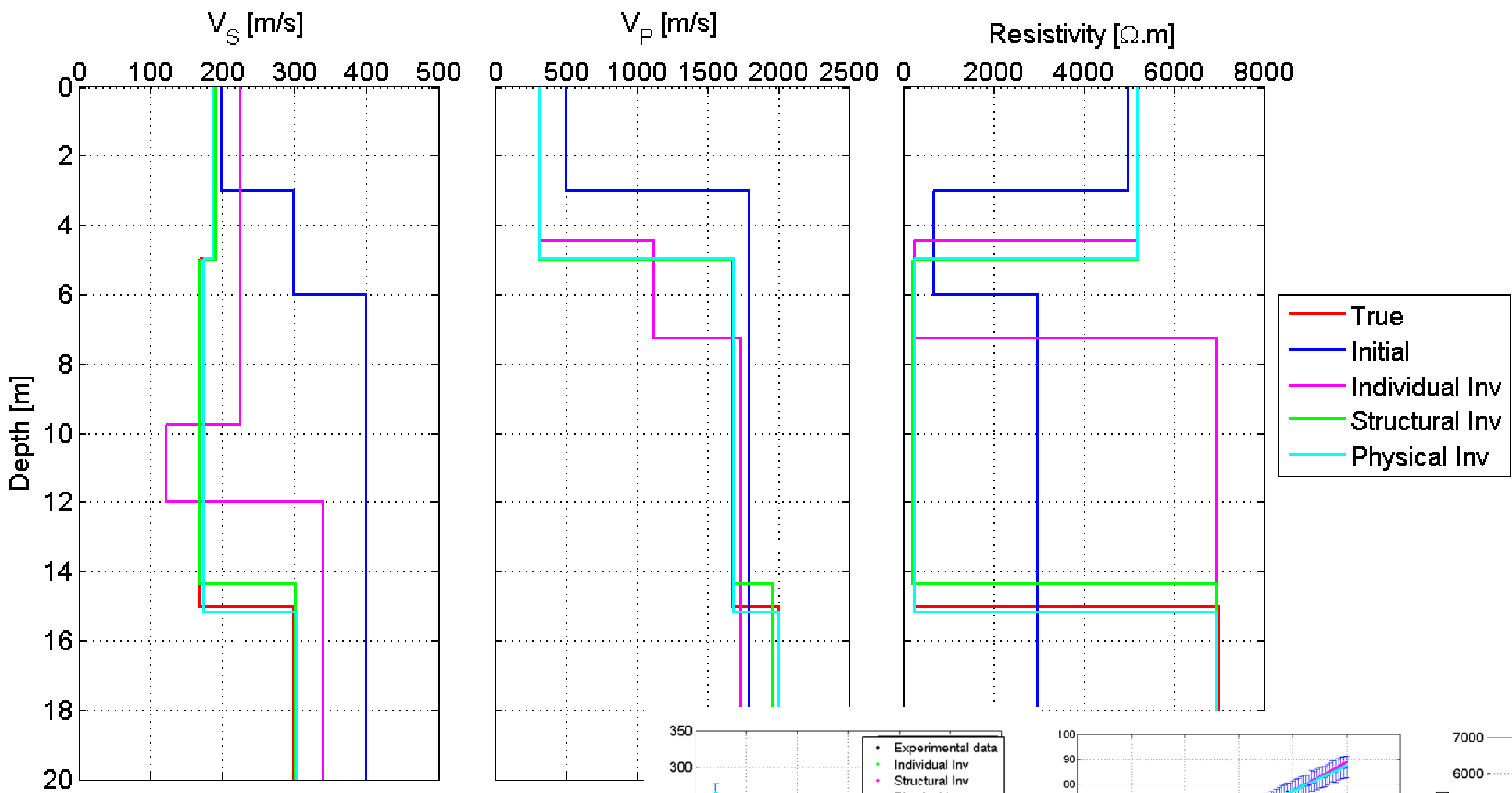
Layer thickness *h*

Resistivity σ → Bruggeman, 1935 (clean formation)

$$\sigma = f(\sigma_W, \boldsymbol{n})$$

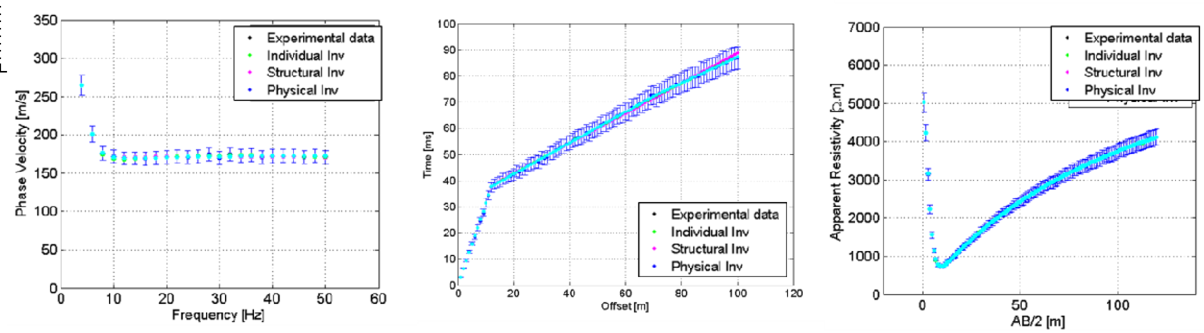
constants	t/m³
Density of soil grain $\boldsymbol{\rho}_s$	2.65
Density of water $\boldsymbol{\rho}_w$	1

Preliminary results on a synthetic model



(a)

Estimated porosity: 0.395
(vs actual porosity 0.4)



(a) (b) (c)

(Garofalo et al., 2013)

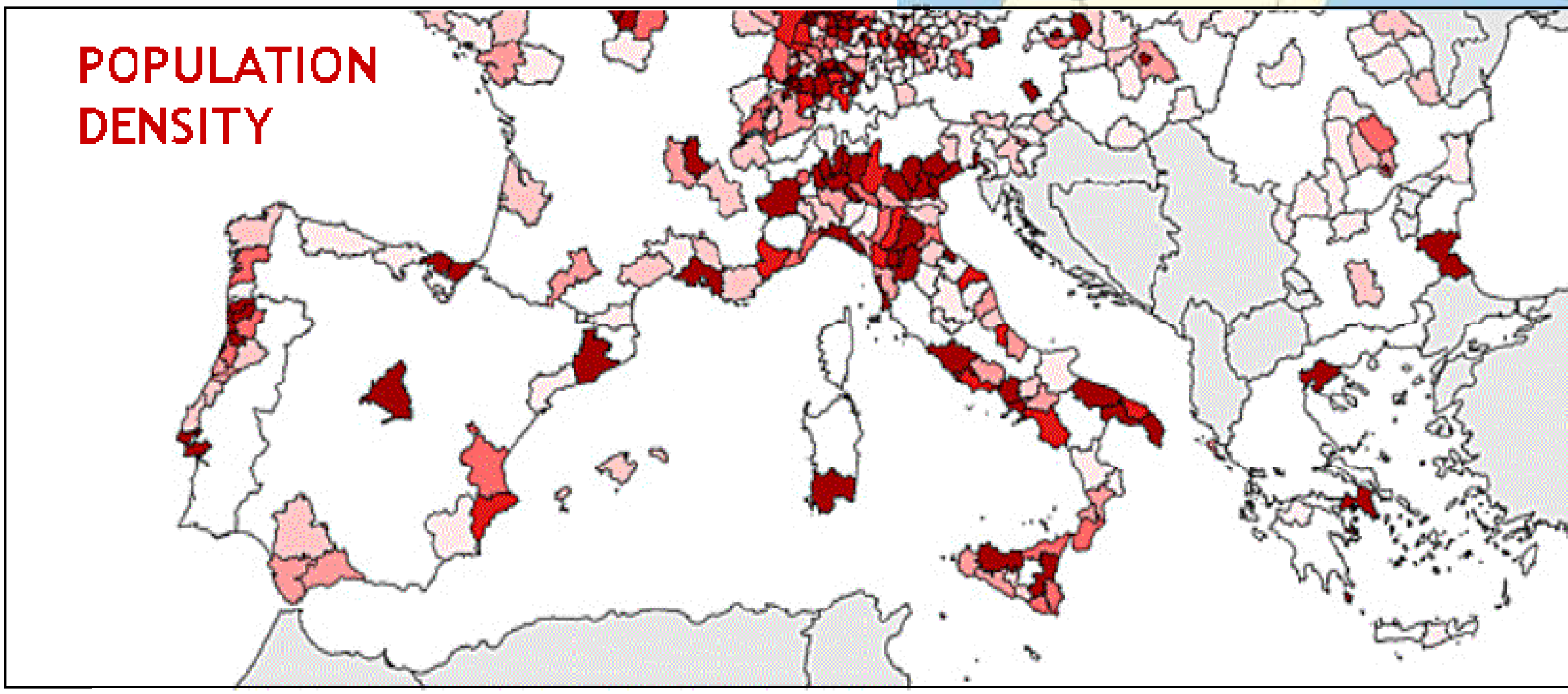
Case History #1

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

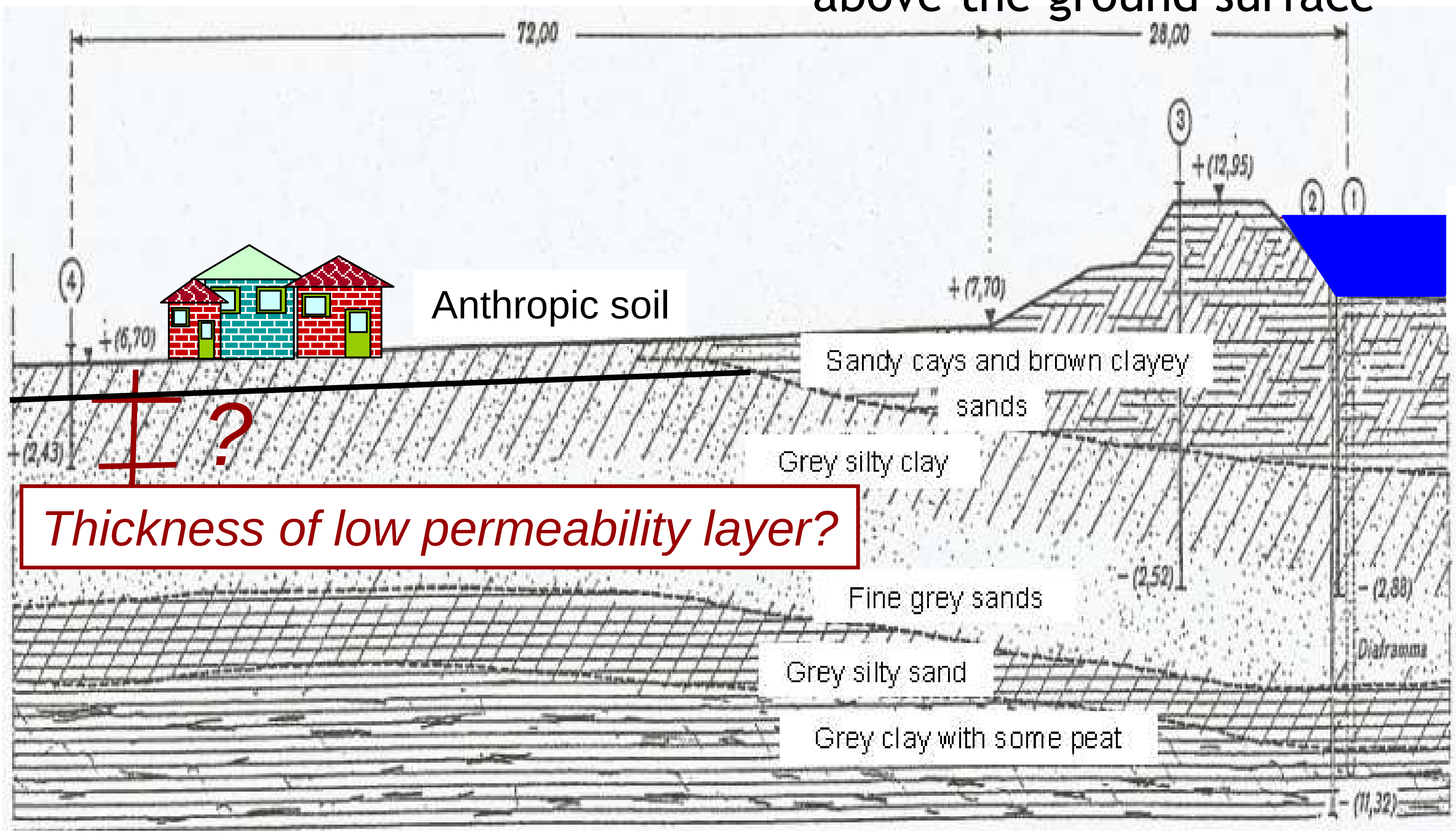
10 extreme events each 100 years

Levees for a total length over 2400 km

Seepage potential

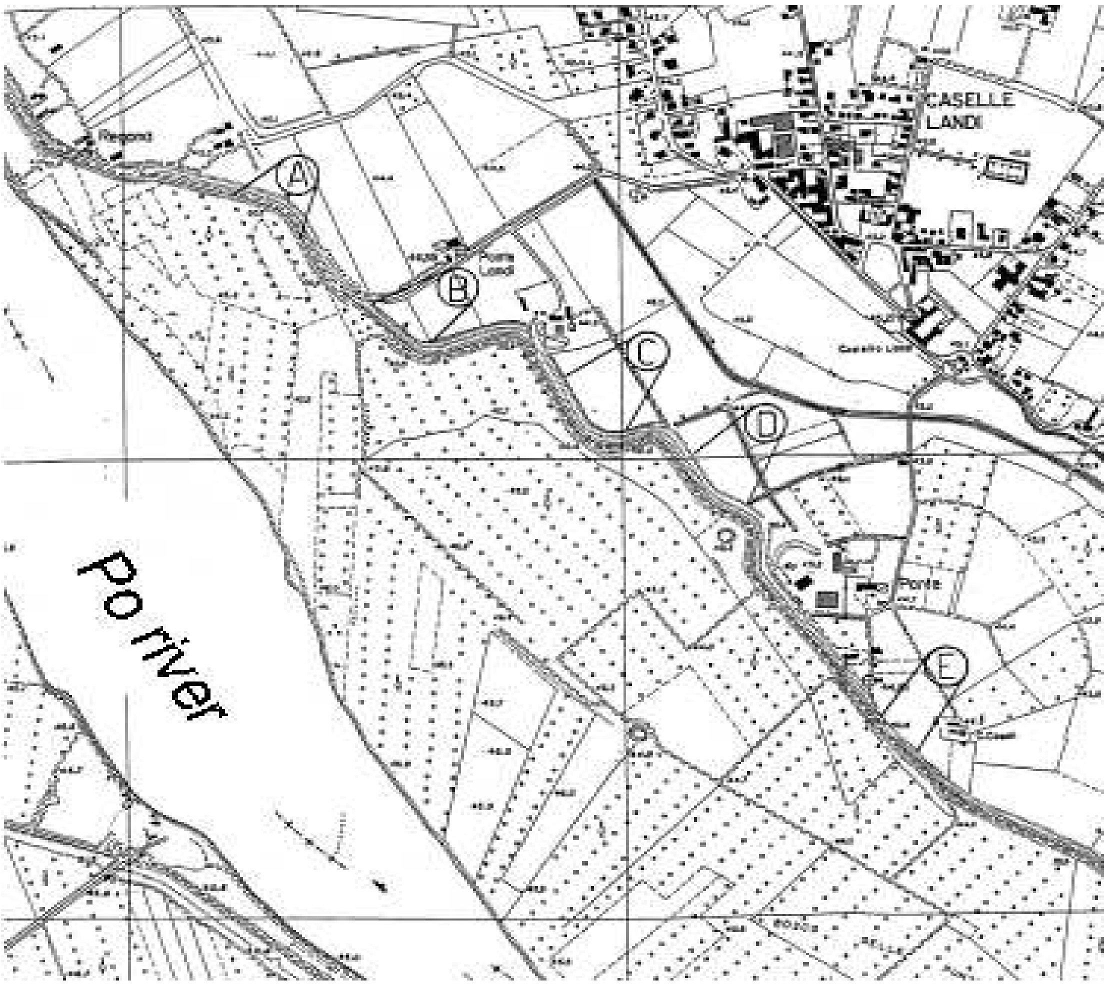
Geology: alluvial deposits: recent sands, gravel, clay
TARGET: clayey layer: continuity, thickness

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}

Surface wave testing

Detection of motion on the ground surface

Processing

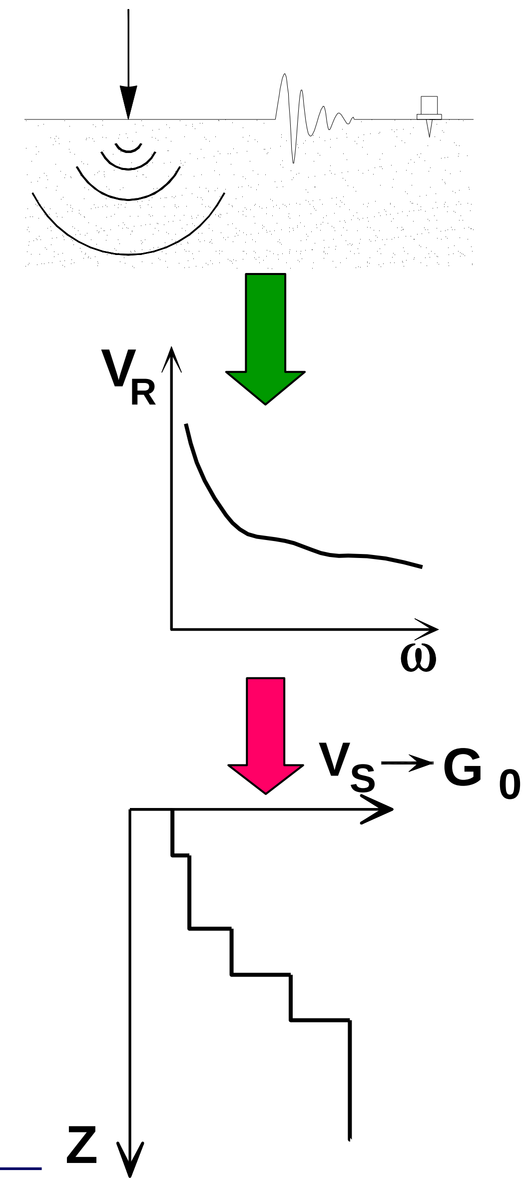
Experimental dispersion curve: Phase velocity of Rayleigh waves vs frequency

Inversion

Variations of Shear Wave velocities with depth

$$G_0 = \rho \cdot V_S^2$$

Small Strain Stiffness profile (G_0 vs depth)



Vertical Electric Soundings

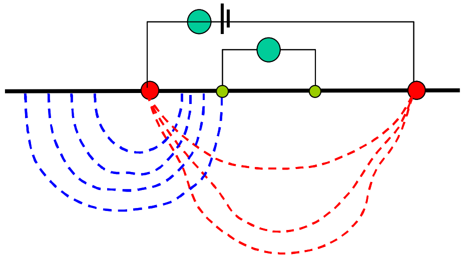
Current injection and potential detection

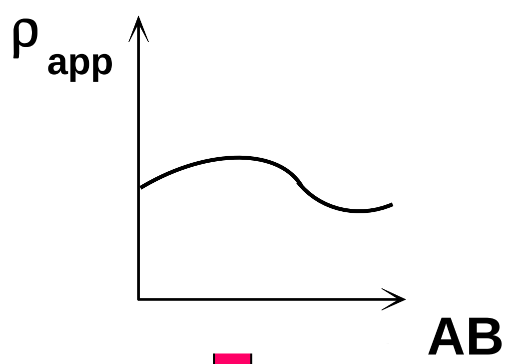
Processing

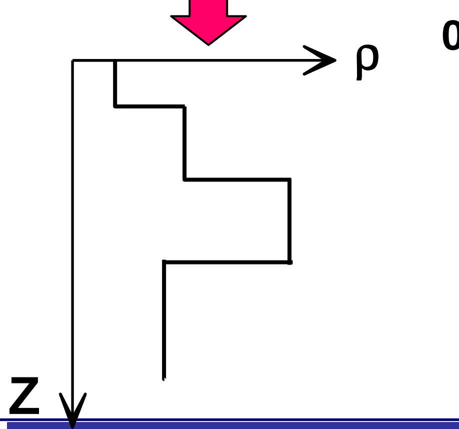
Experimental apparent resistivity vs aperture

Inversion

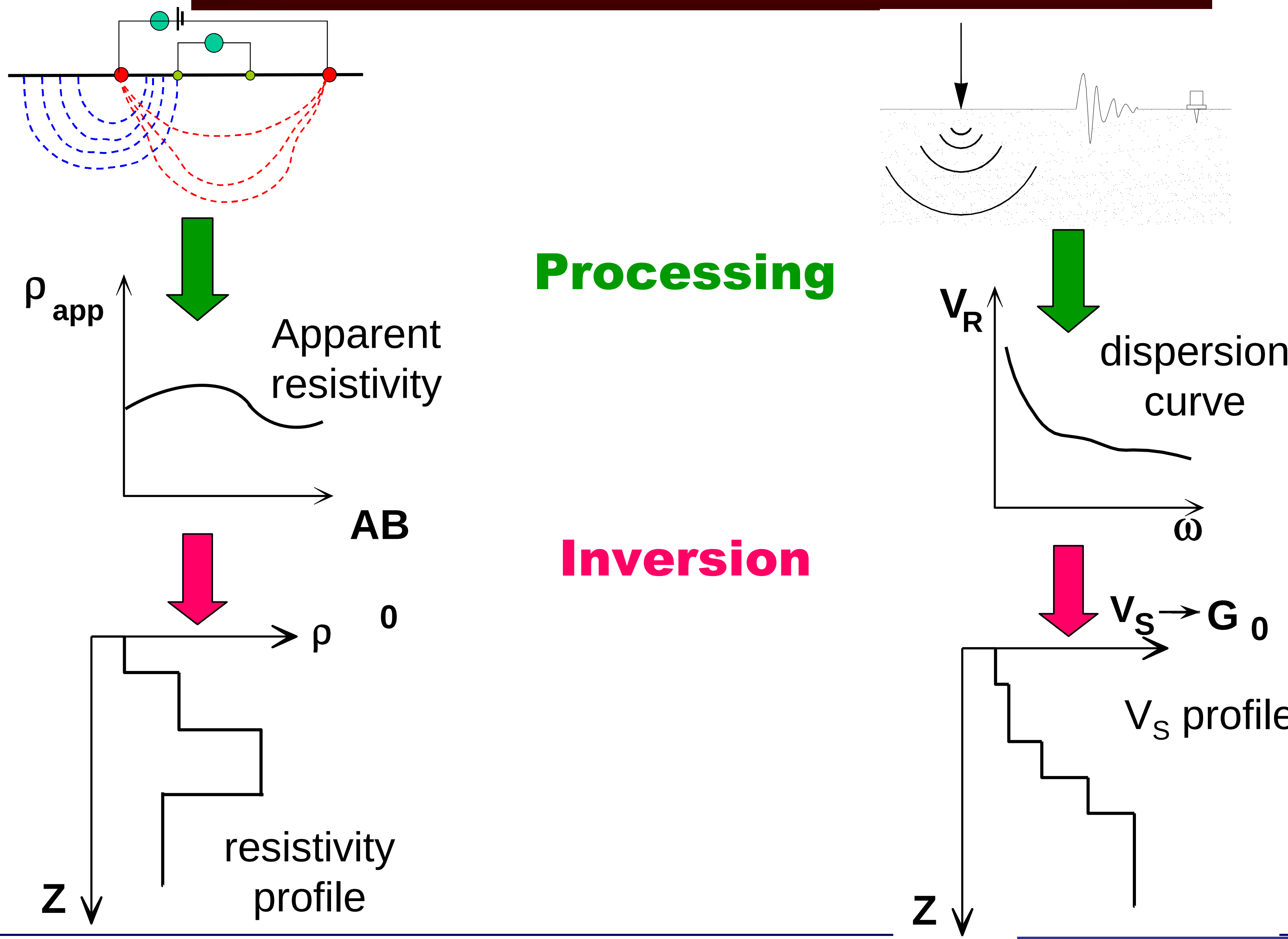
Variations of resistivity with depth







Combinations MASW + VES

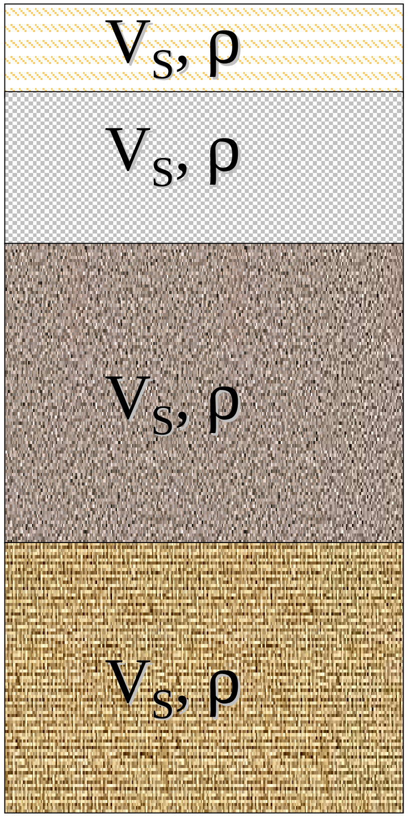


Joint inversion VES + MASW

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

MODEL PARAMETERS:

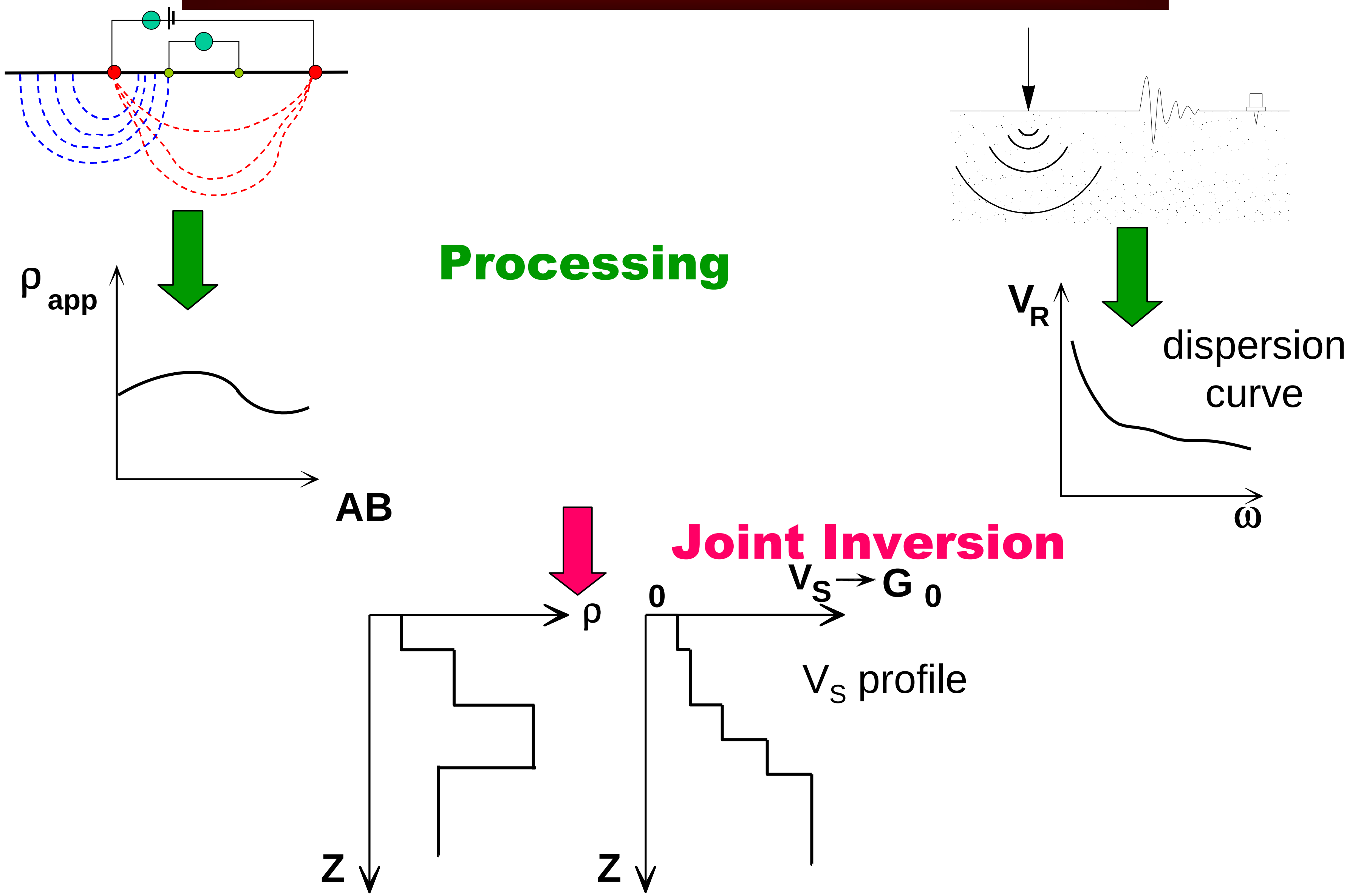
n	ρ
n	V_S
n-1	H



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)

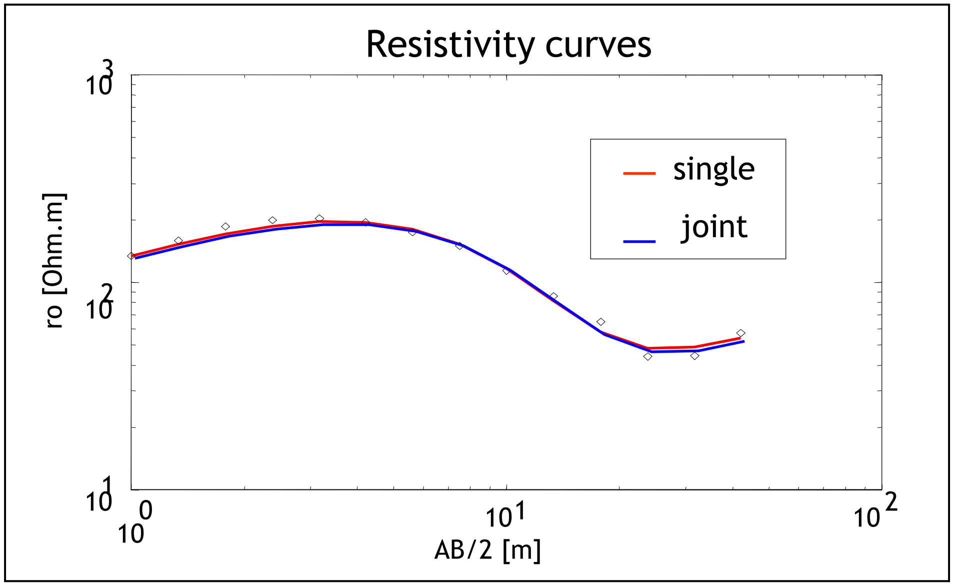
From 4n-2 to 3n-1 unkowns
with the same experimental information

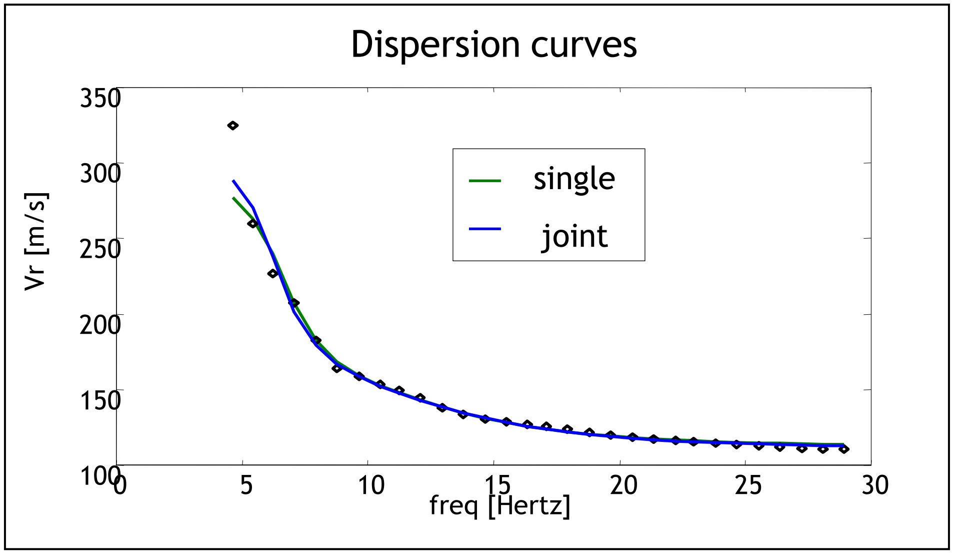
Joint inversion VES + MASW

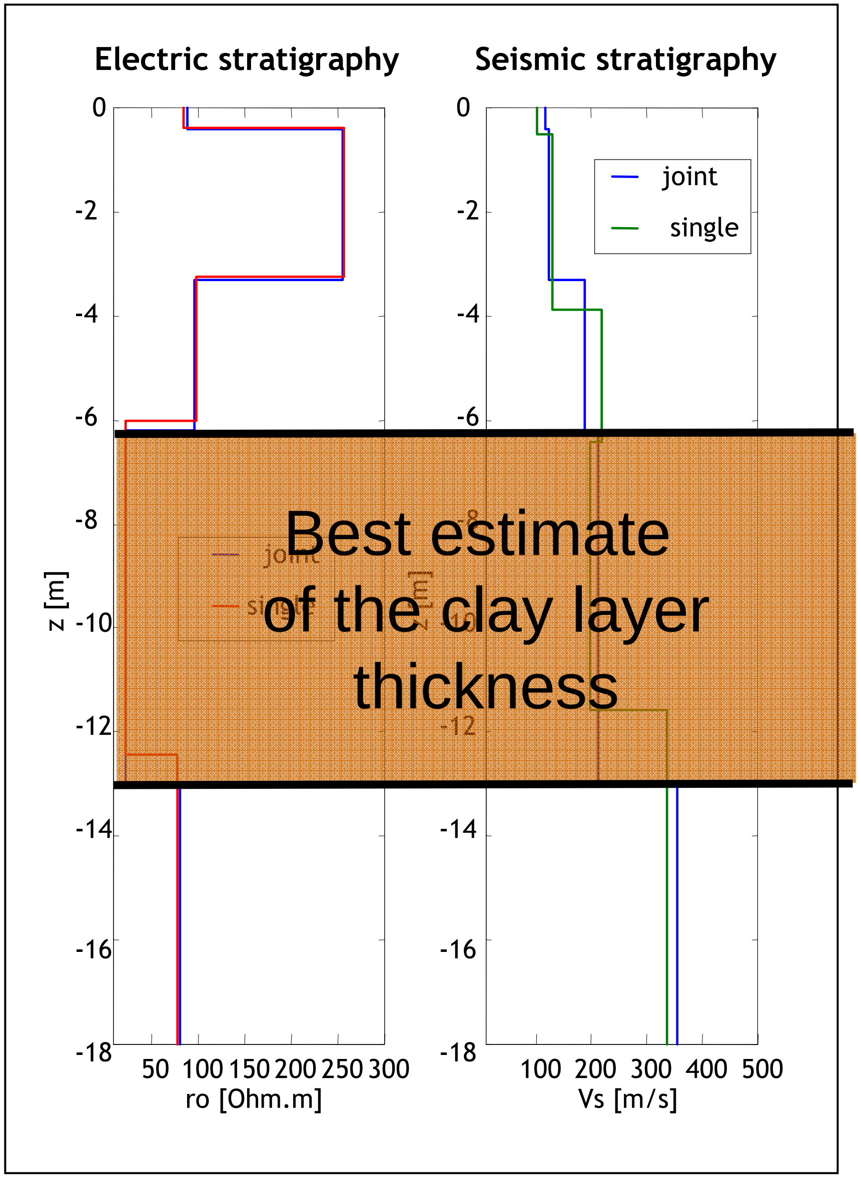


Field test results

(Comina et al., 2004)





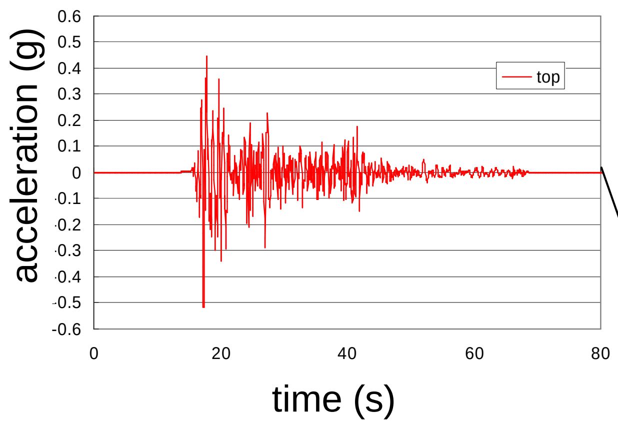


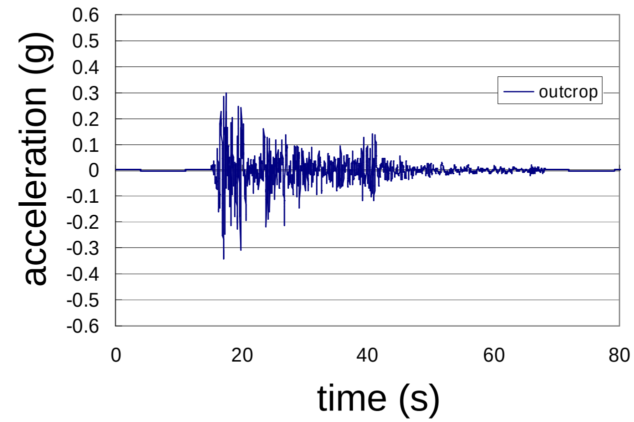
Case history #2

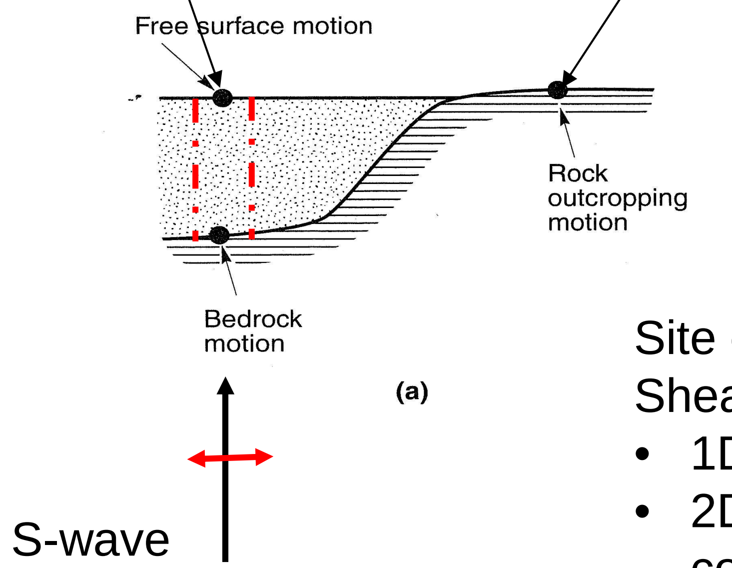
Building a shear wave velocity model for seismic site response studies

- 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







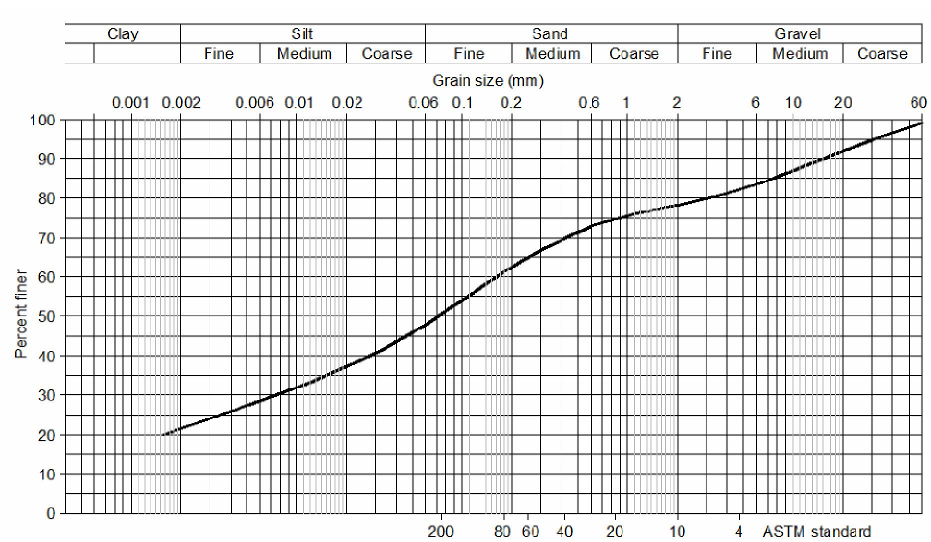
Site characterization:
Shear wave velocity model

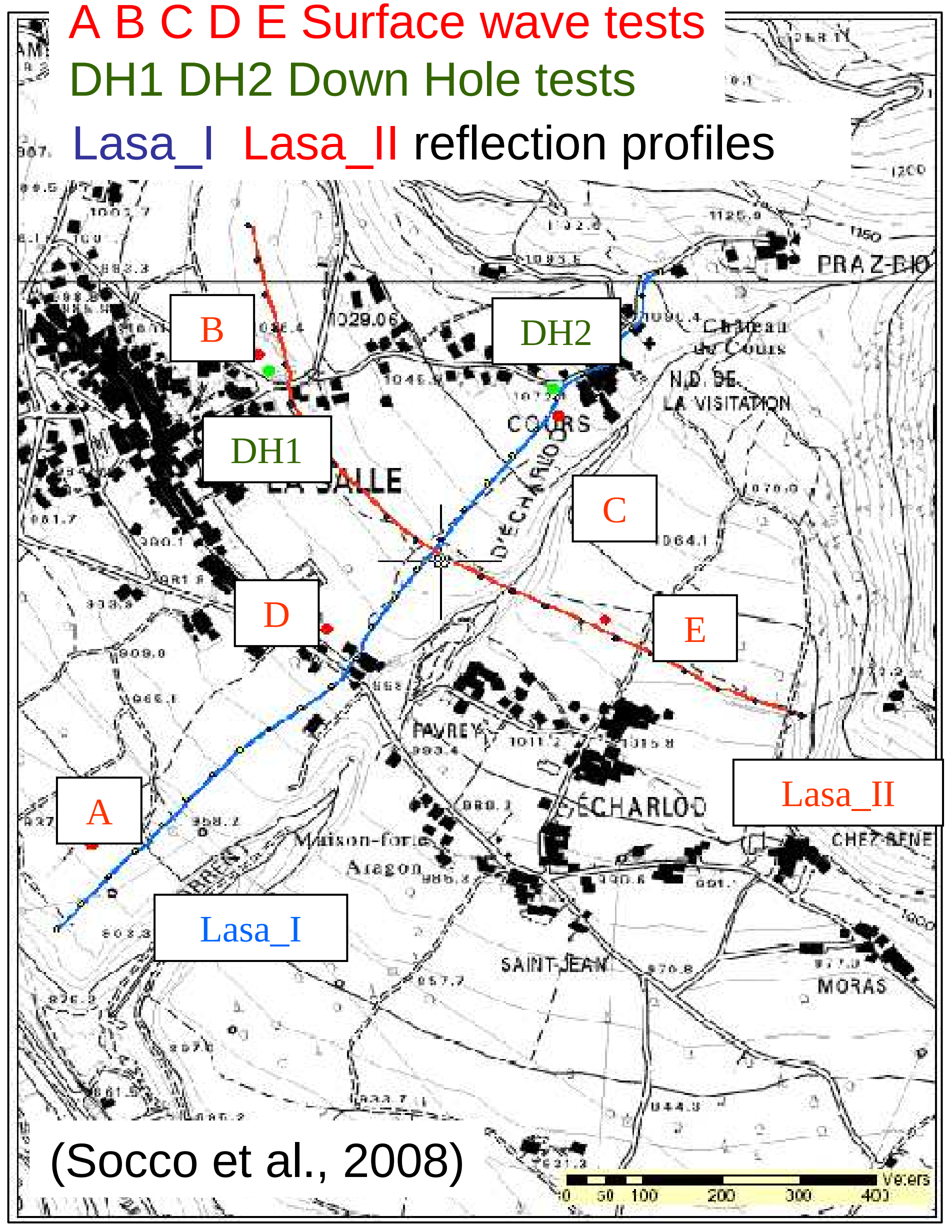
- 1D Vs profile
- 2D/3D Vs models to simulated complex situation (e.g. valley edges)

Case Study: La Salle, Italy

Alluvial Fan

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

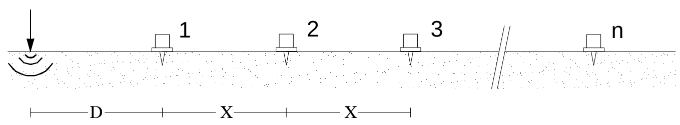




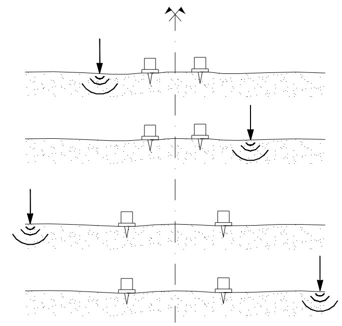
SWM techniques for near surface characterization

Active methods

Multistation:
f-k, τ-p, MASW, …

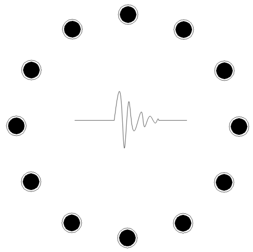


Two-station (SASW)

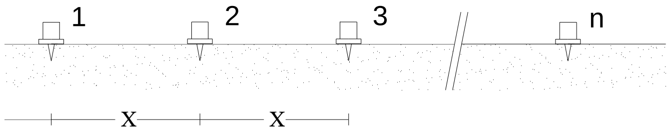


Passive methods

Spatial Array:
Spatial Autocorrelation
(SPAC, ESAC), f-k spectra
(FDBF, MLM, Music), ...

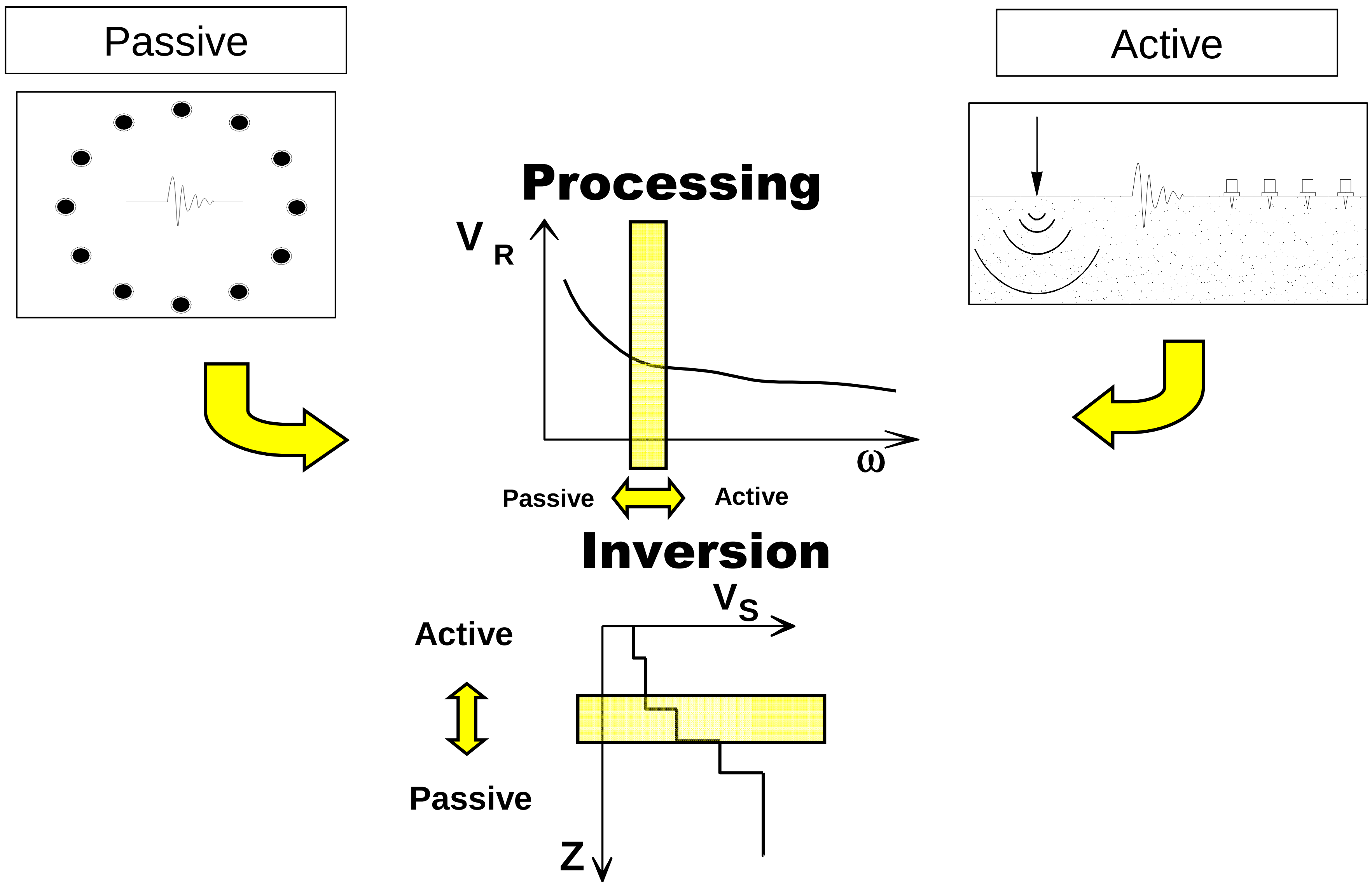


Linear array (ReMi)

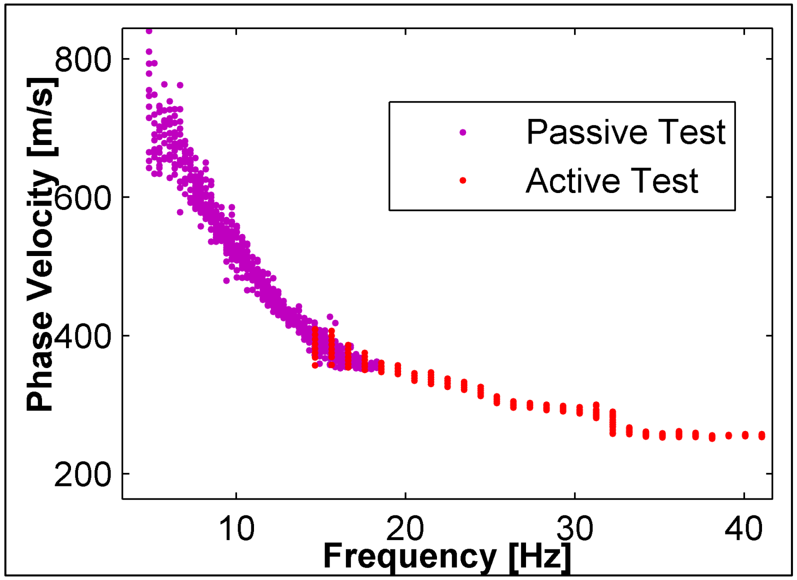


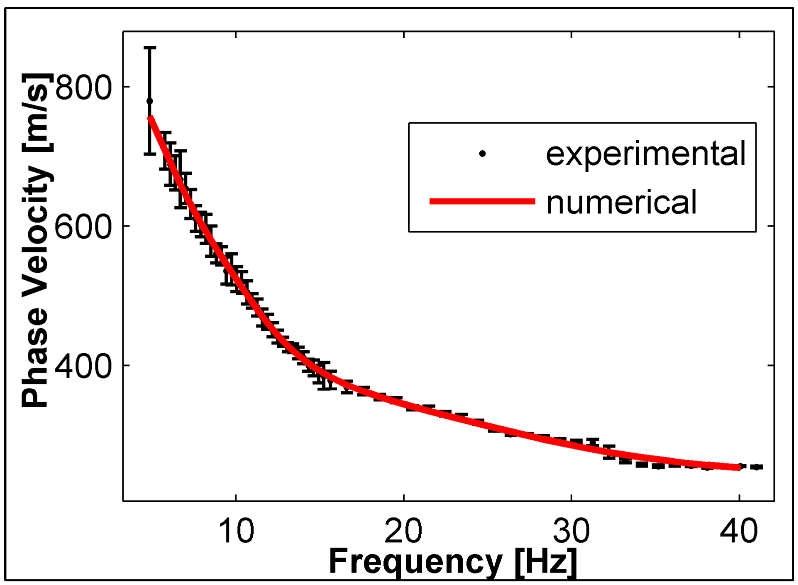
?

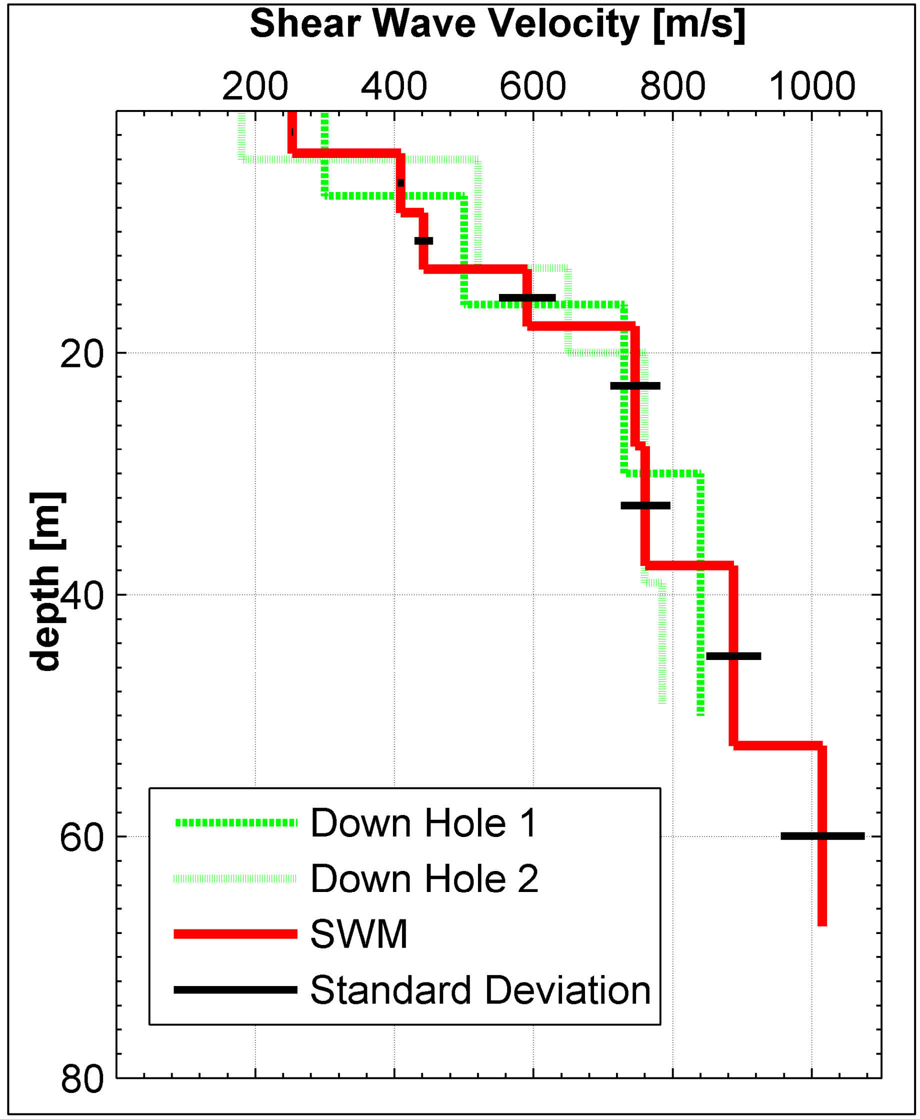
Active+Passive - SW Tests



Example: La Salle (site E)

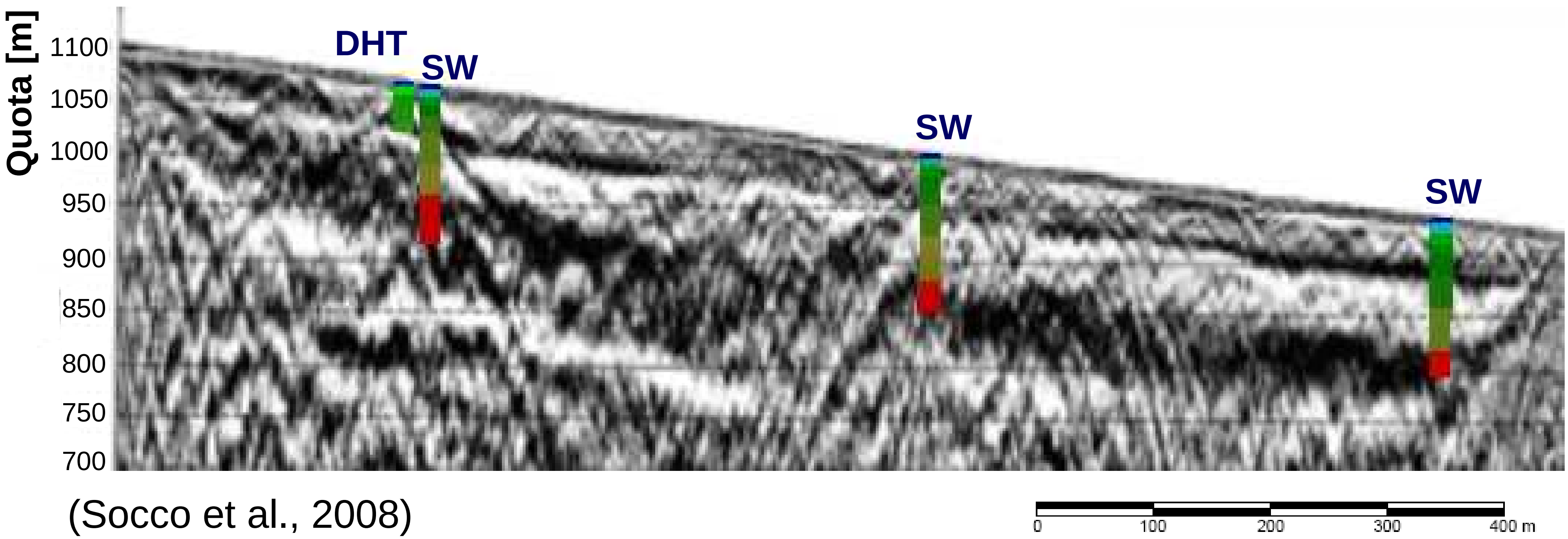




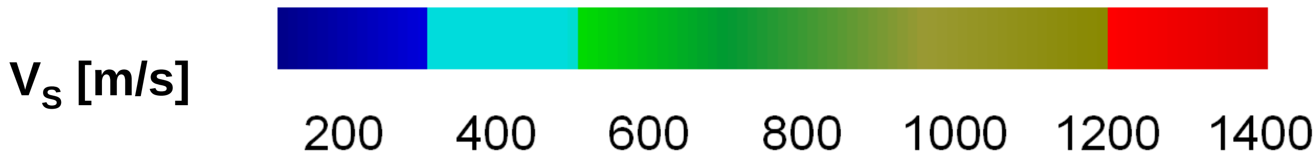


(Foti et al., 2007)

Seismic reflection vs. SWM (A+P)

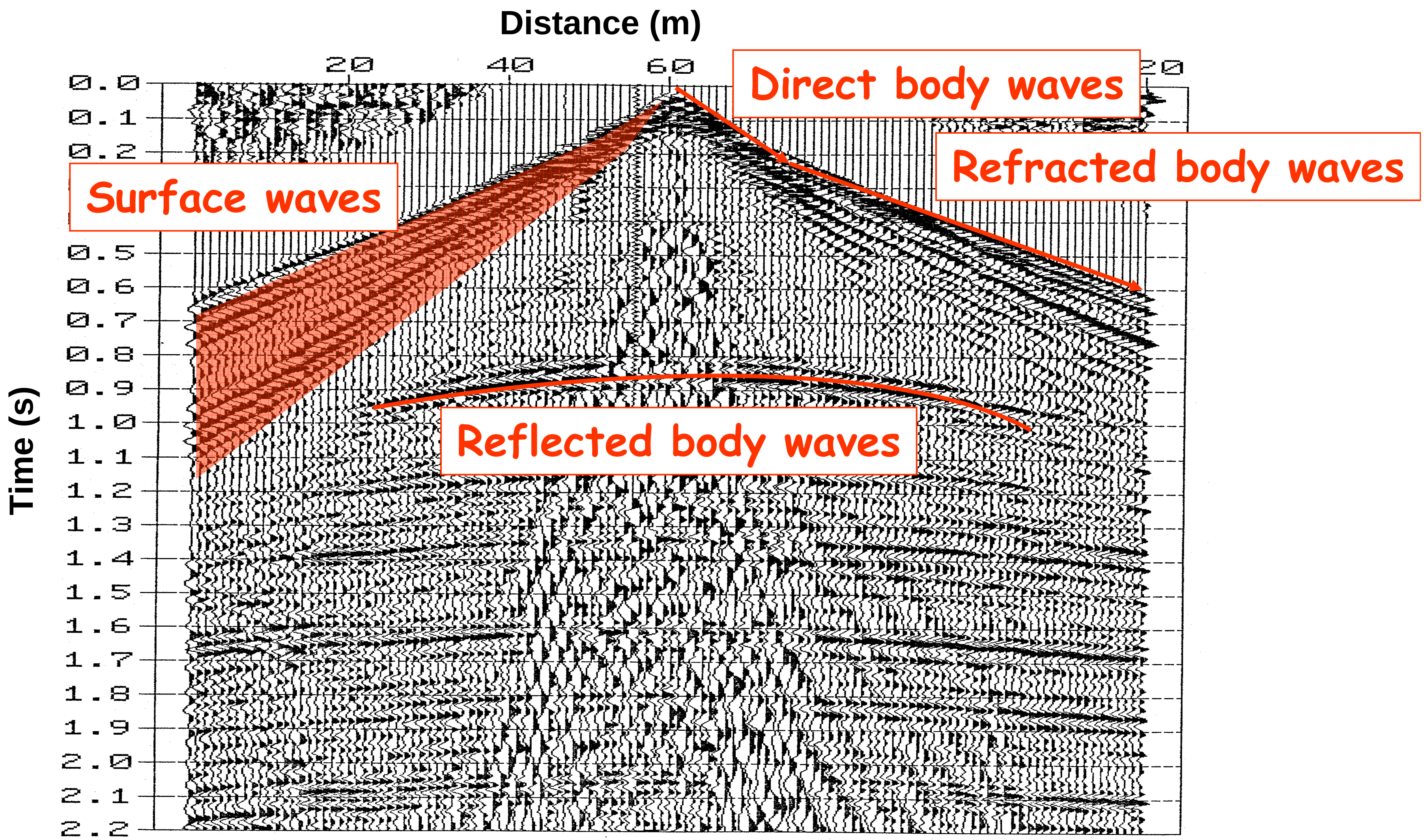


(Socco et al., 2008)

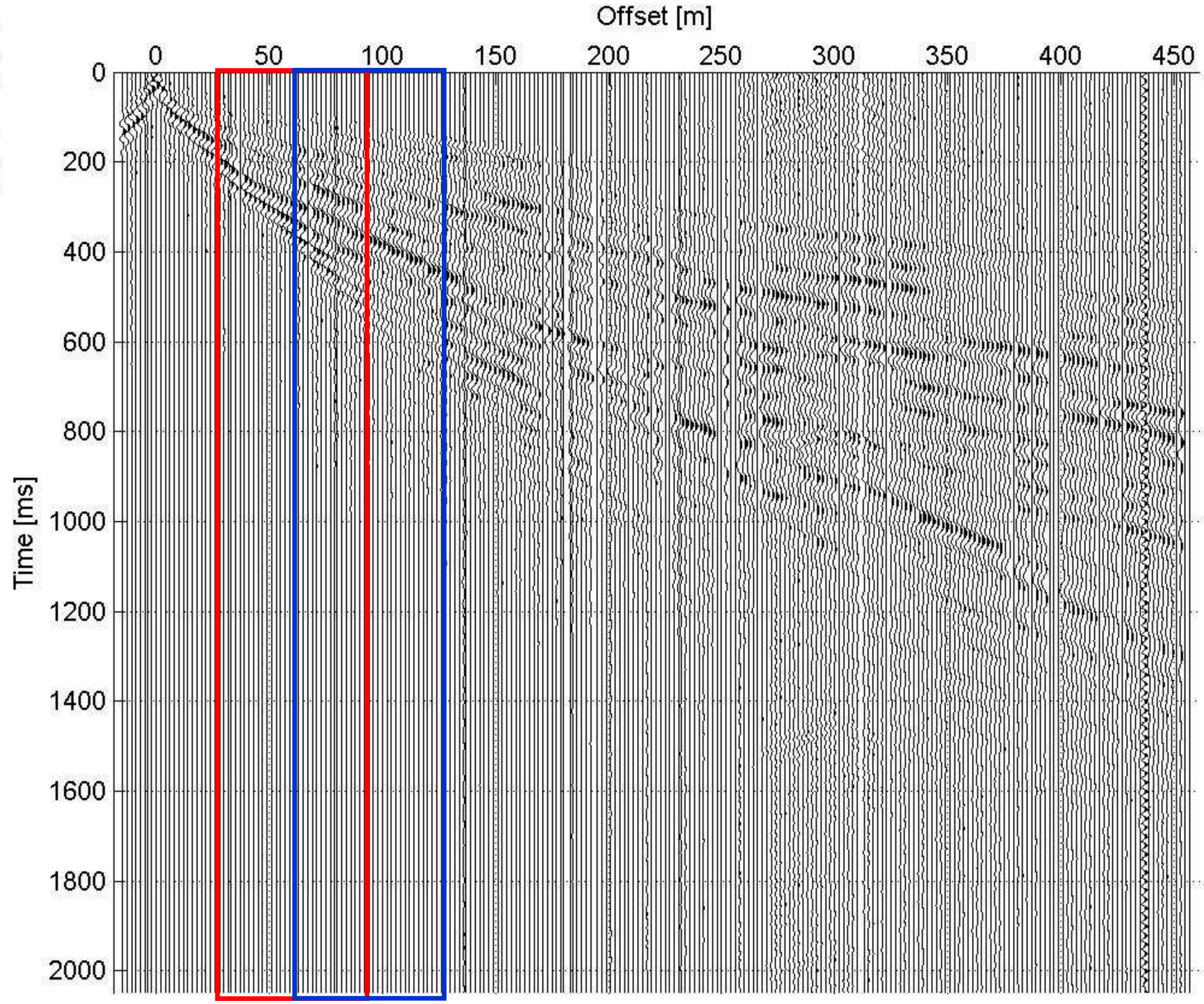


Surface waves confirm that second reflection is the bedrock.

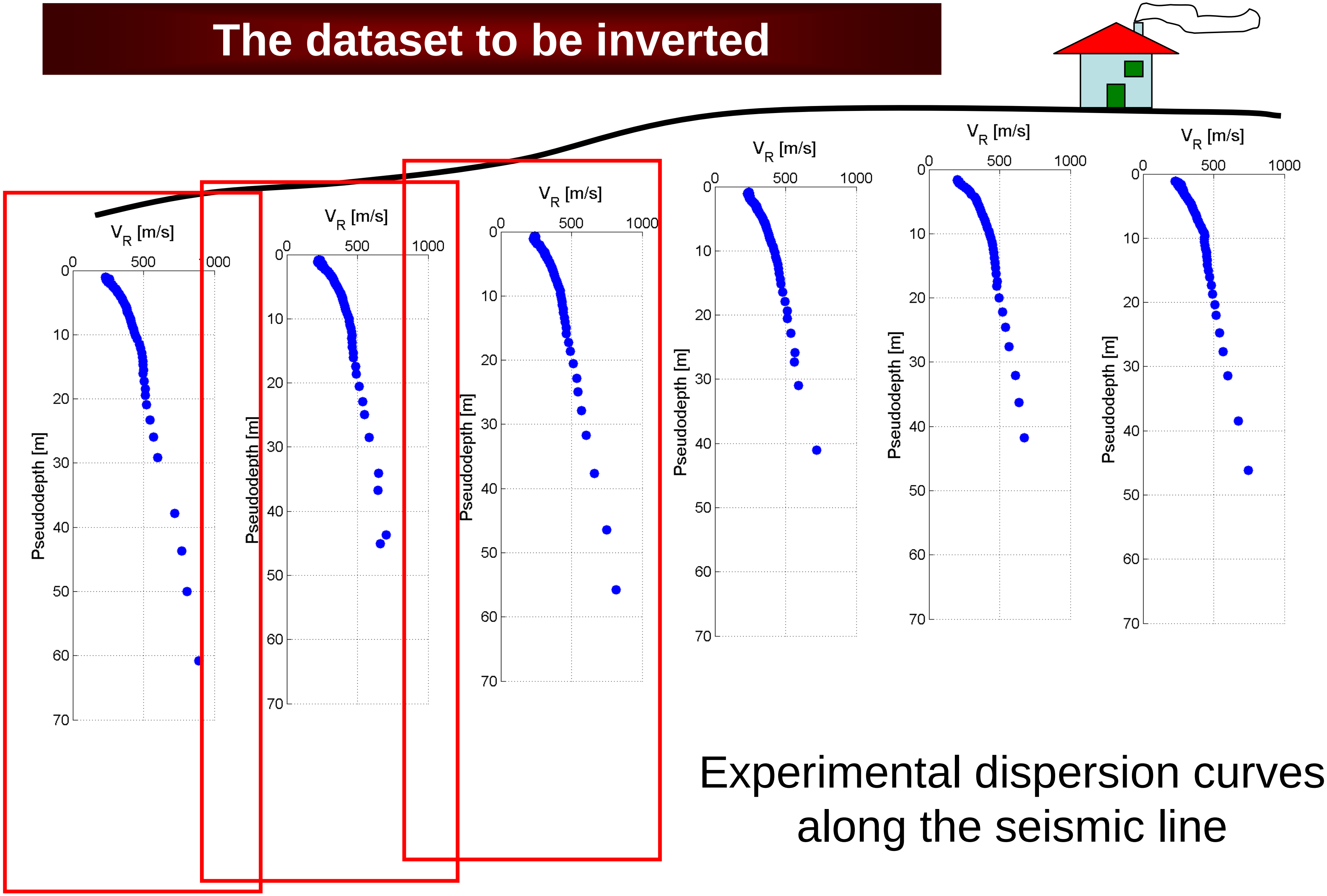
Seismograms



Seismic Dataset for reflection line #1



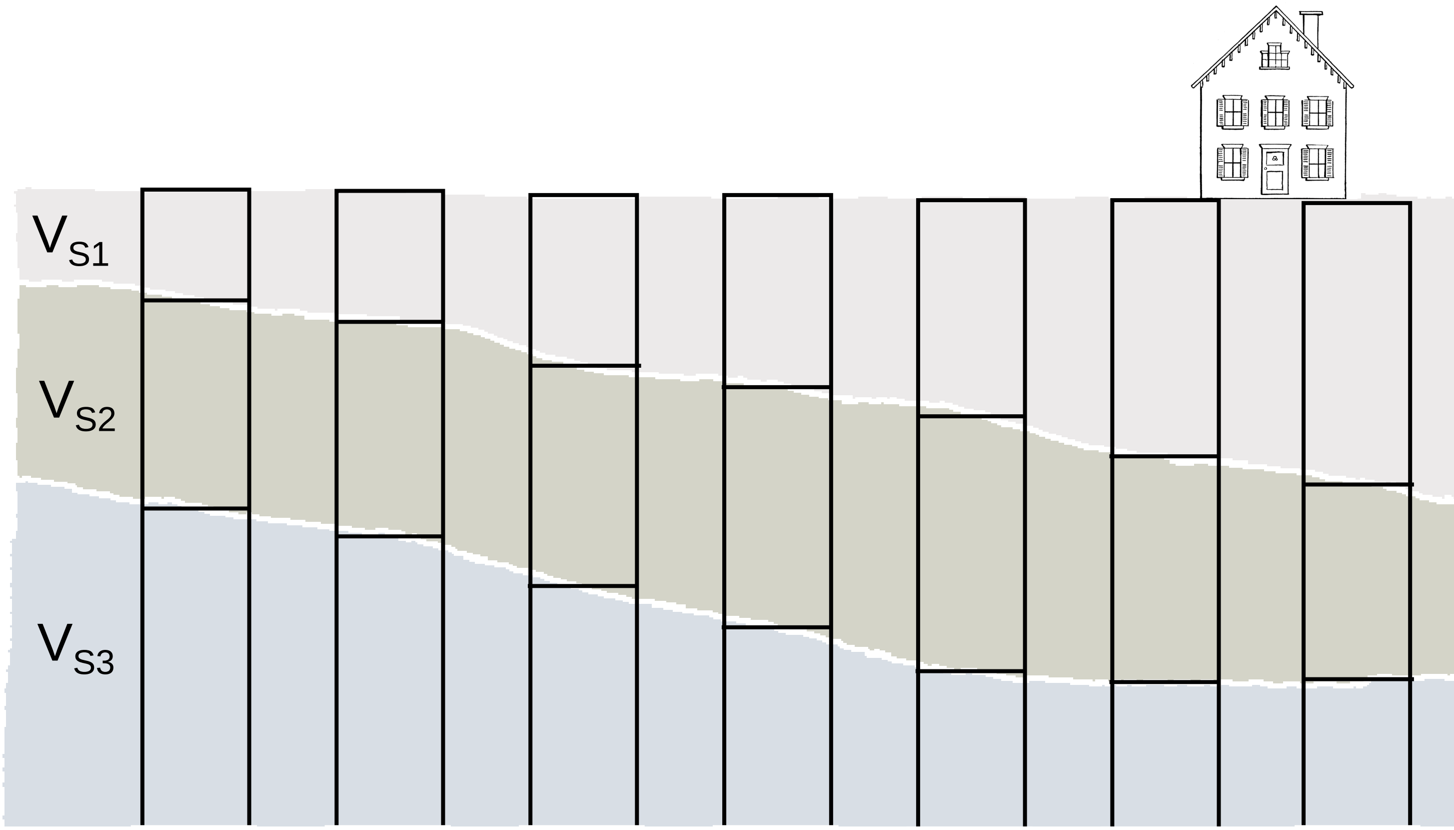
The dataset to be inverted



Experimental dispersion curves along the seismic line

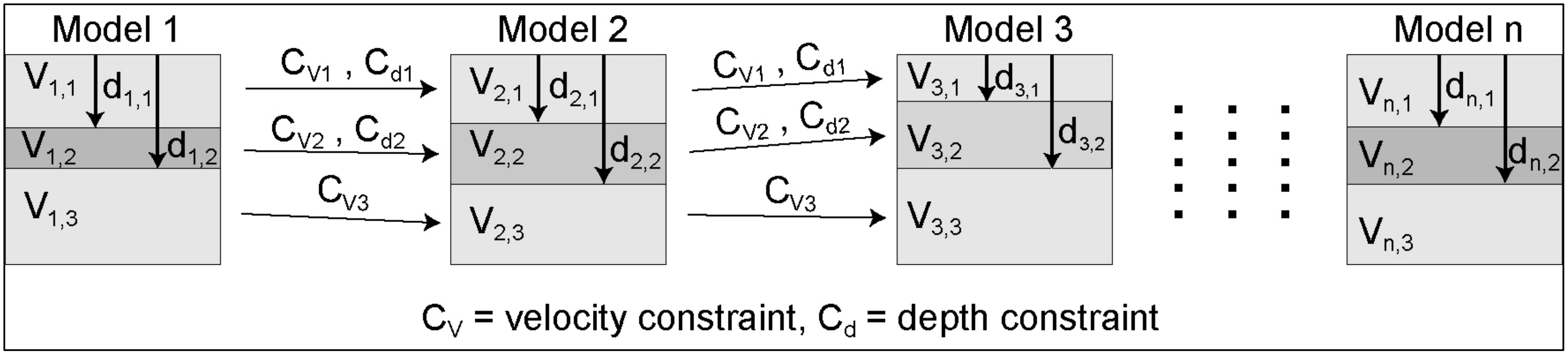
Pseudo-2D (3D)

Local approximation of submerged structure with 1D profiles



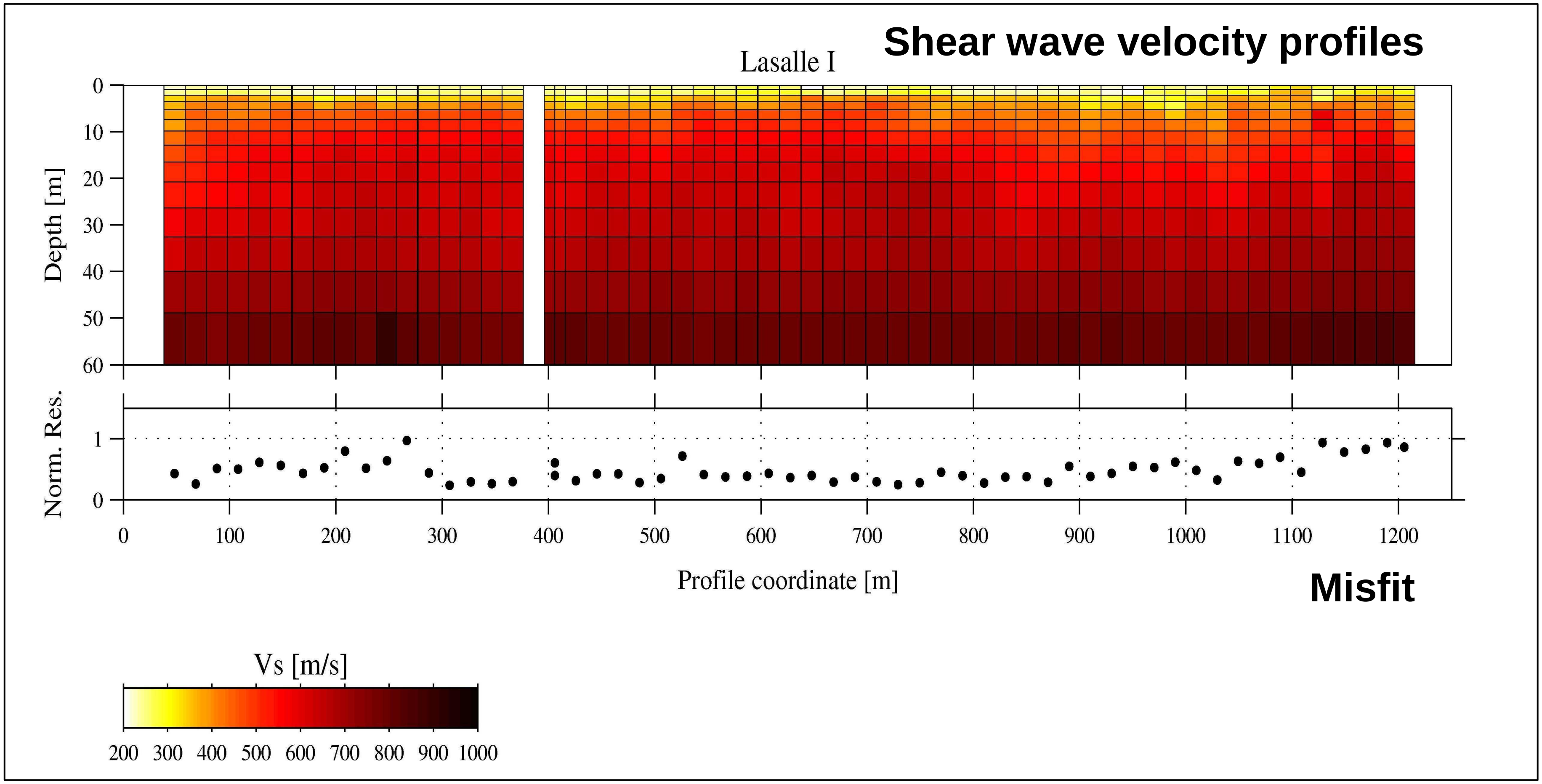
The Laterally Constrained Inversion

[Auken and Christiansen, 2004]; [Wisén and Christiansen, 2005]



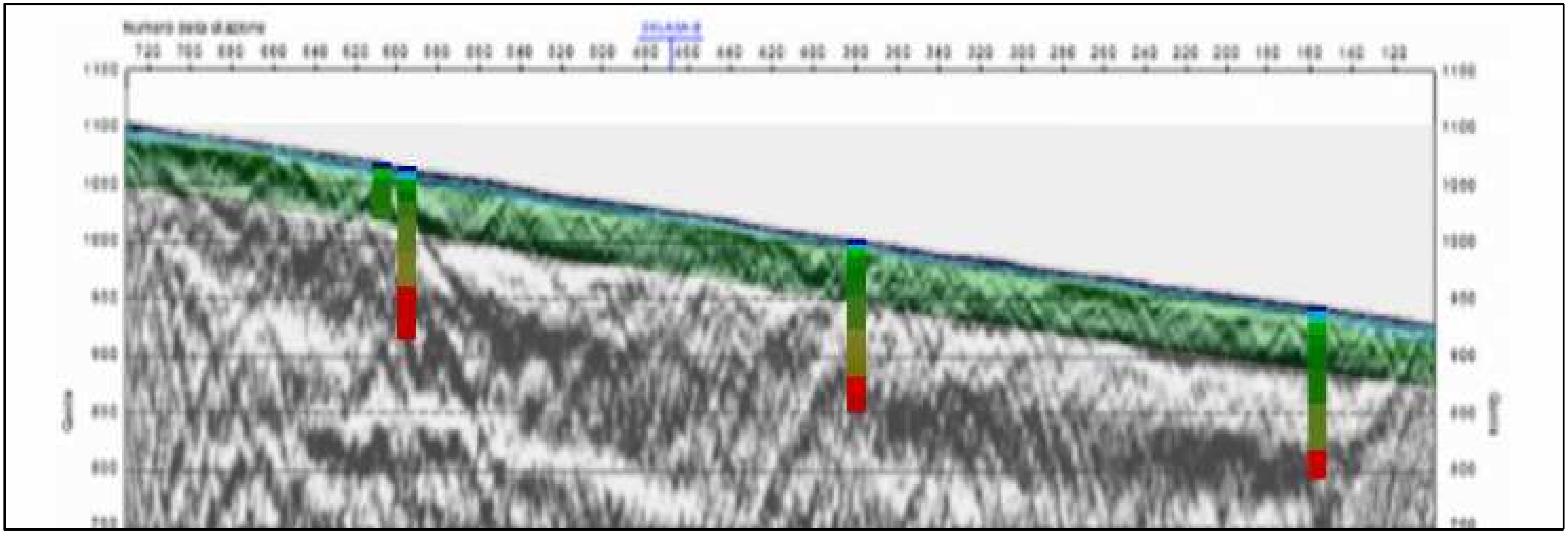
- Full model built up of a number of 1D shear wave velocity models, model parameters are shear wave velocities and depths;
- Lateral constraints couple the different 1D-models. The constraints consist of the spatially dependent covariance between the model parameters
- ... and can be considered as a priori information on the geological variation in the area;
- LCI allows for smooth transitions in model parameters along the profile;
- All data are inverted simultaneously as one system

LINE 1 – shear wave velocity model from groundroll



(Socco, Boiero, Comina, Wisen, Foti 2008)

Data Integration – Vs model and seismic reflection



Case history #3

Investigation of volcanoclastic slopes

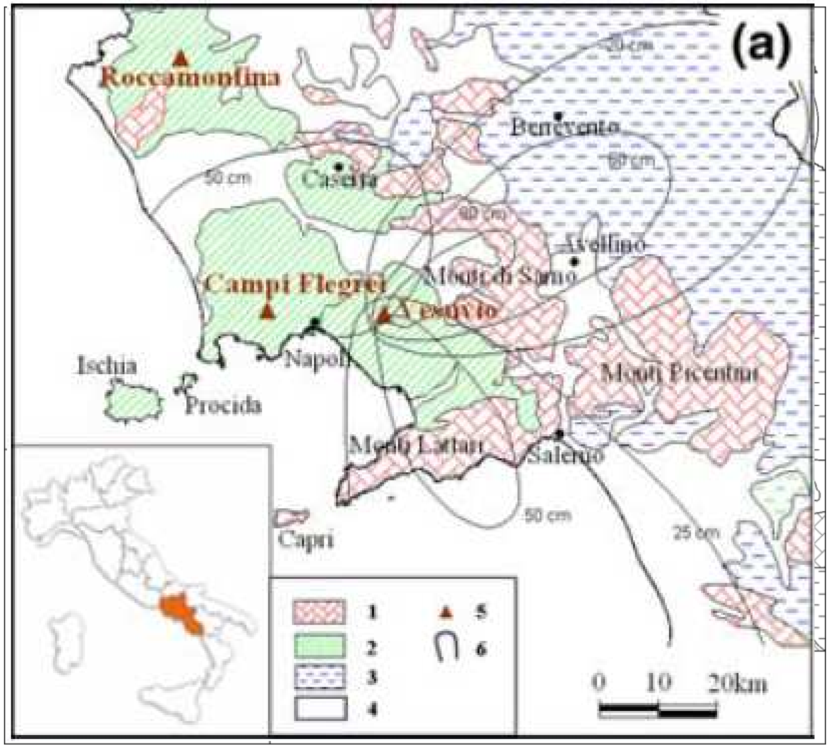
- Combination of several in situ geophysical tests to increase the reliability of the results
- Combination of laboratory and in situ testing for the assessment of saturation conditions

Flowslides of 1998 in Campania

(AP Photo)

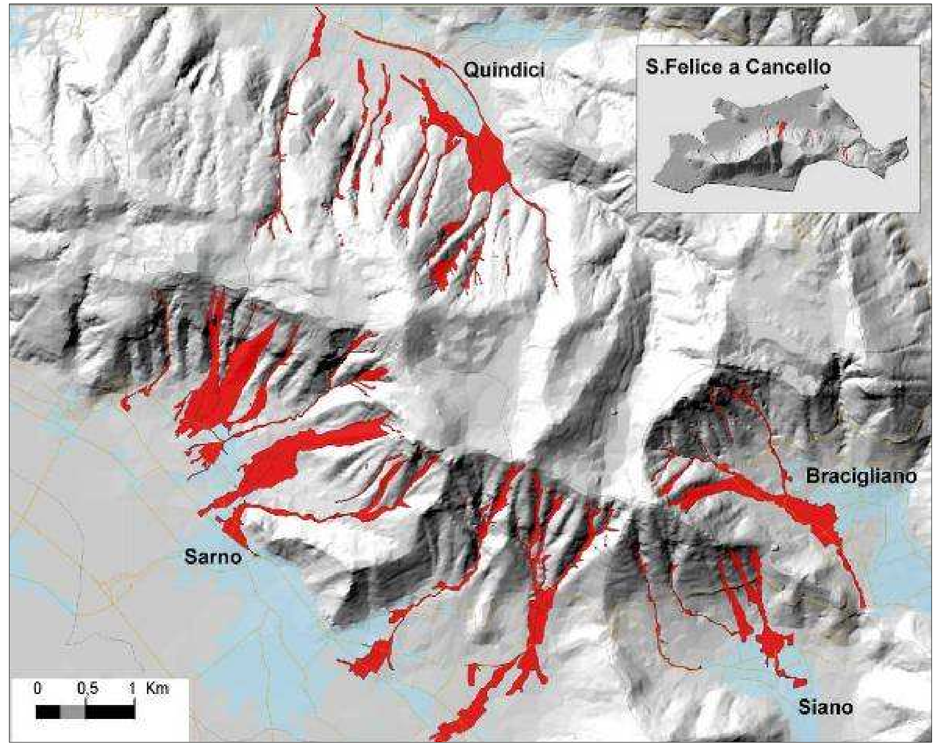
Sarno

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

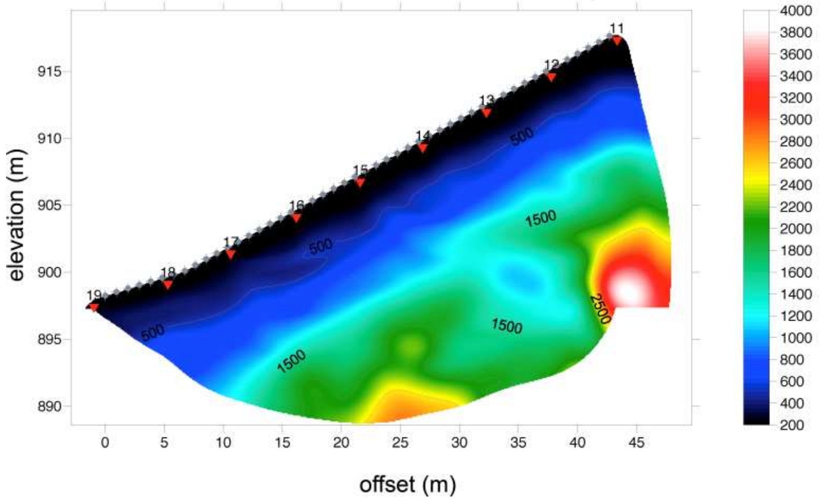
- Quantification of potential volume of the flow (for the design of mitigation infrastructures): **thickness of the soil cover**
- Prevision of onset of the flowslide: assessment and monitoring of **saturation condition of the soil cover**

Critical issues

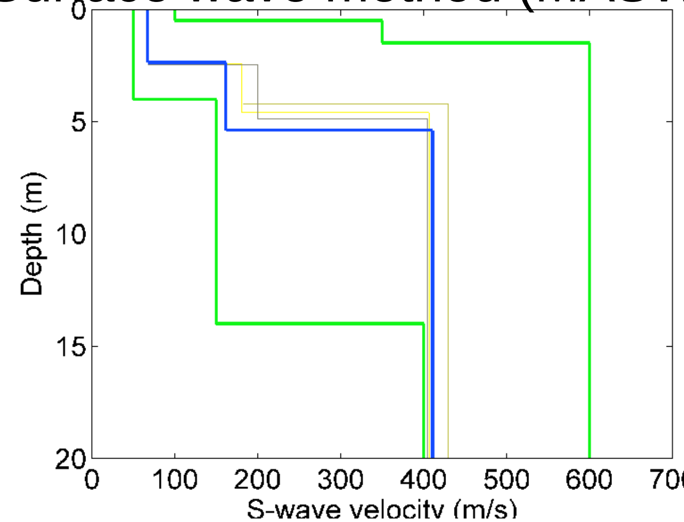
- Very difficult site logistics with steep and vegetated slopes poses strong limitations in the use of conventional site tests (boreholes and penetration testing)
- Necessity of investigating large areas

Combination of different geophysical approaches

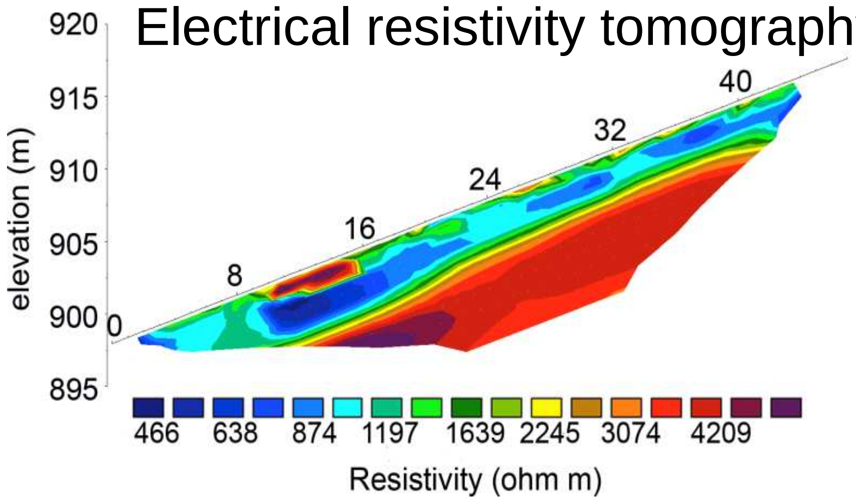
Seismic tomography (V_P)

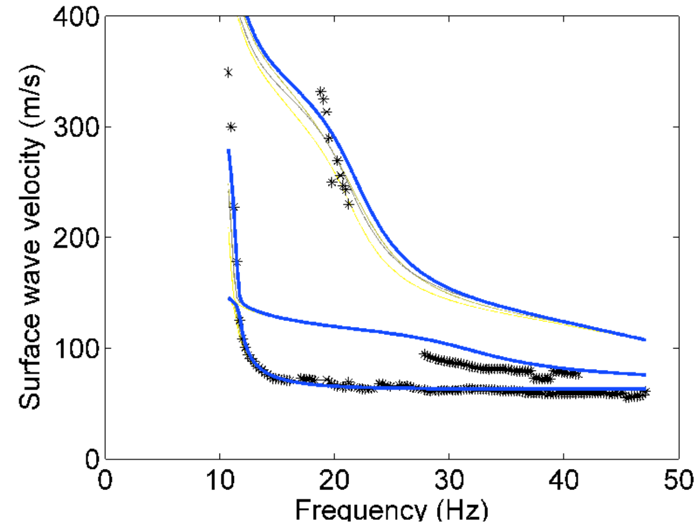


Surface wave method (MASW)



Electrical resistivity tomography



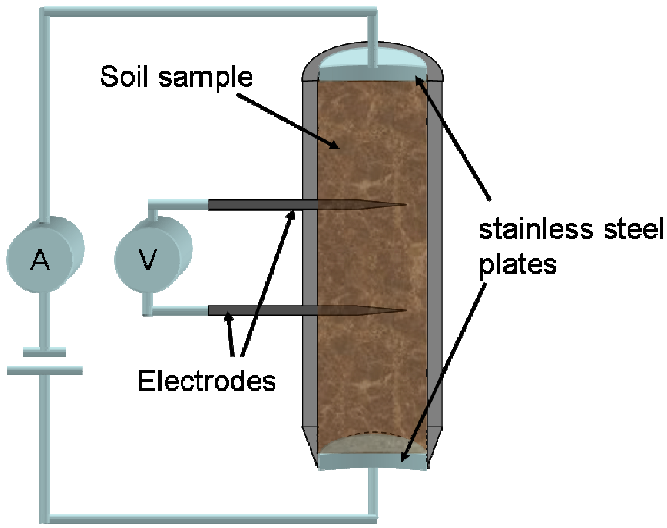


(Cosentini et al., 2012)

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

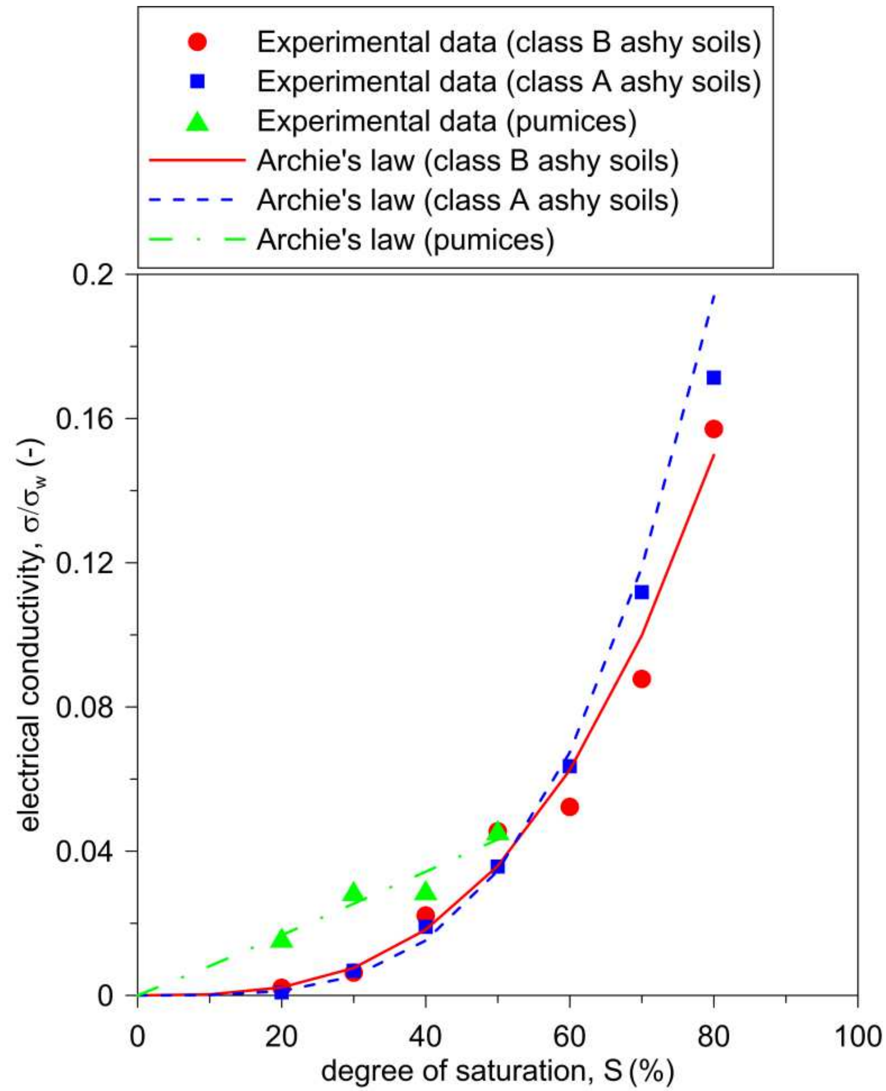


$$\sigma_t = \sigma_w \, n^m \, S_r^p$$

n: porosity

S: saturation

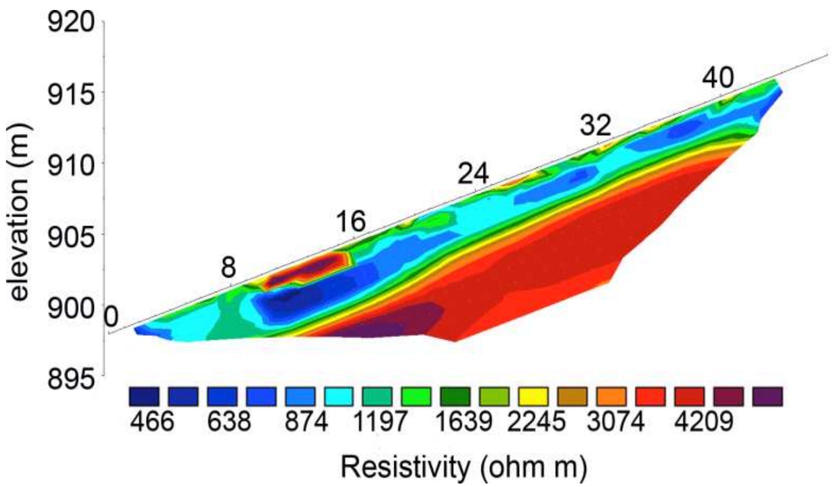
σ_w : pore fluid conductivity

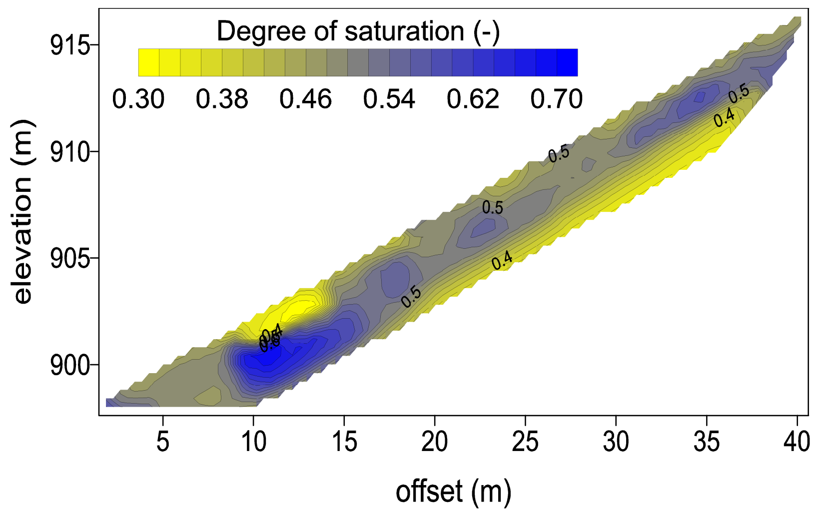


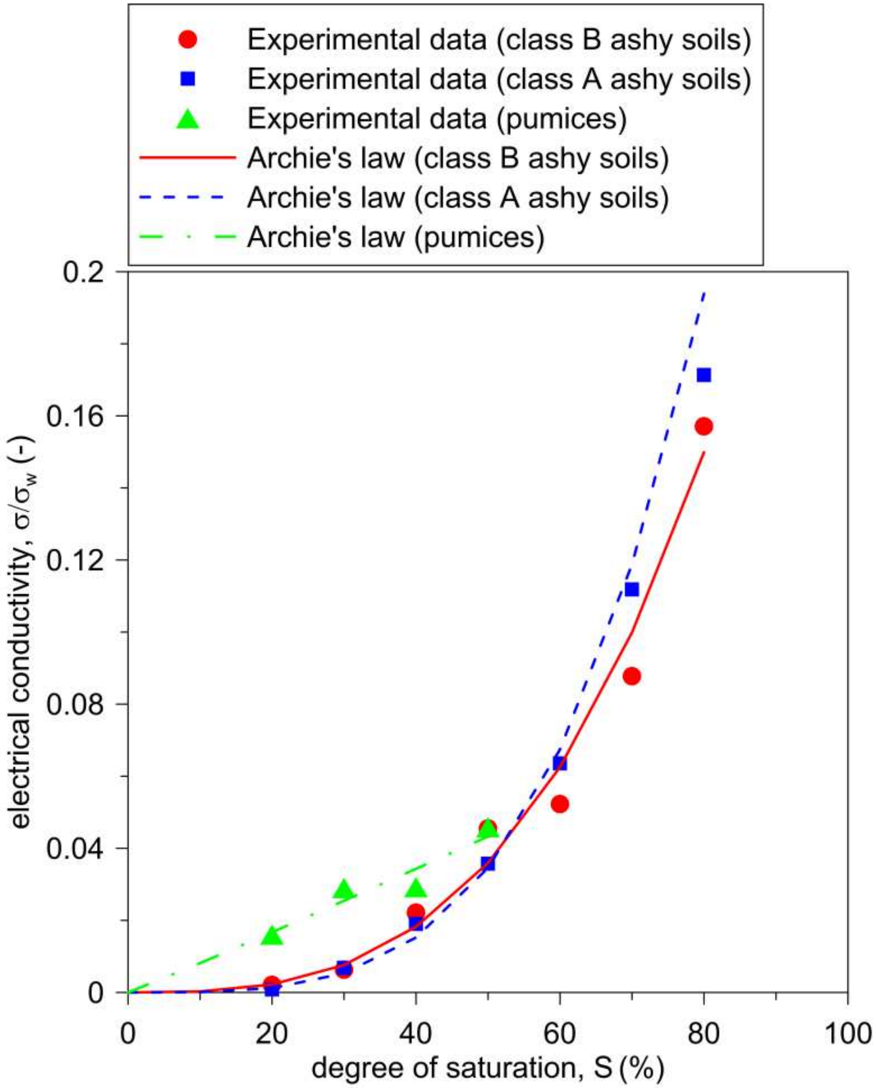
(Cosentini et al., 2012)

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

Mapping resistivity into degree of saturation







(Cosentini et al., 2012)

Closing Remarks

- Geophysical test provide useful tools for geotechnical site characterization
  - 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.
- $V_S \rightarrow G_0$; sample quality
- $V_P \rightarrow$ saturation; porosity ($+M_0 \rightarrow \nu$ for dry soils)
- Surface wave methods are cost and time effective but their interpretation is not simple

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

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Thank you for your attention

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