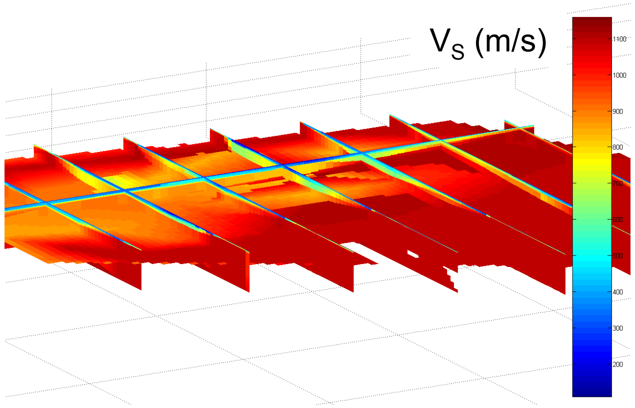
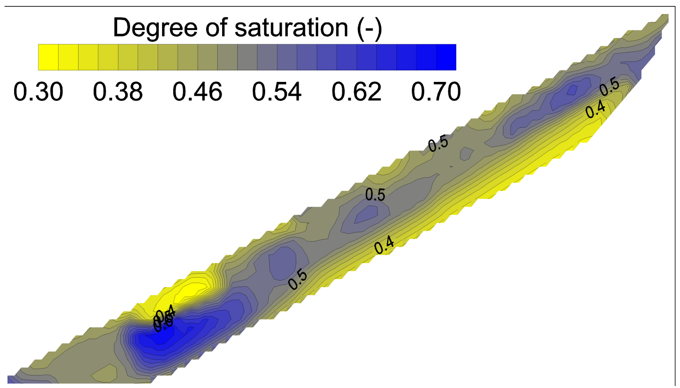
IV International workshop

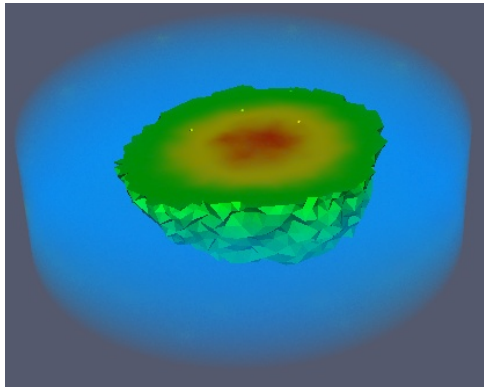
Modern Trends in Geomechanics

Assisi, May 16 -18 2016

Data integration in site characterization







POLITECNICO DI TORINO

(ITALY)

Sebastiano Foti

Outline

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

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)

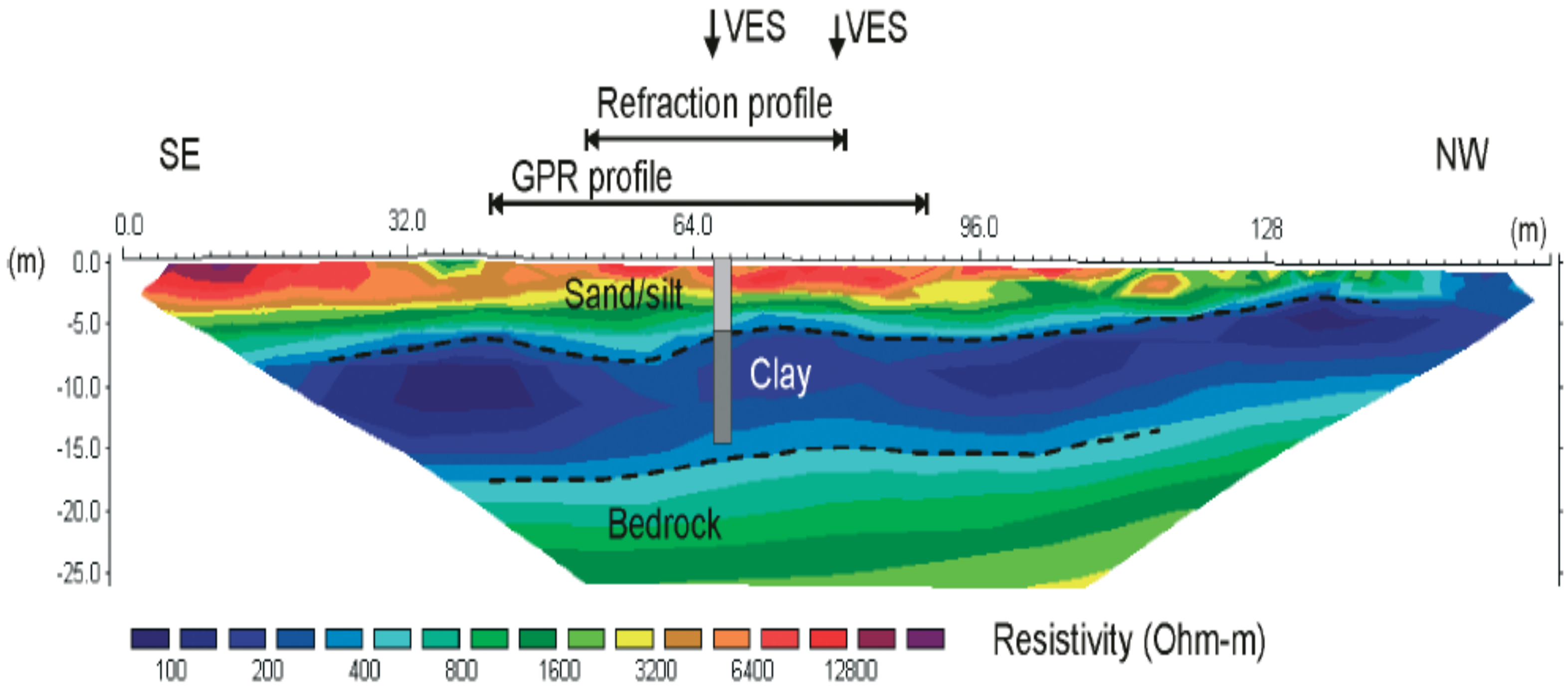
Geotechnical and geoenvironmental site characterization

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

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



Turesson and Lind, 2005

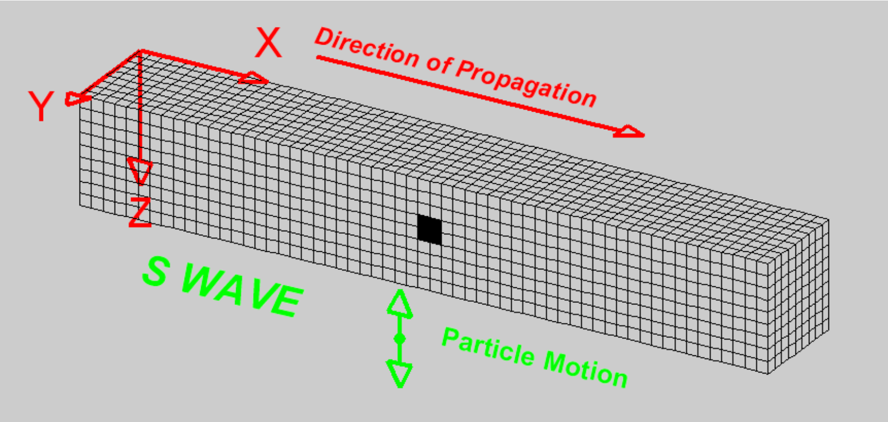
Powerful tools to investigate lateral variations at the site
(e.g. for assessing the potential for differential settlements)

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



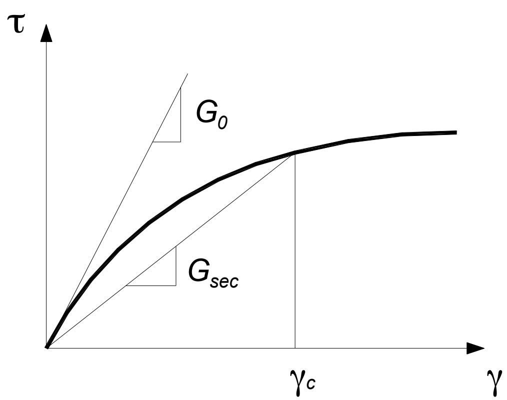
Animation courtesy of
Dr. L. Braile, Purdue University

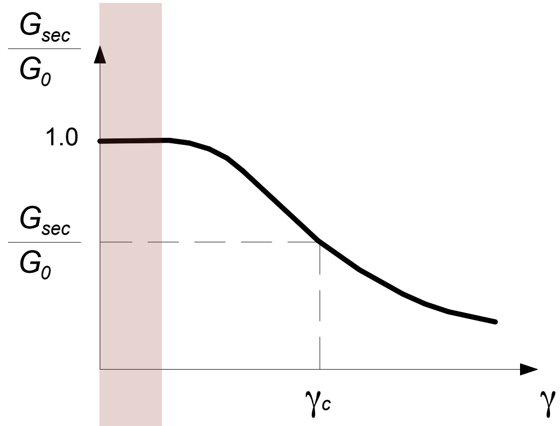
In a linear elastic medium

$$G = \rho V_S^2$$

In soils

$$G_0 = \rho V_S^2$$

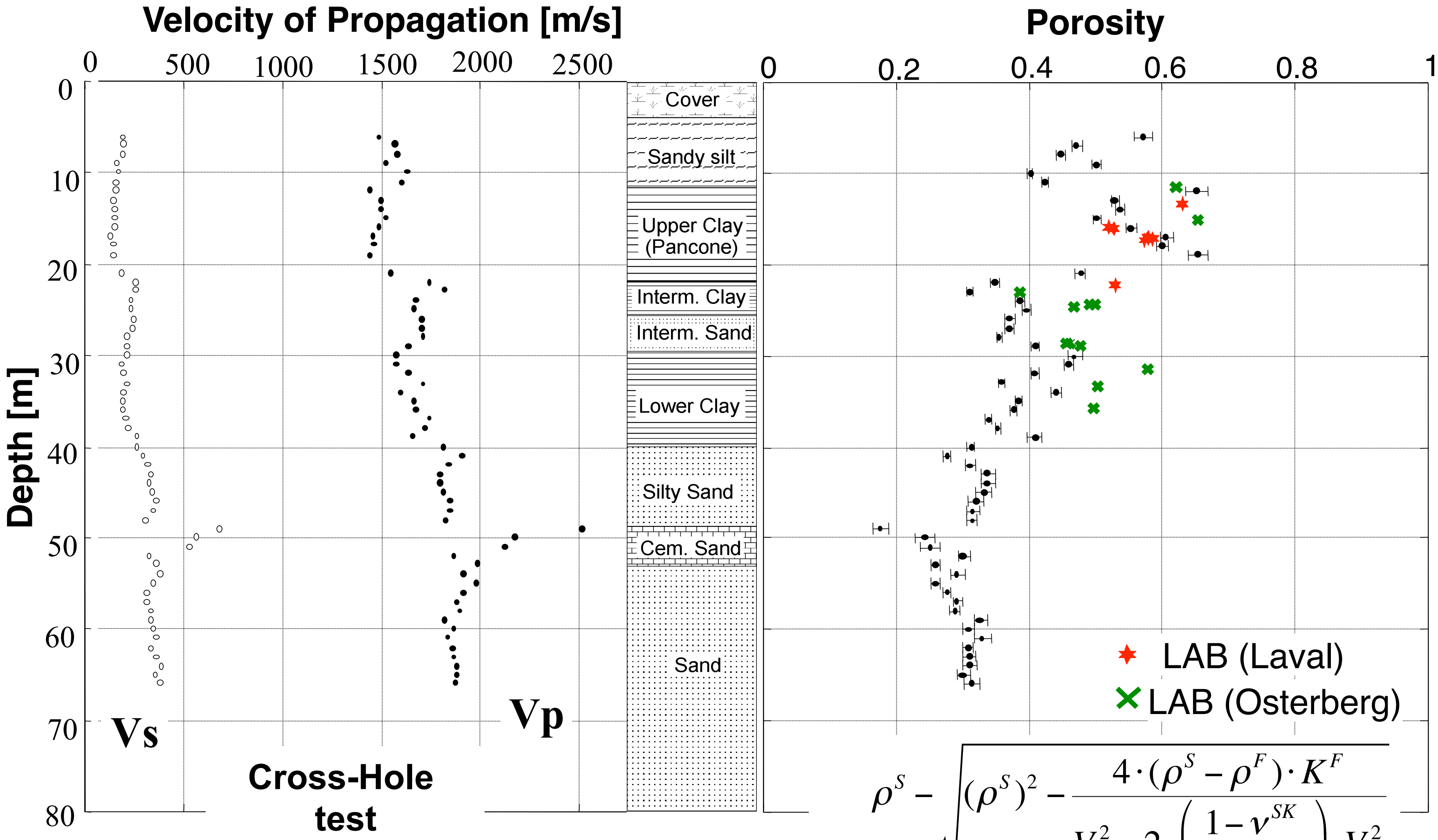




Strain range of
geophysical test

Soil porosity from seismic velocities

Leaning Tower of Pisa site



(Foti et al., 2002)

from Biot's theory:

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

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:

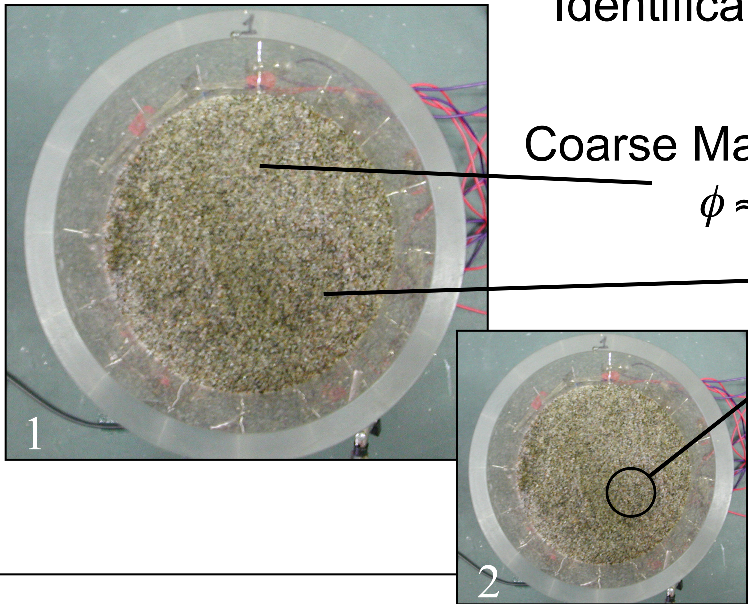
- fluid properties (solubility of ionic species, concentration); σ_w : pore fluid conductivity
- mineralogy and specific surface of the solid grains;
- porosity and fabric

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

Example at Lab scale

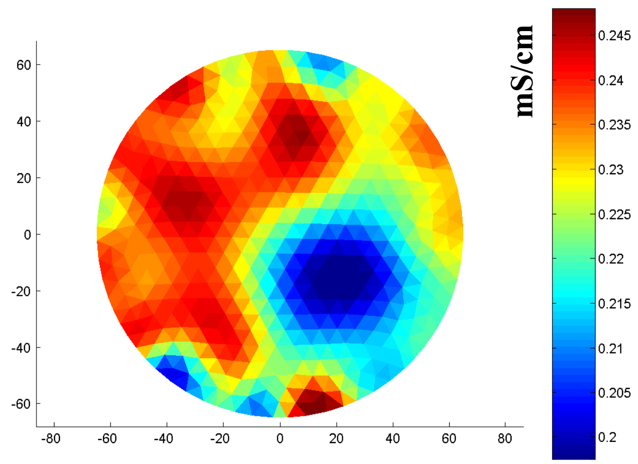
Polito – 2D ERT (Borsic et al., 2005)

Identification of zones with different compaction levels in sand



Coarse Matrix $\phi \approx$ **0.48**

Dense Inclusion $\phi \approx$ **0.43**



3. Tomographic reconstruction

Estimated values with Bruggeman equation

Matrix $\phi \approx$ **0.46**

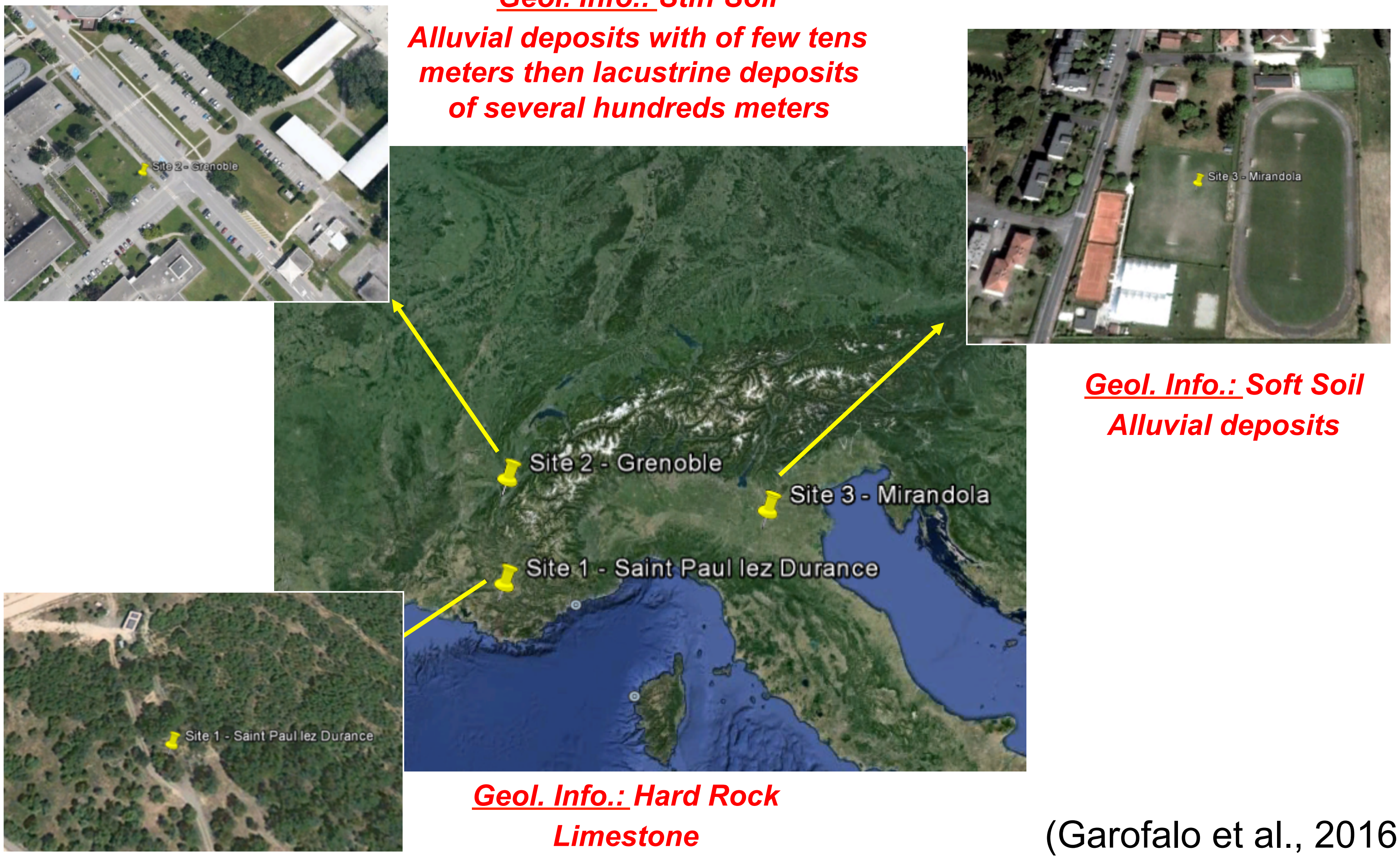
Inclusion $\phi \approx$ **0.42**

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)

Interpacific benchmark: test sites



***Geol. Info.:* Stiff Soil**

Alluvial deposits with of few tens meters then lacustrine deposits of several hundreds meters

***Geol. Info.:* Soft Soil**

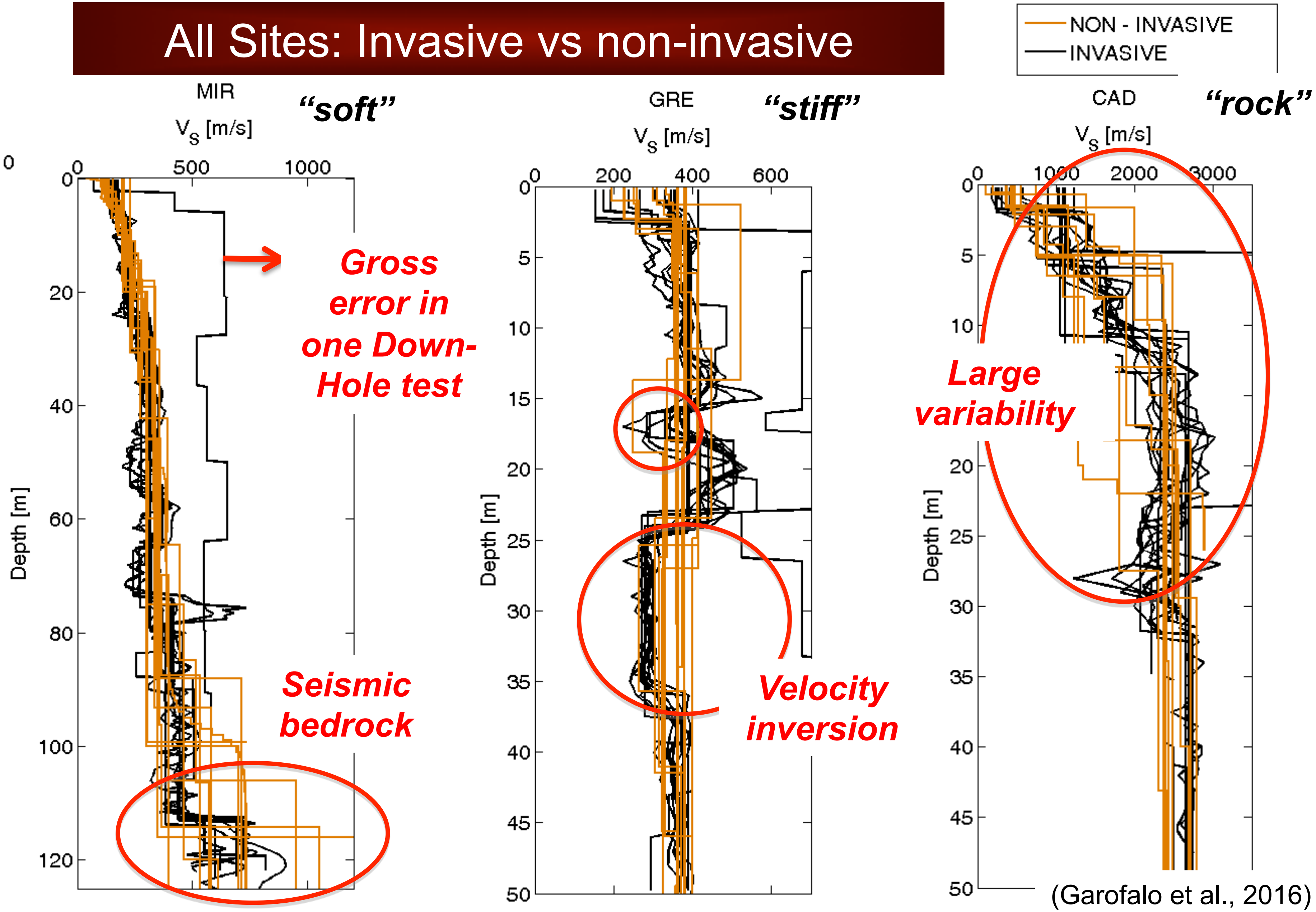
Alluvial deposits

***Geol. Info.:* Hard Rock**

Limestone

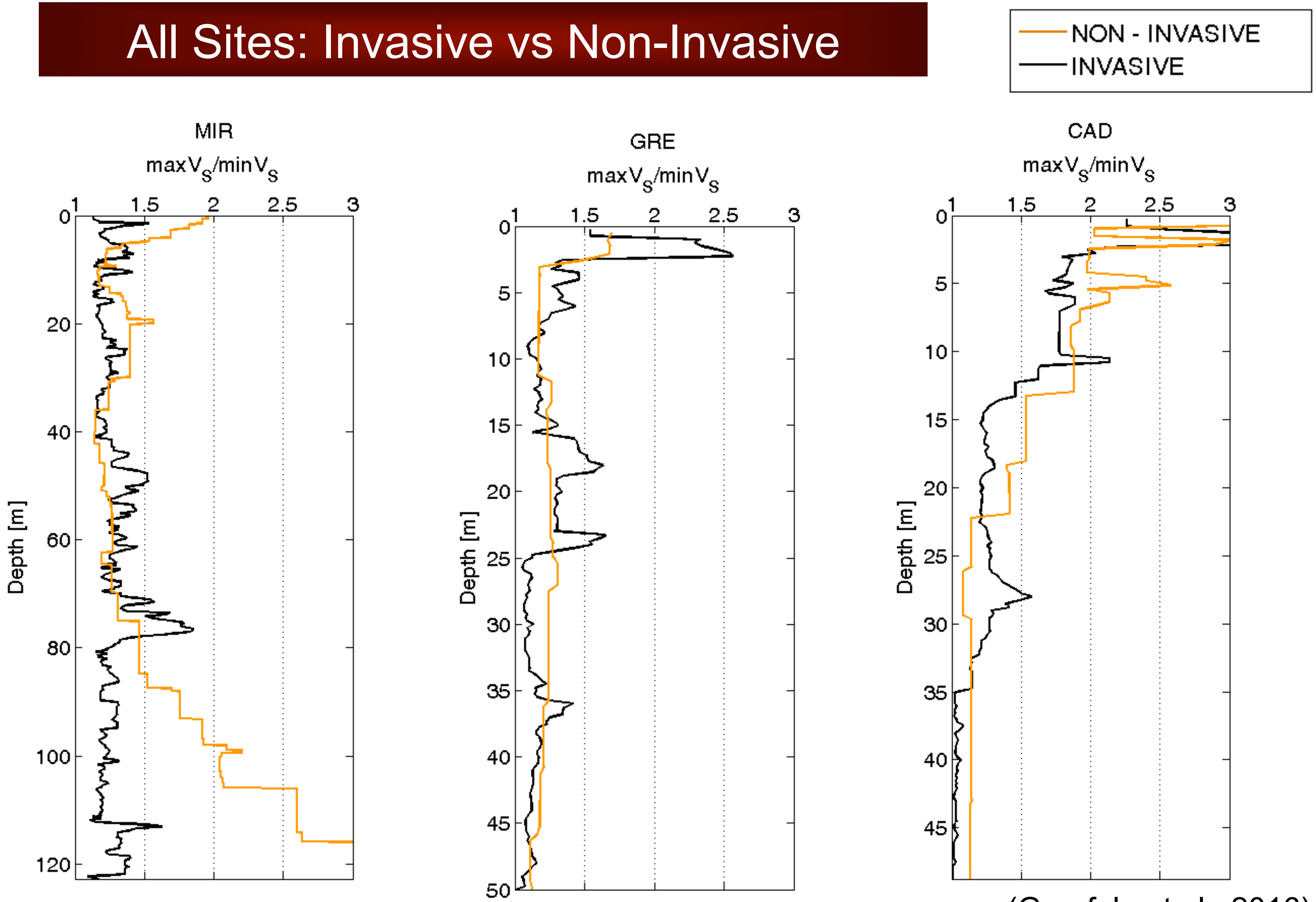
(Garofalo et al., 2016)

All Sites: Invasive vs non-invasive



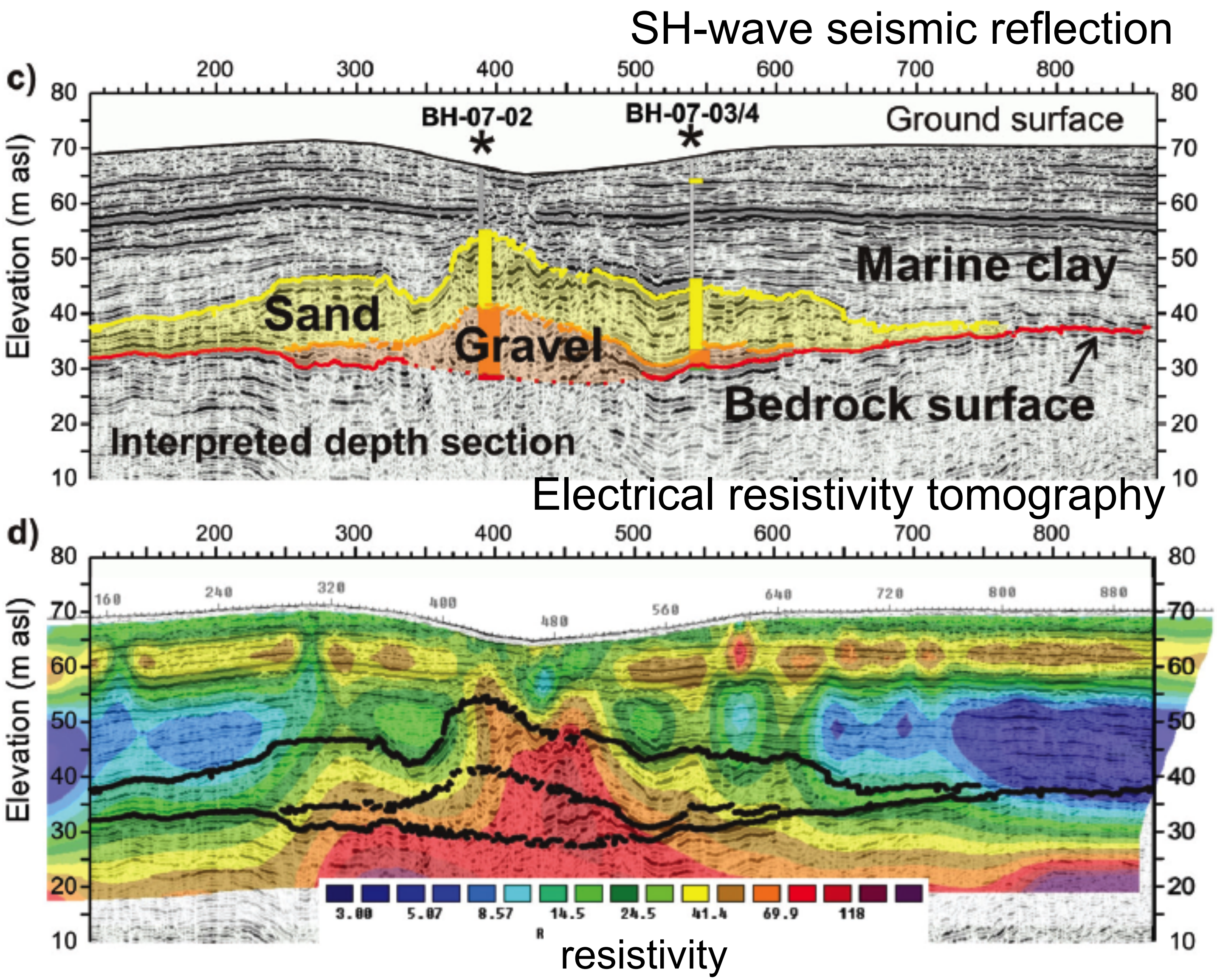
(Garofalo et al., 2016)

All Sites: Invasive vs Non-Invasive



(Garofalo et al., 2016)

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

Most geophysical methods require the solution of inverse problems which are inherently ill-posed and hence subject to solution non-uniqueness.
A-priori information and additional data may provide supplementary constraints to improve the reliability of the solution

Level 4: joint inversion

(Piatti et al., 2012b)

EXAMPLE

A single inversion problems is solved considering all the available experimental information: e.g. the best fit parameters for both V_P and V_S models are obtained from seismic refraction and surface wave data

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

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

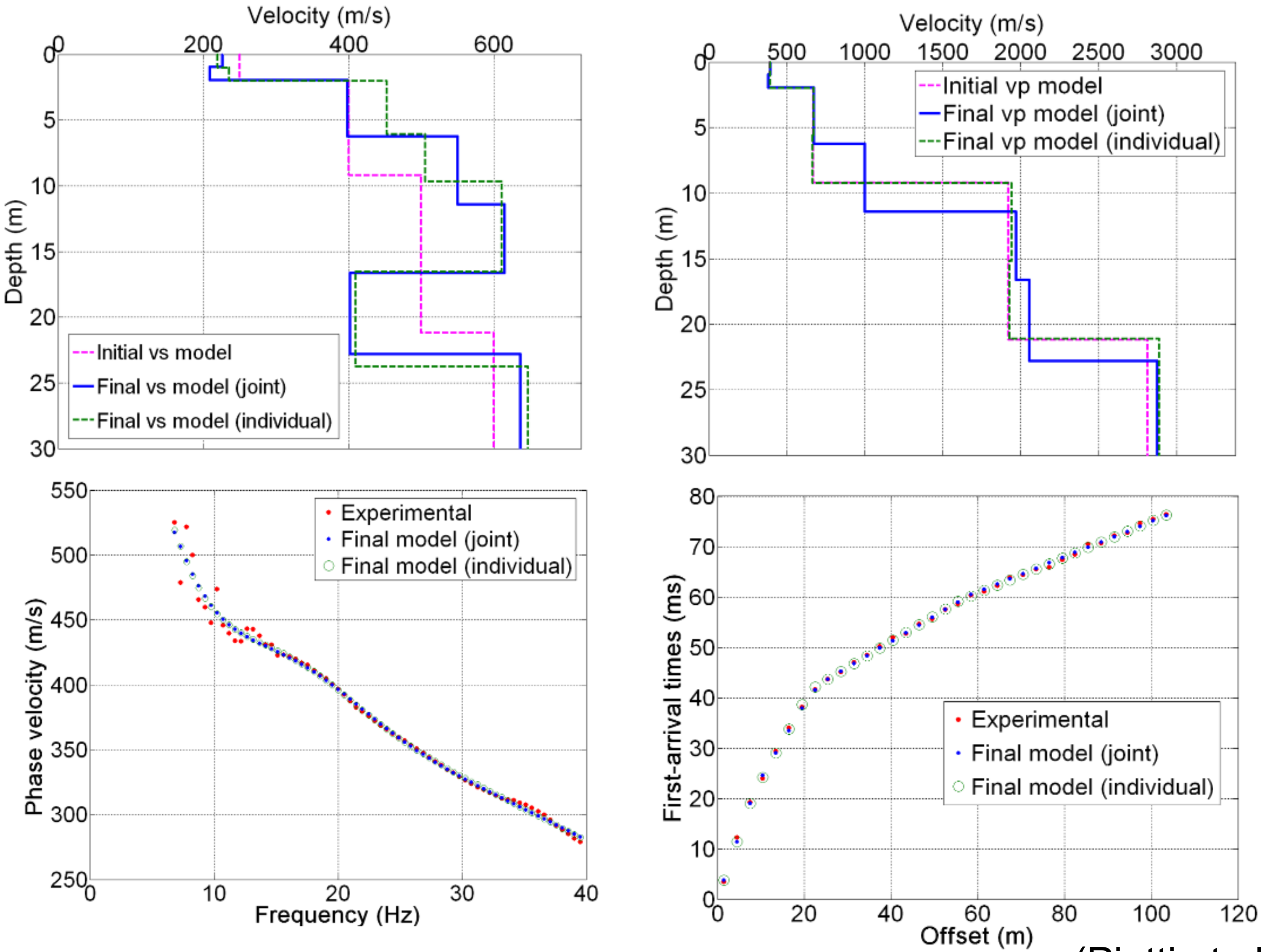
$$\mathbf{d}_{obs} = \left[\left(\log(V_{R1}),\ \log(V_{R2}),\ ....,\ \log(V_{RN'}) \right) \left(\log(t_1),\ \log(t_2),\ ....,\ \log(t_{N''}) \right) \right]$$

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

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

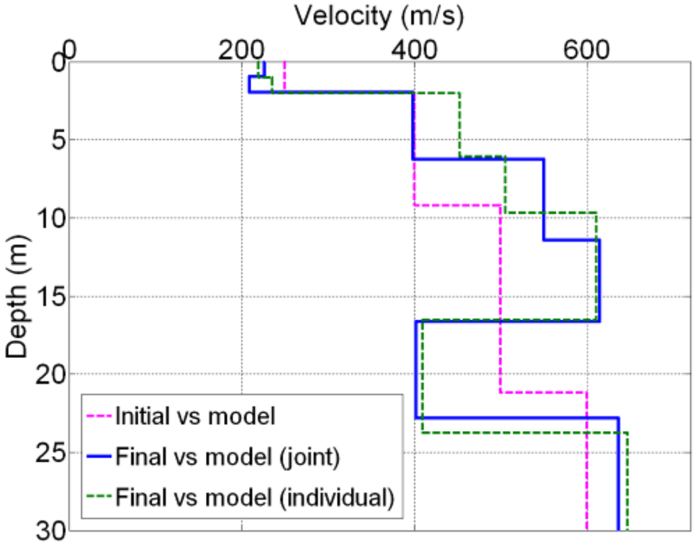
Structural link: the two layered models share the same geometry

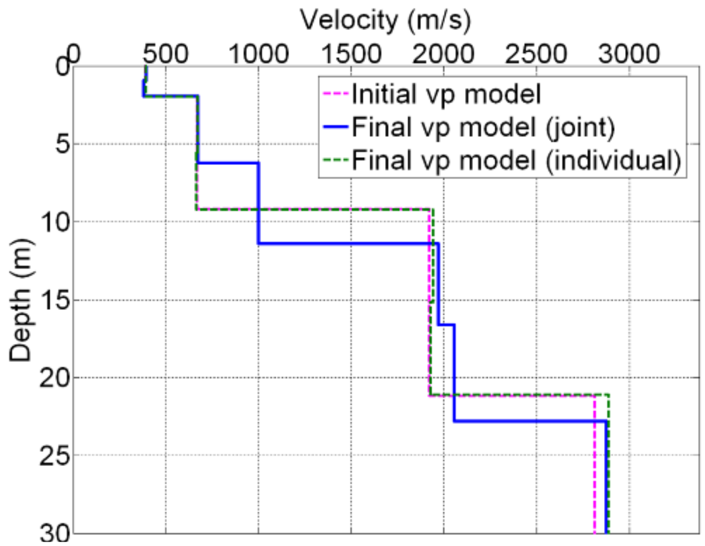
Experimental data

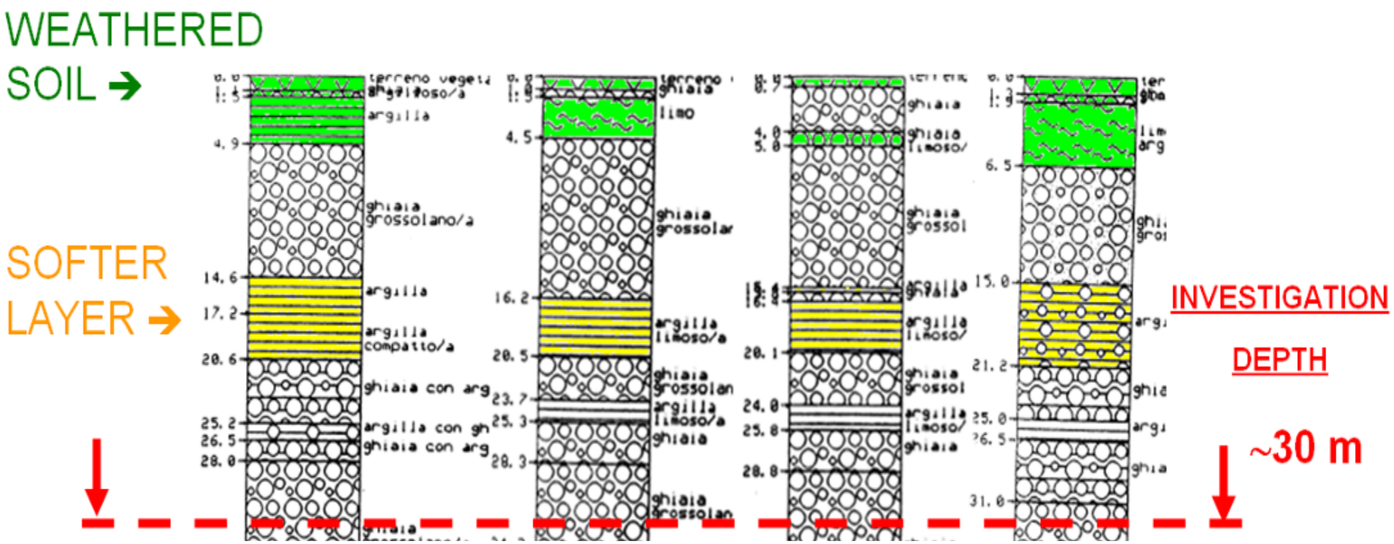


(Piatti et al., 2012b)

Experimental data







(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

Seepage potential

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

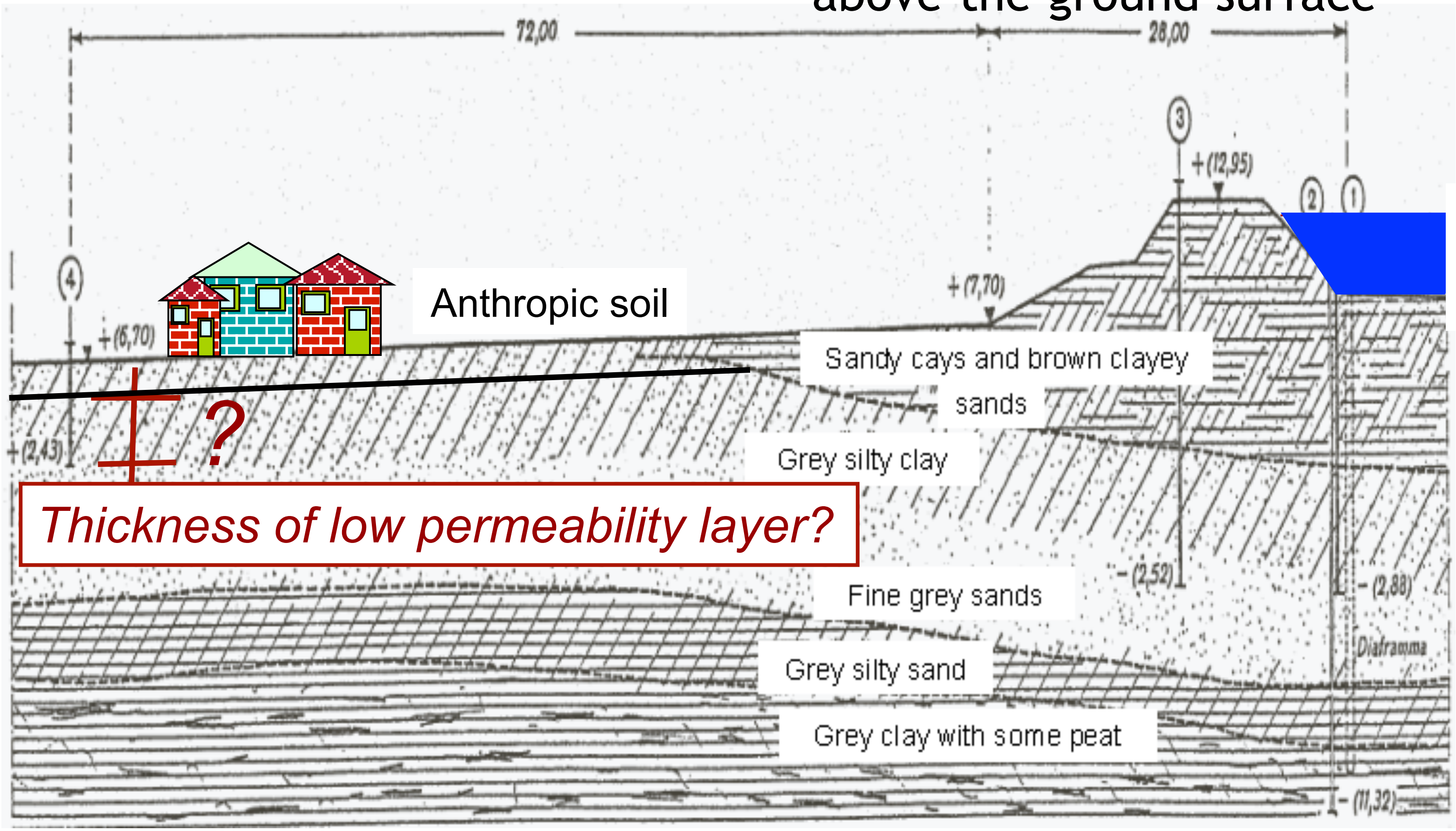
10 extreme events each 100 years

Levees for a total length over 2400 km

Seepage potential

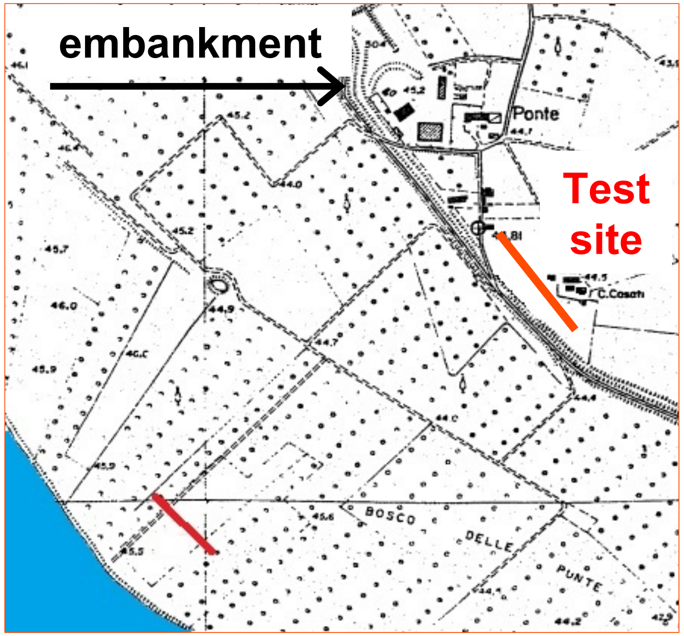
Geology: alluvial deposits: recent sands, gravel, clay
TARGET: clayey layer: continuity, thickness

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



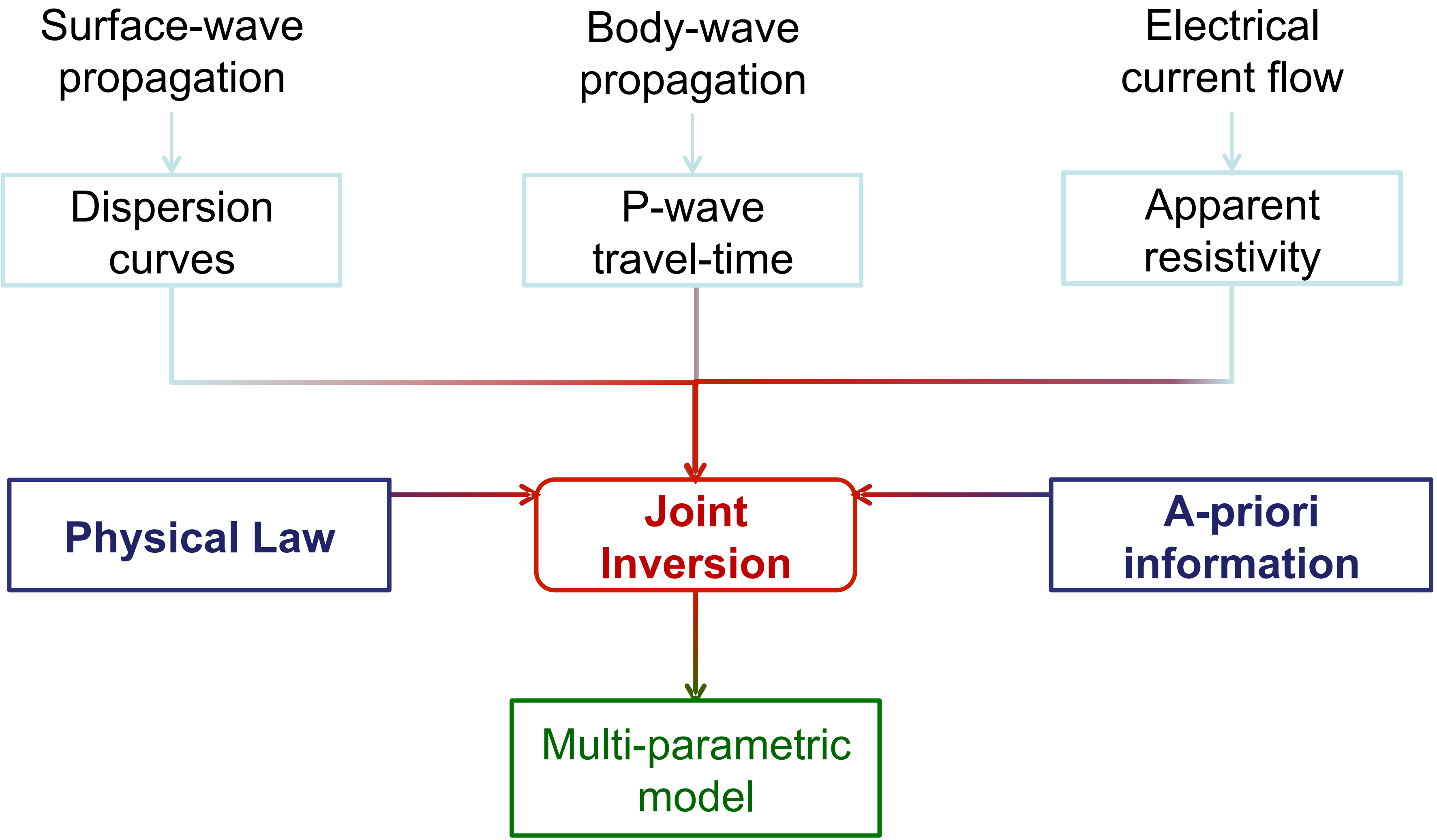
Local geology: layers of sand and clay.
Expected shallow water table

Integrated geophysical survey:

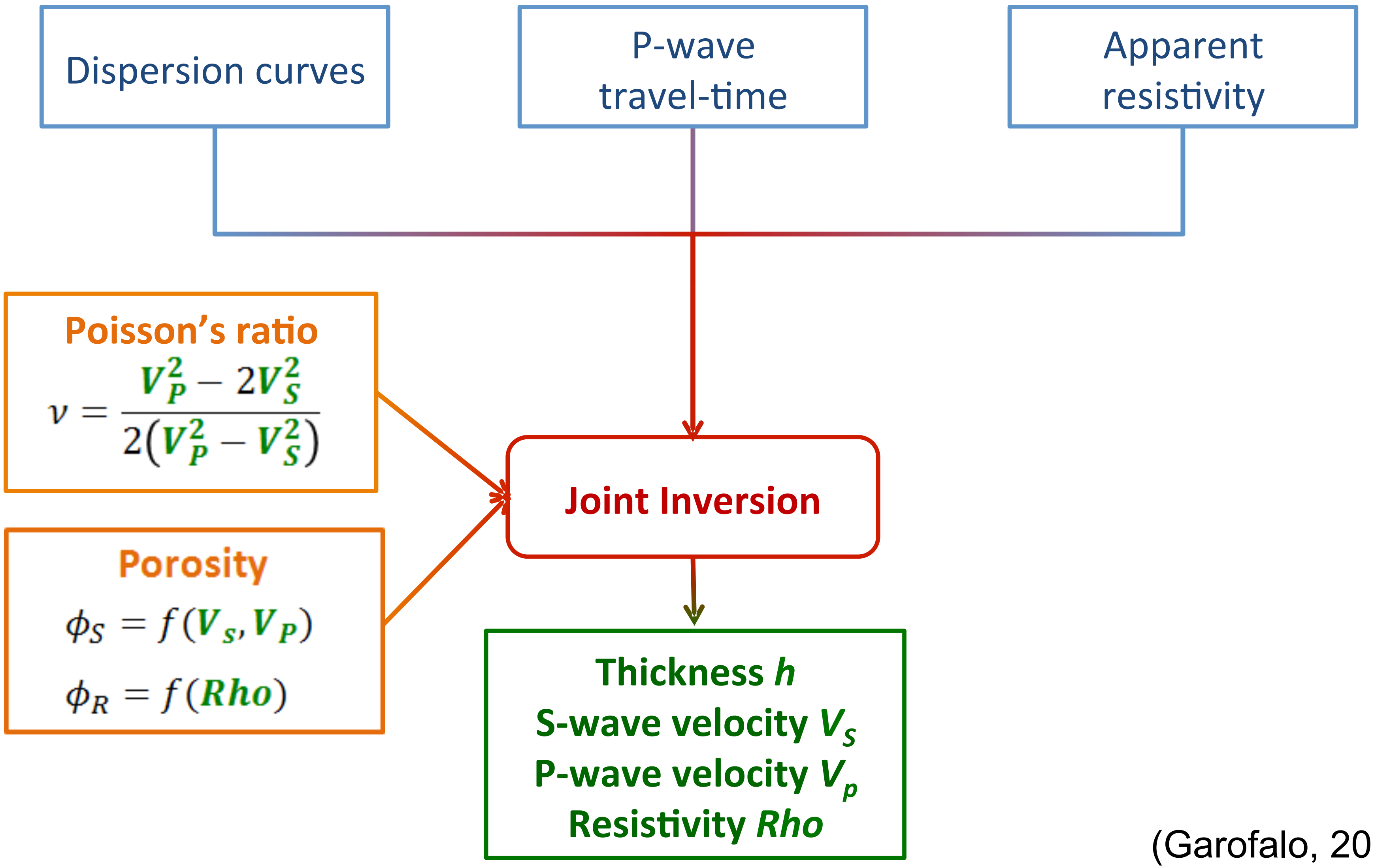
- Seismic acquisition for surface wave
- Seismic acquisition for P-wave refraction
- Vertical Electrical Sounding

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



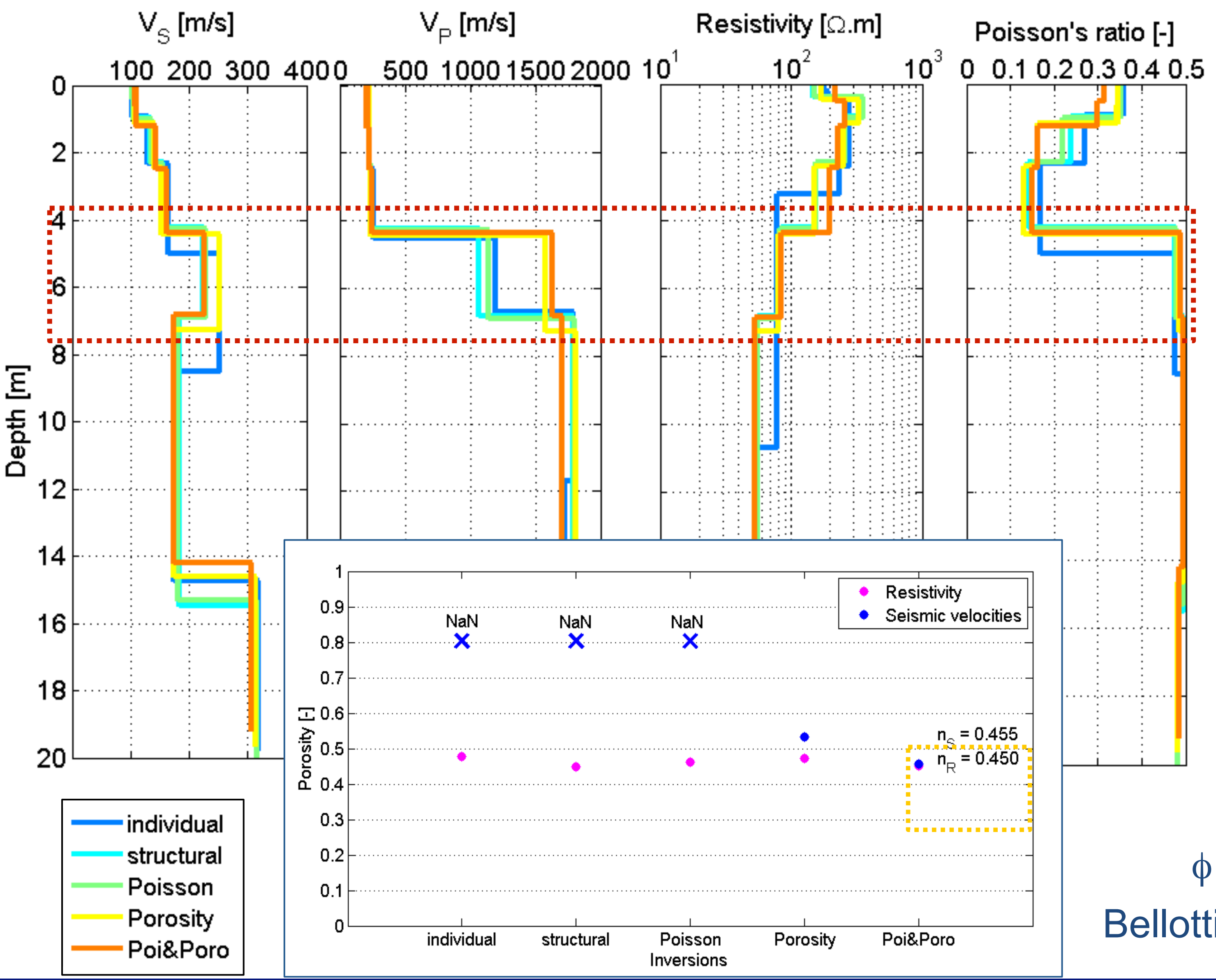
Joint inversion algorithm



(Garofalo, 2014)

Field case - results

(Garofalo, 2014)

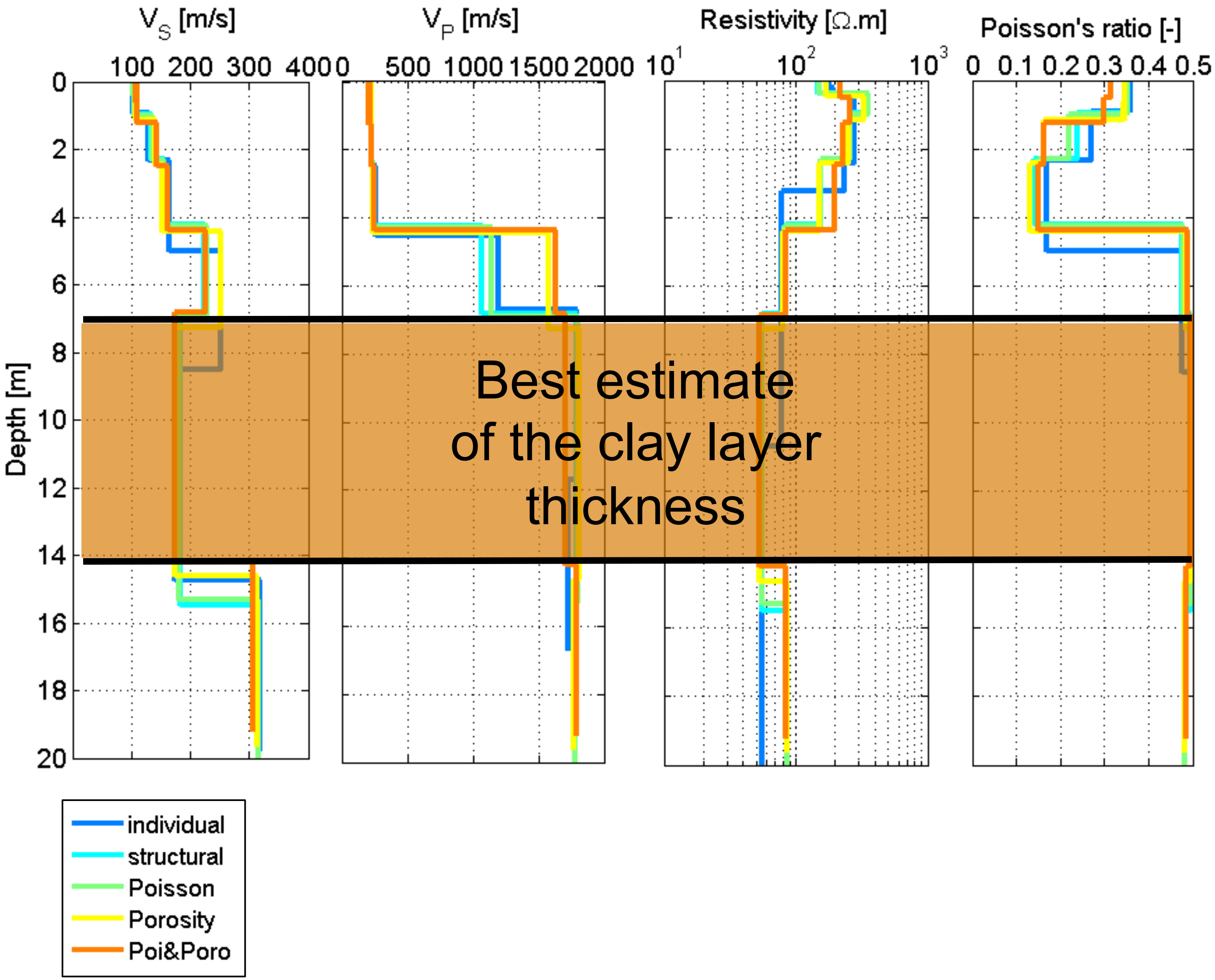


- Saturated layer (sand)

$\phi = 0.42 - 0.52$

Bellotti and Selleri (1969)

Field case - results



(Garofalo, 2014)

Case history #3

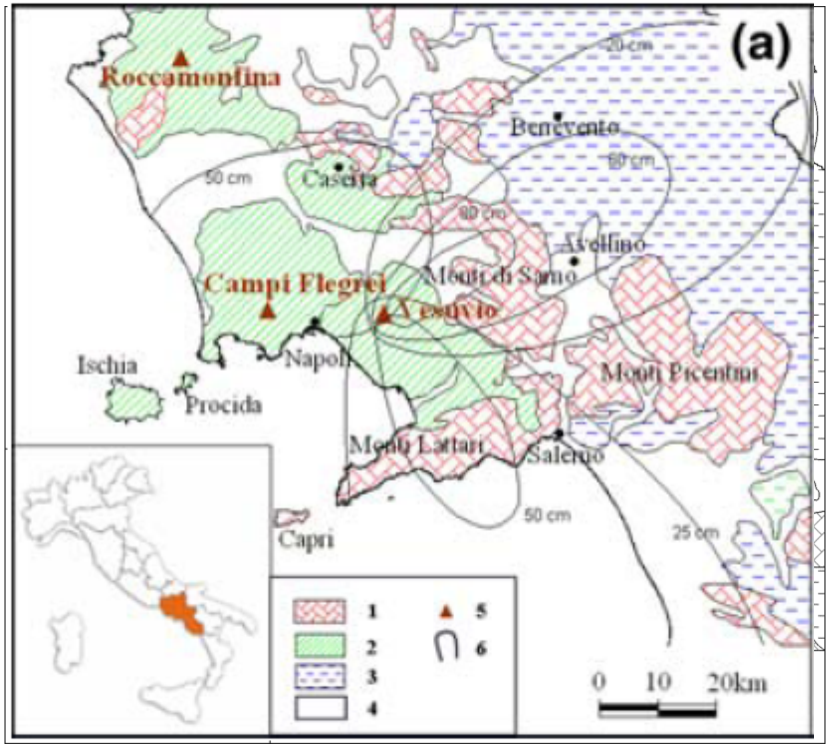
Investigation of volcanoclastic slopes

- 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

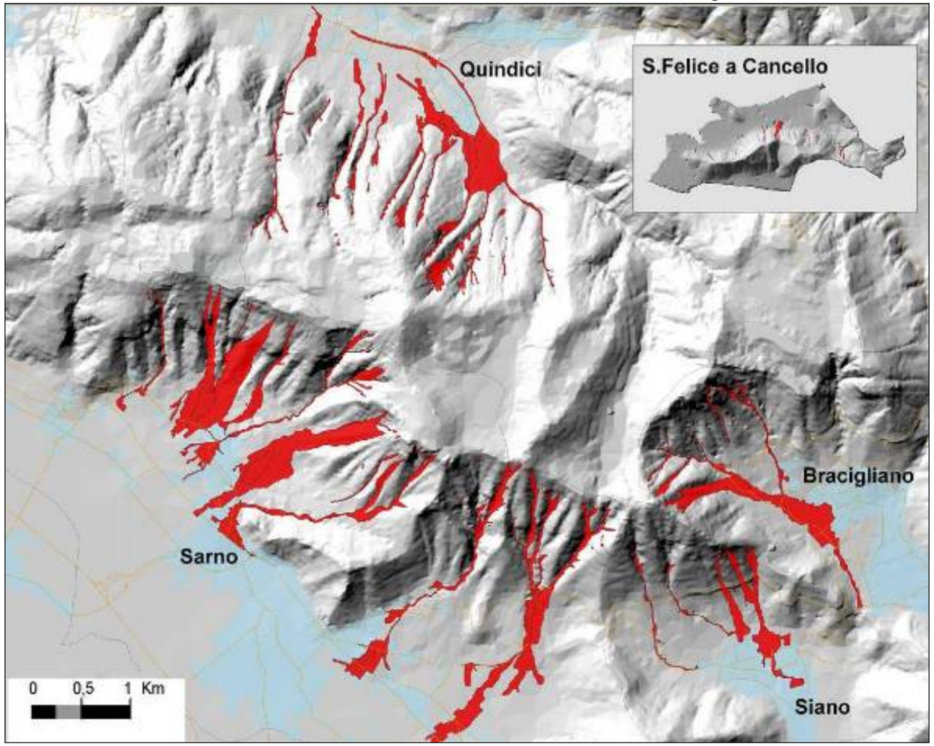
Sarno

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

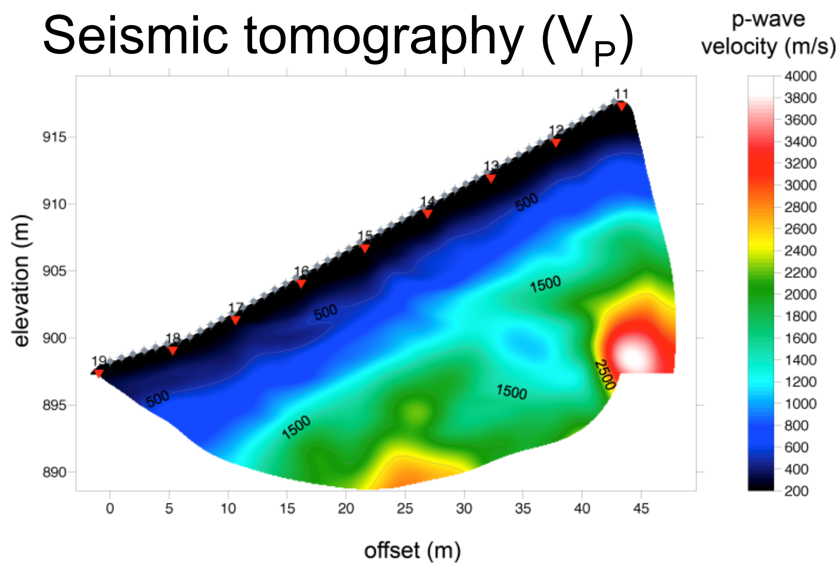
- Quantification of potential volume of the flow (for the design of mitigation infrastructures): **thickness of the soil cover**
- Prevision of onset of the flowslide: assessment and monitoring of **saturation condition of the soil cover**

Critical issues

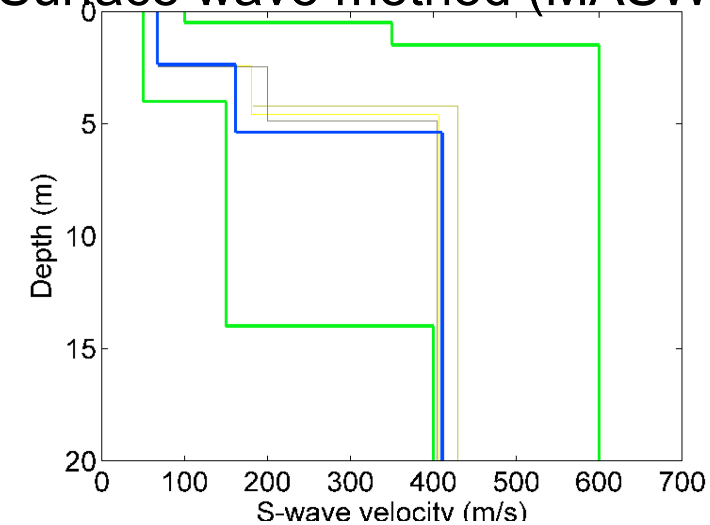
- Very difficult site logistics with steep and vegetated slopes poses strong limitations in the use of conventional site tests (boreholes and penetration testing)
- Necessity of investigating large areas

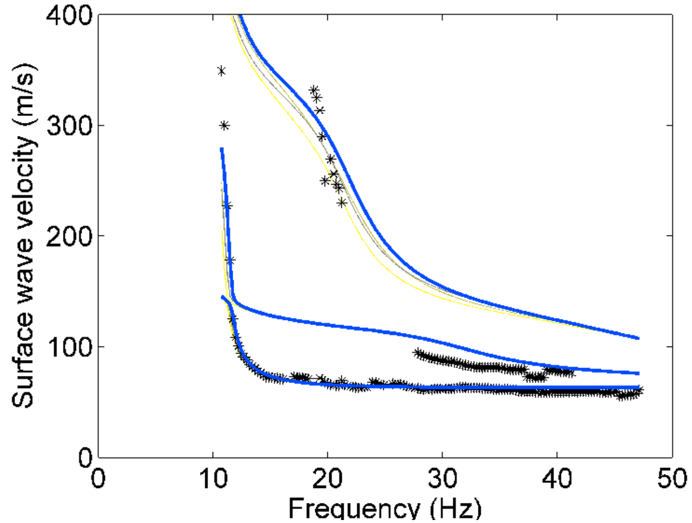
Combination of different geophysical approaches

Seismic tomography (V_P)

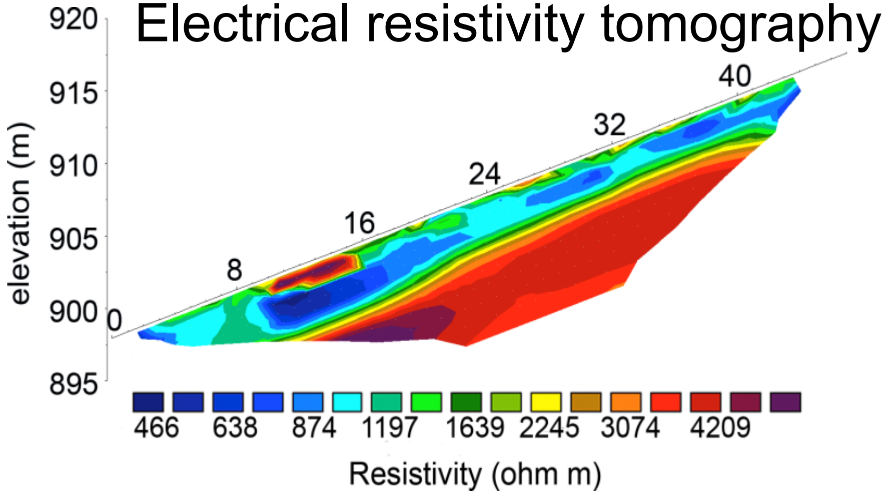


Surface wave method (MASW)



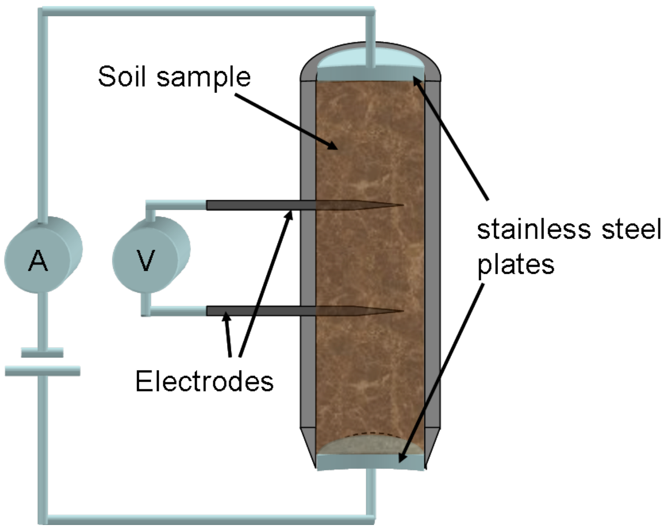


Electrical resistivity tomography



(Cosentini et al., 2012)

Laboratory calibration of Archie's law for unsat materials

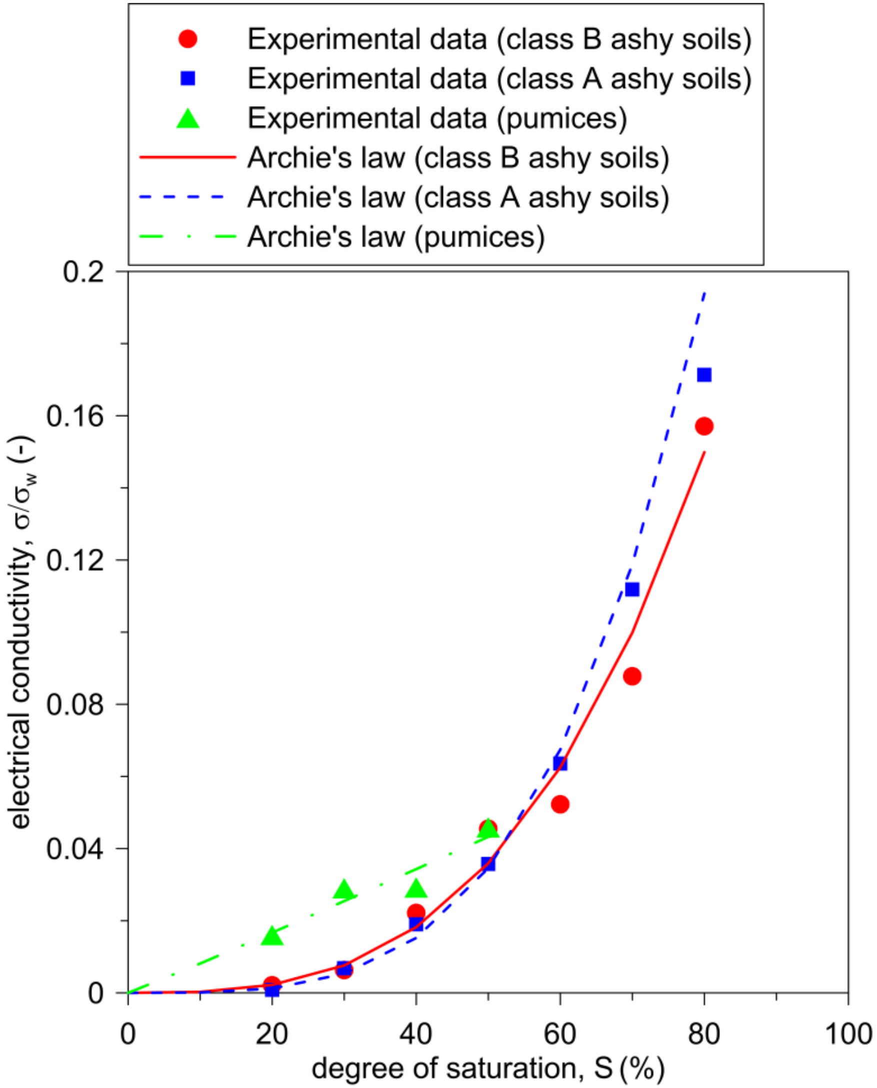


$$\sigma_t = \sigma_w \, \phi^m \, S_r^{\,p}$$

ϕ: porosity

S: saturation

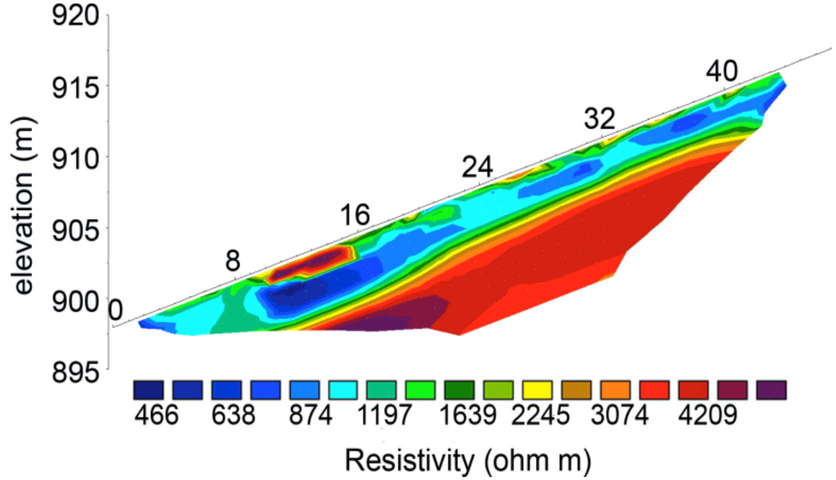
σ_w : pore fluid conductivity

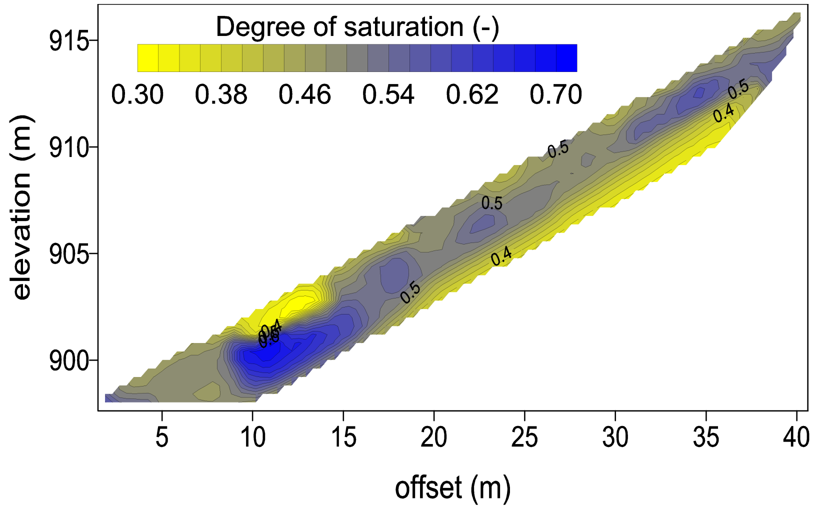


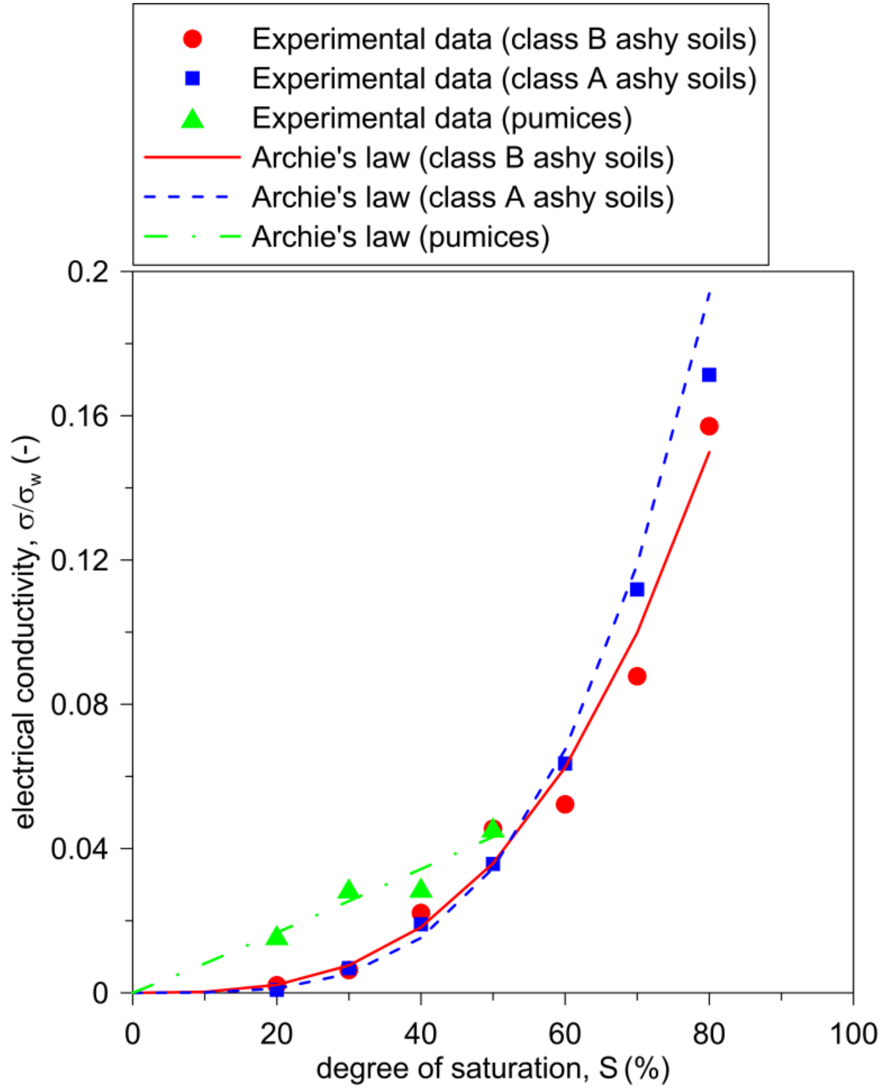
(Cosentini et al., 2012)

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

Mapping resistivity into degree of saturation







(Cosentini et al., 2012)

Porosity assumed a-priori on the basis of independent estimates

Porosity & Degree of Saturation

- Wave propagation in unsat porous media (Conte et al., 2009)

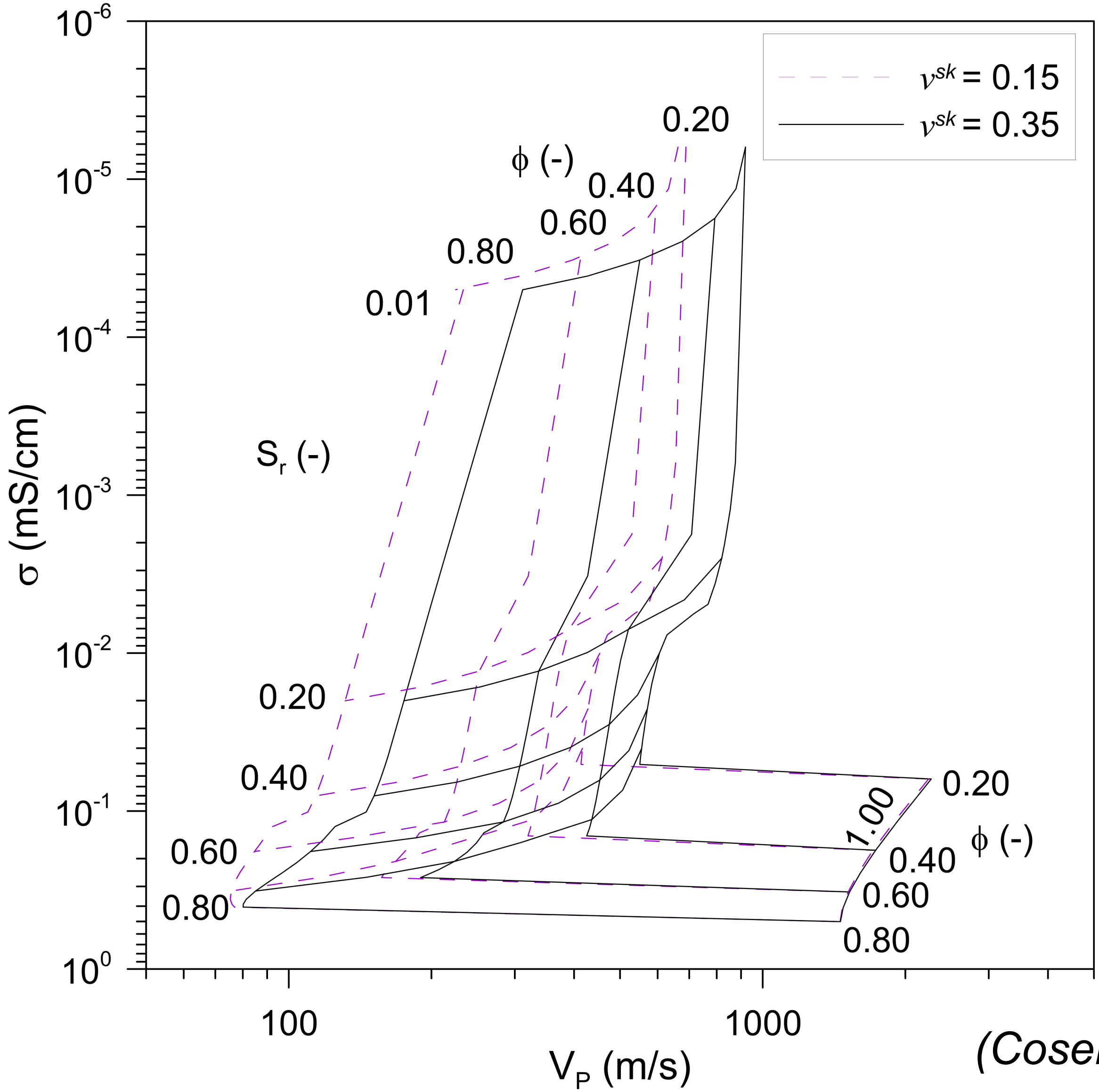
$$V_P^2 = \frac{\frac{2(1-\nu^{sk})}{1-2\nu^{sk}}G + \frac{K^a K^w \left[m_2^w - \frac{3(1-2\nu^{sk})S_r^2}{2(1+\nu^{sk})G}\right] + \phi S_r(1-S_r)\left[K^w S_r + K^a(1-S_r)\right]}{\phi\left[K^a S_r + K^w(1-S_r)\right]\left[m_2^w - \frac{3(1-2\nu^{sk})S_r^2}{2(1+\nu^{sk})G}\right] + \phi^2 S_r(1-S_r)}}{(1-\phi)\rho_s + S_r\phi\rho_w + (1-S_r)\phi\rho_a}$$

$$V_S^2 = \frac{G}{(1-\phi)\rho_s + S_r\phi\rho_w + (1-S_r)\phi\rho_a}$$

- Archie's Law (electrical conductivity)

$$\sigma = \sigma_w \phi^p S_r^q$$

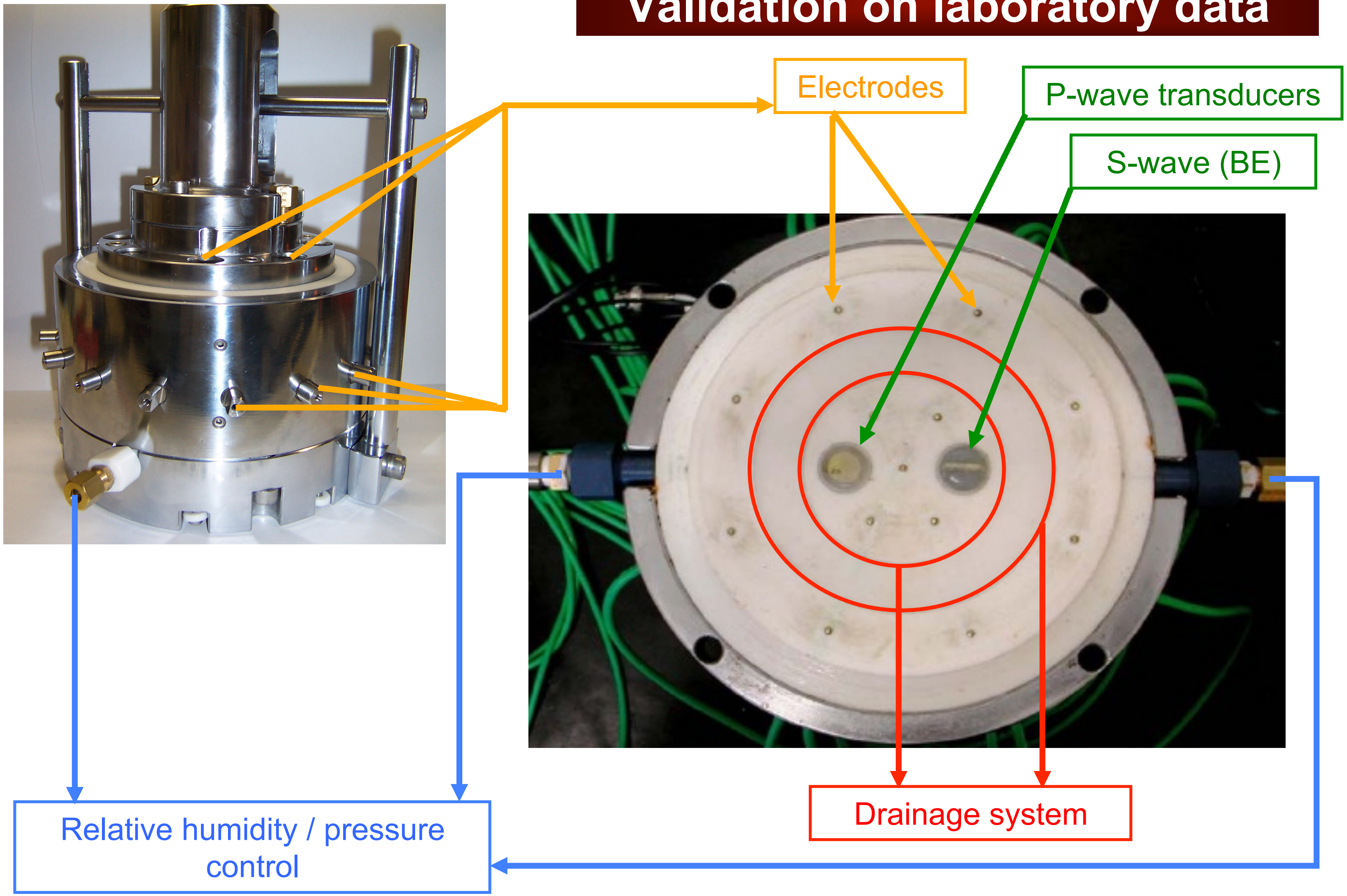
Seismo-electrical model for unsat soils



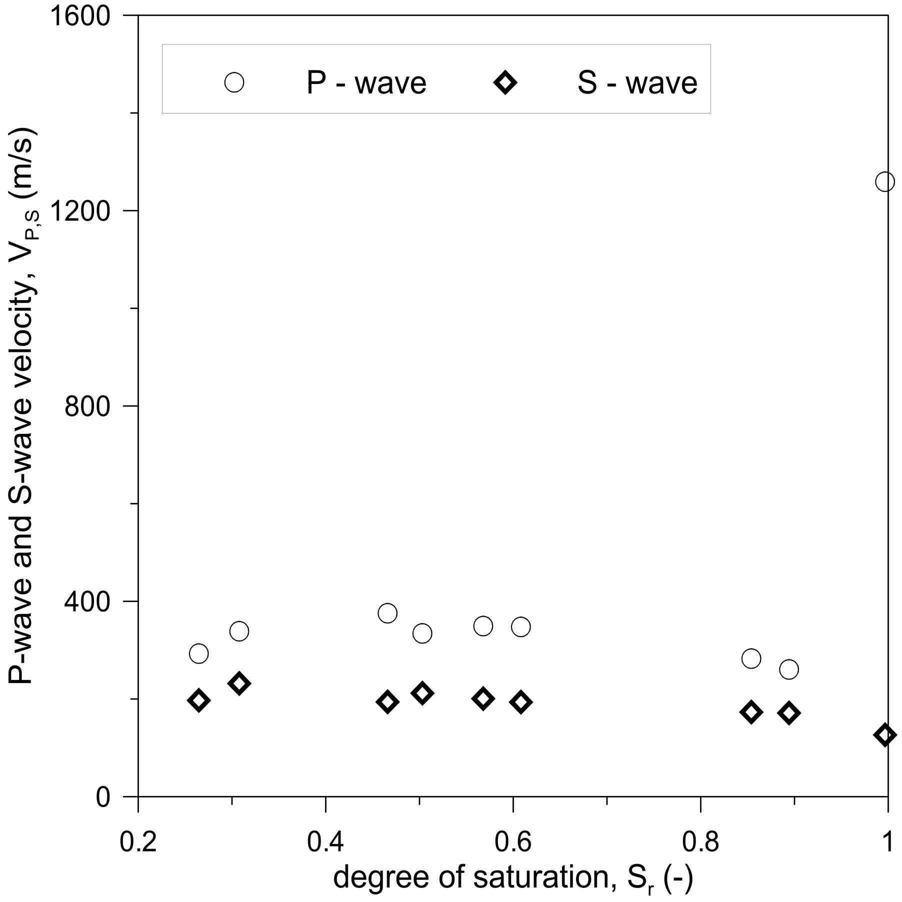
(Cosentini & Foti, 2014)

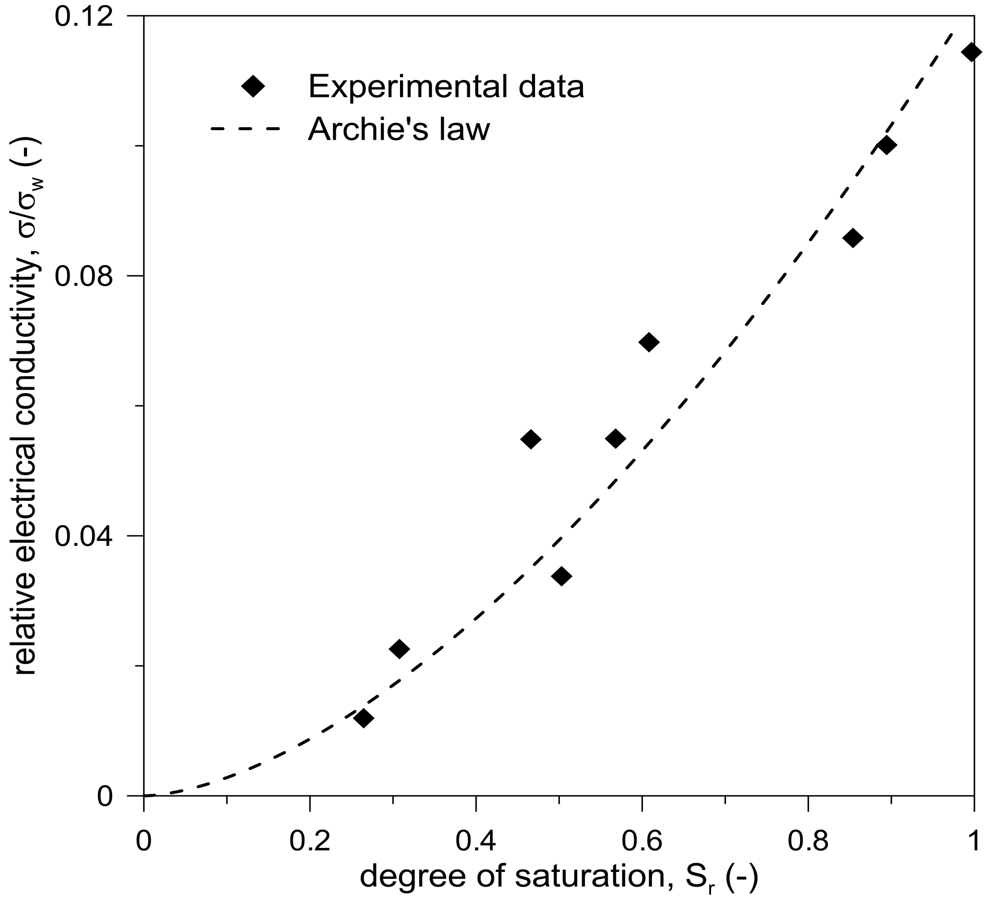
Validation on laboratory data

EiT Oedometer (Comina et al., 2008)



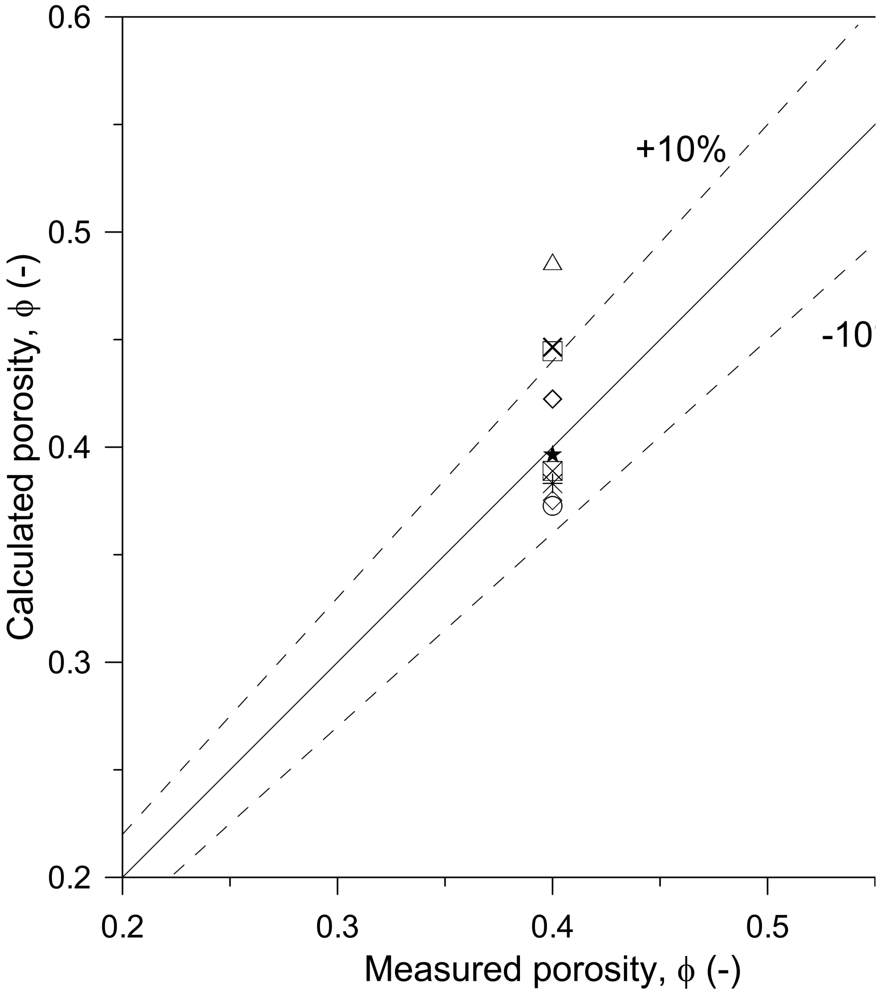
Experimental data

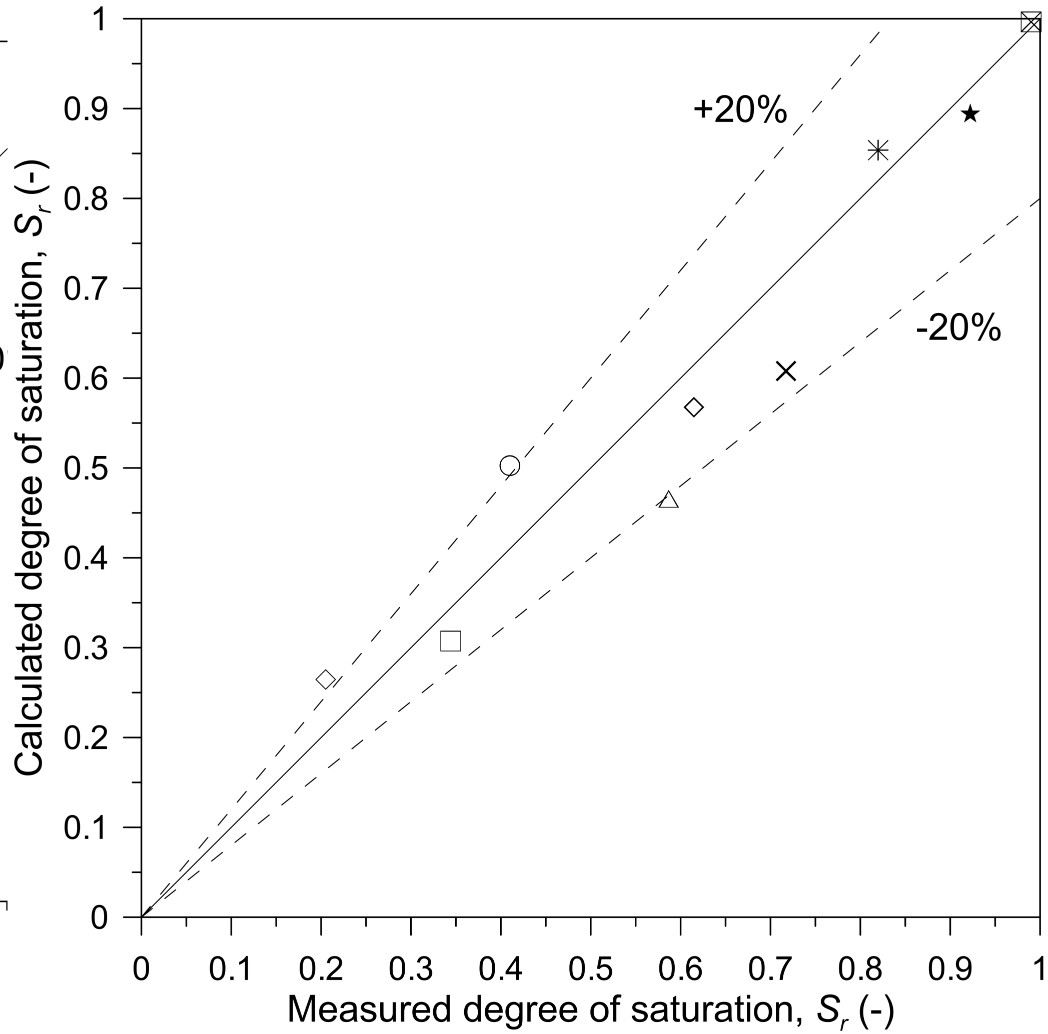




(Cosentini & Foti, 2014)

Predicted values





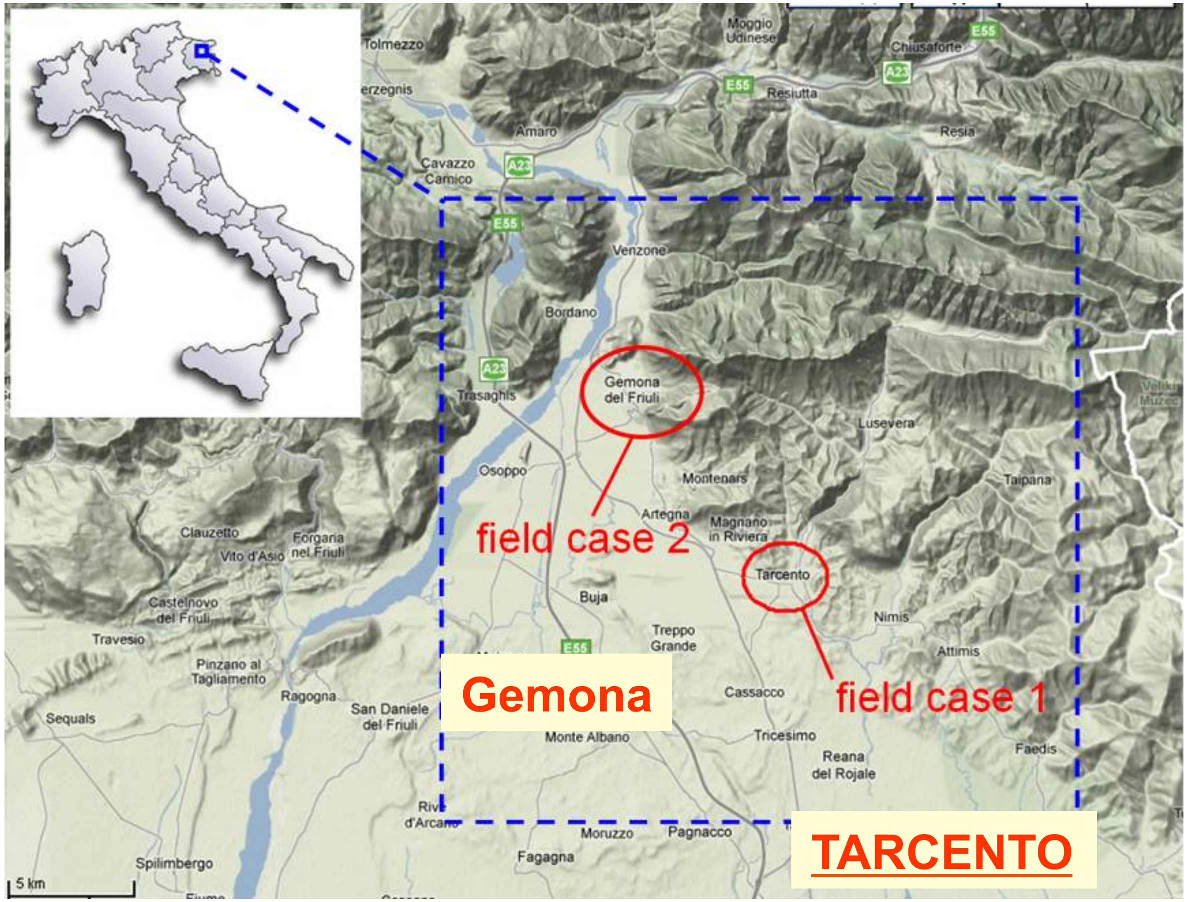
(Cosentini & Foti, 2014)

Case history #3

Building a shear wave velocity model for seismic site response studies

- Laterally constrained inversion
- A-priori information
- Integration of information

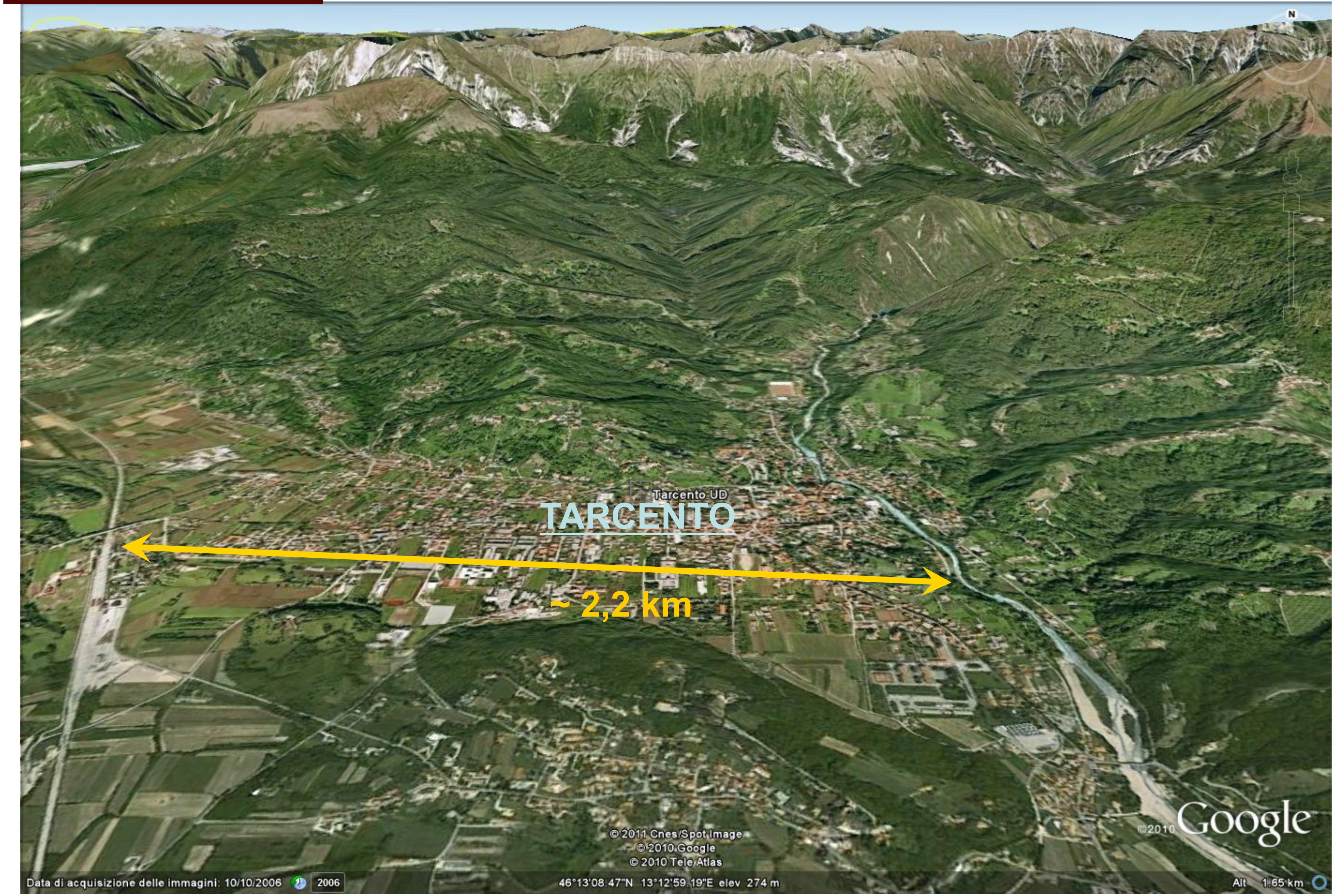
Geographical position



Friuli was severely affected by a seismic sequence in 1976

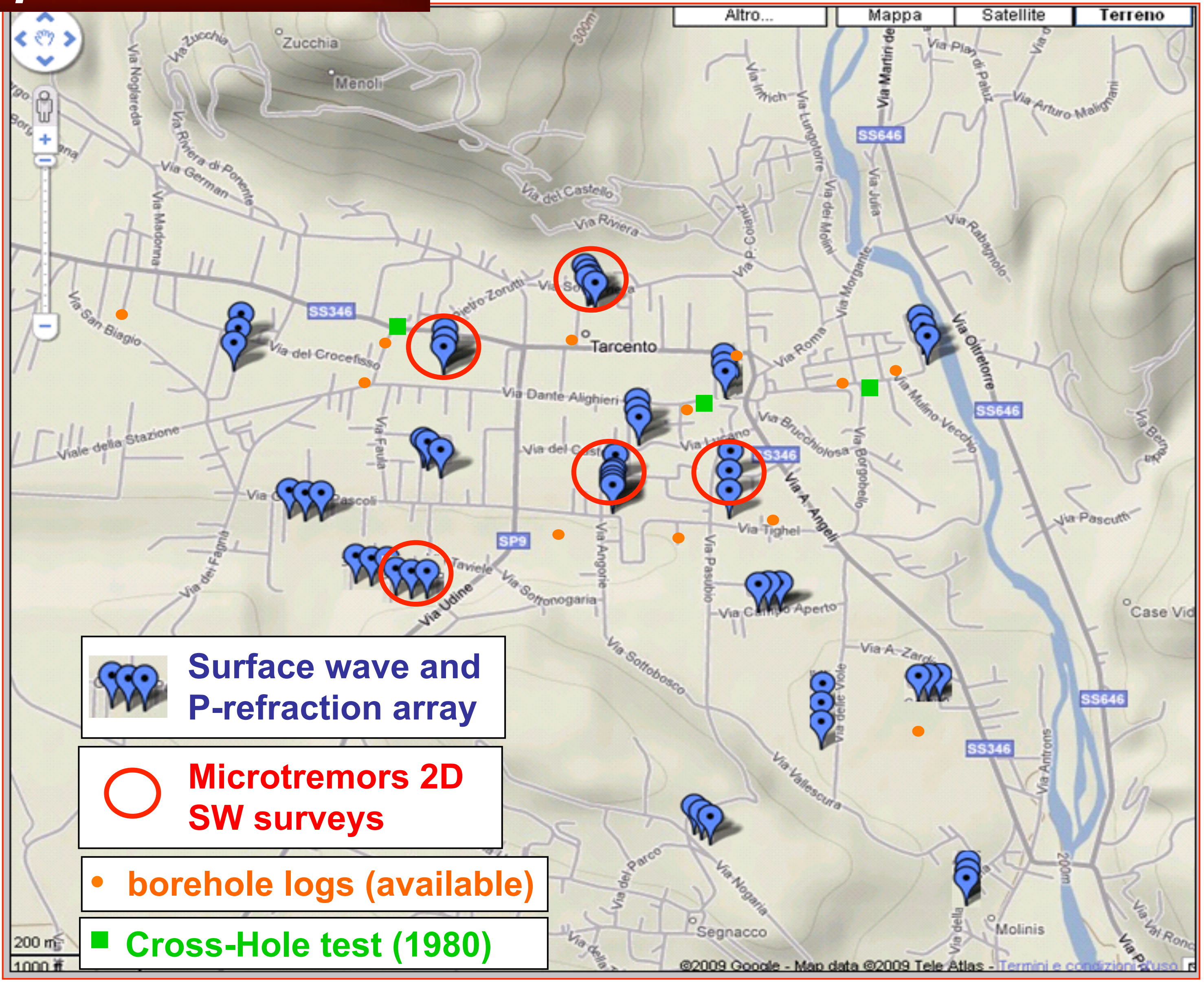
6 May 1976	M_L 6.4
11 September 1976	M_L 6.1
15 September 1976	M_L 6.0

Topography


TARCENTO
Tarcento UD
~ 2,2 km
© 2011 Cnes/Spot Image
© 2010 Google
© 2010 Tele Atlas
Google
©2010
Data di acquisizione delle immagini: 10/10/2006
2006
46°13'08.47"N 13°12'59.19"E elev 274 m
Alt 1.65 km

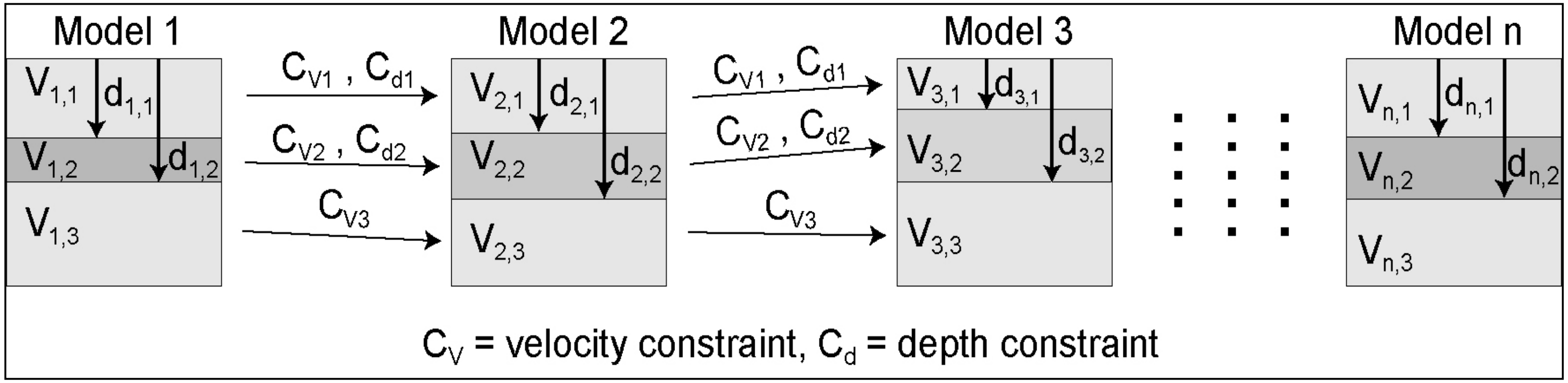
Experimental data

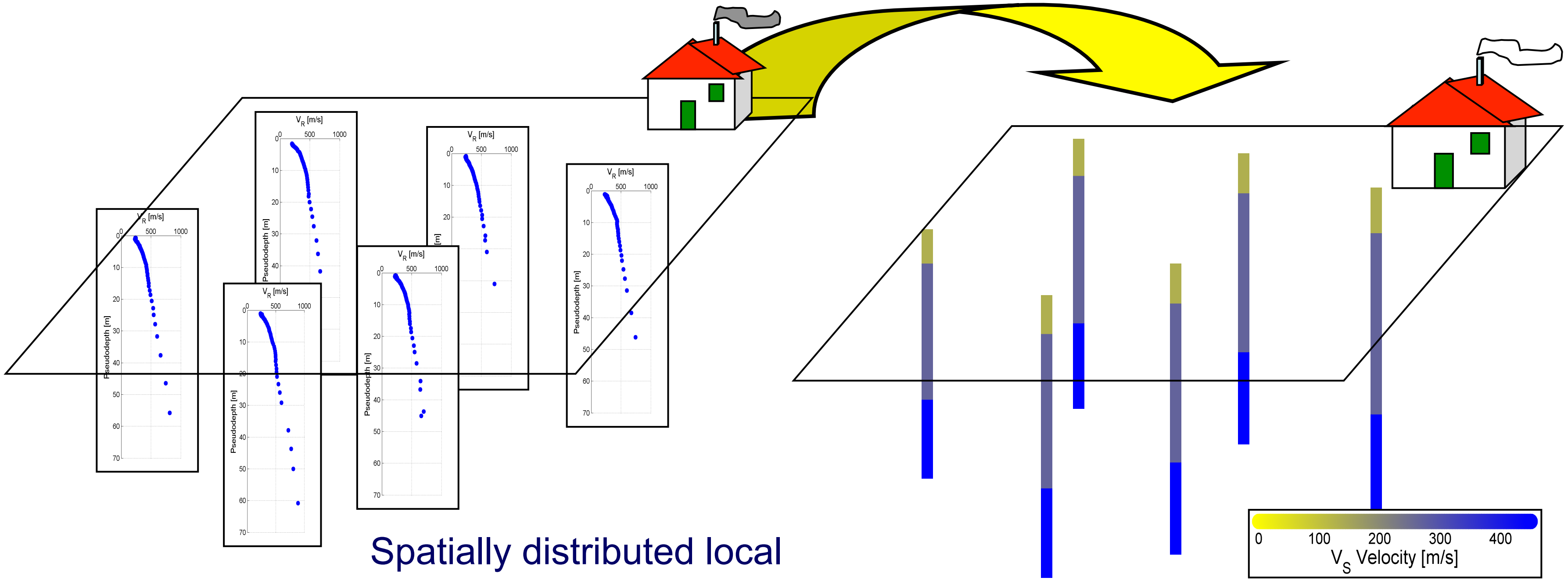
(Piatti et al., 2013b)



Laterally Constrained Inversion (LCI)

[Auken and Christiansen, 2004]





Spatially distributed local dispersion curves

The LCI Algorithm

[Auken and Christiansen, 2004]

$$m_{n+1} = m_n + \left(\left[G^T C_{obs}^{-1} G + C_{prior}^{-1} + P_h^T C_{h\text{-}prior}^{-1} P_h + R_p^T C_{Rp}^{-1} R_p + R_h^T C_{Rh}^{-1} R_h + \lambda I \right]^{-1} \times \left[G^T C_{obs}^{-1} \left(d_{obs} - g(m_n) \right) + C_{prior}^{-1} \left(m_{prior} - m_n \right) + P_h^T C_{h\text{-}prior}^{-1} \left(h_{prior} - h_n \right) + R_p^T C_{Rp}^{-1} \left(-R_p m_n \right) + R_h^T C_{Rh}^{-1} \left(-R_h m_n \right) \right] \right)$$

Experimental Data

A Priori Information

Lateral Constraints

m : Model Parameters

h : Depths Parameters

m_{prior} : Priori Model Parameters

h_{prior} : Priori Depths Parameters

d_{obs} : Experimental Data

G : Sensitivities

C_{obs} : Observational Covariance Matrix

C_{prior} : Priori Model Covariance Matrix

P_h : Derivatives with respect to Priori Depths

$C_{h\text{-}prior}$: Priori Depth Model Covariance Matrix

R_p : Roughening Matrix

C_{Rp} : Strength on the Constrain Covariance Matrix

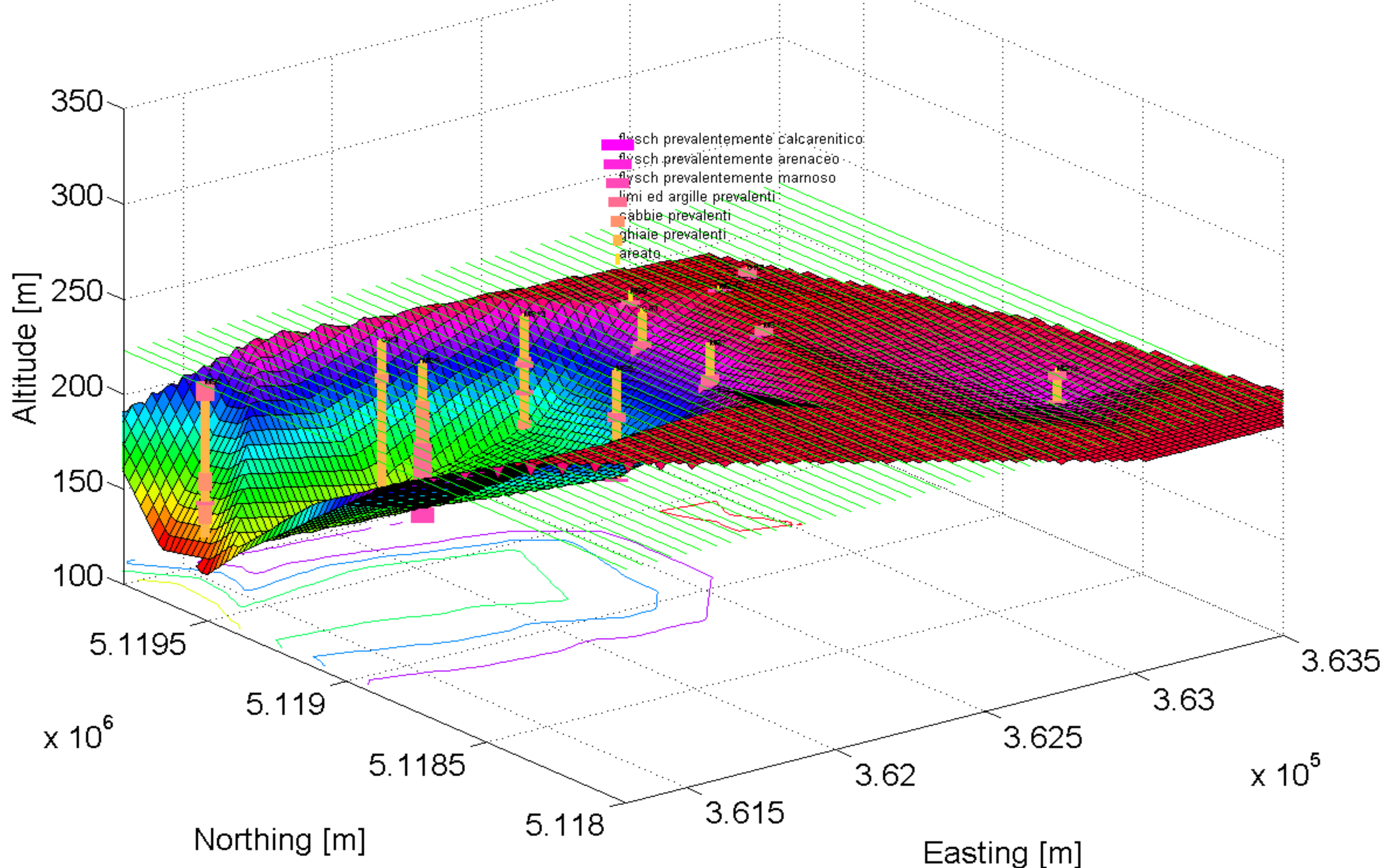
R_h : Derivatives with respect to Depths

C_{Rh} : Strength on the Depth Constrain Covariance Matrix

λ: Marquart Damping Parameter

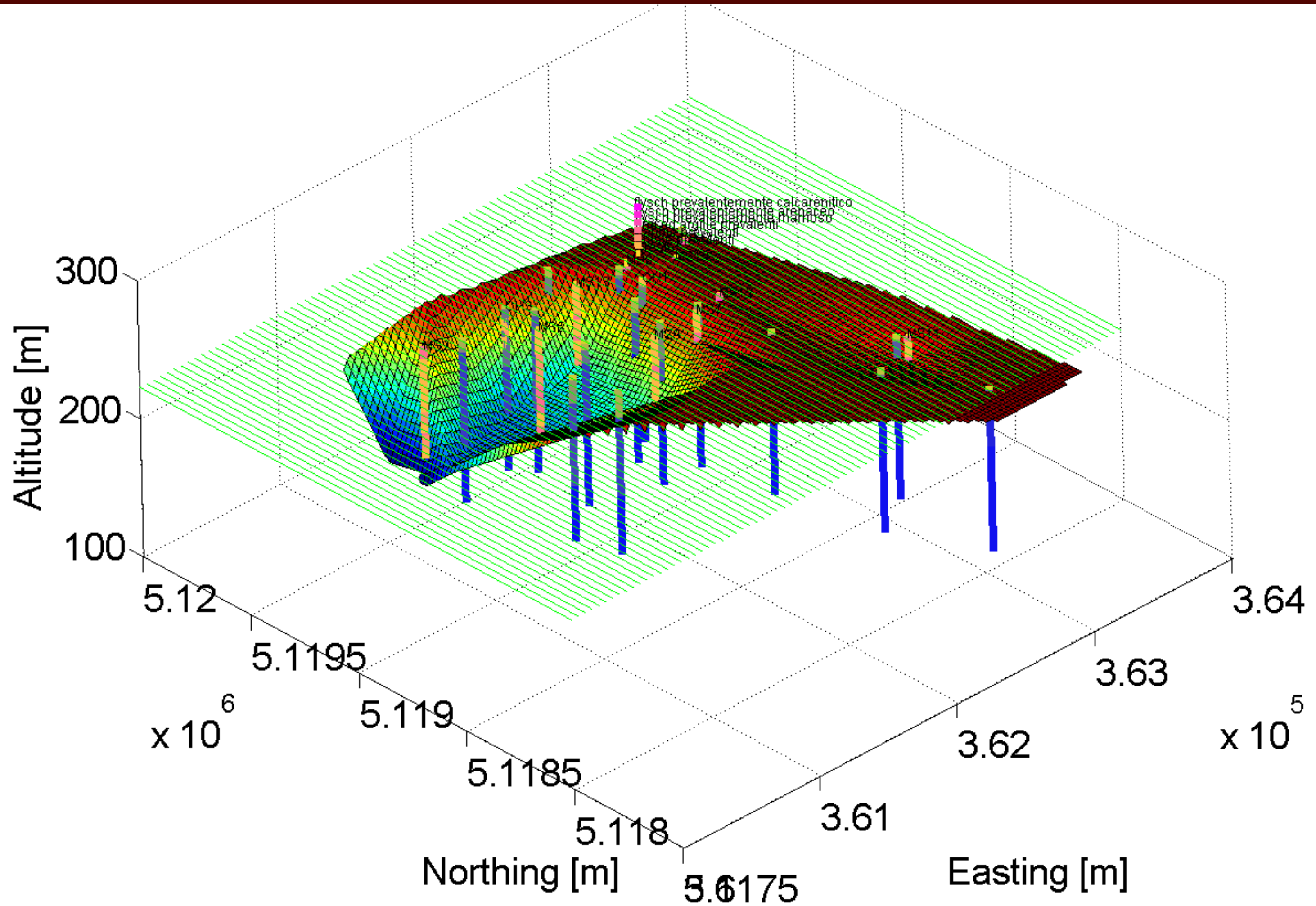
A-priori information

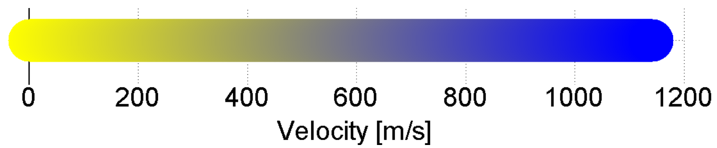
Bedrock position as reconstructed from boreholes logs and previous studies



(Piatti et al., 2013b)

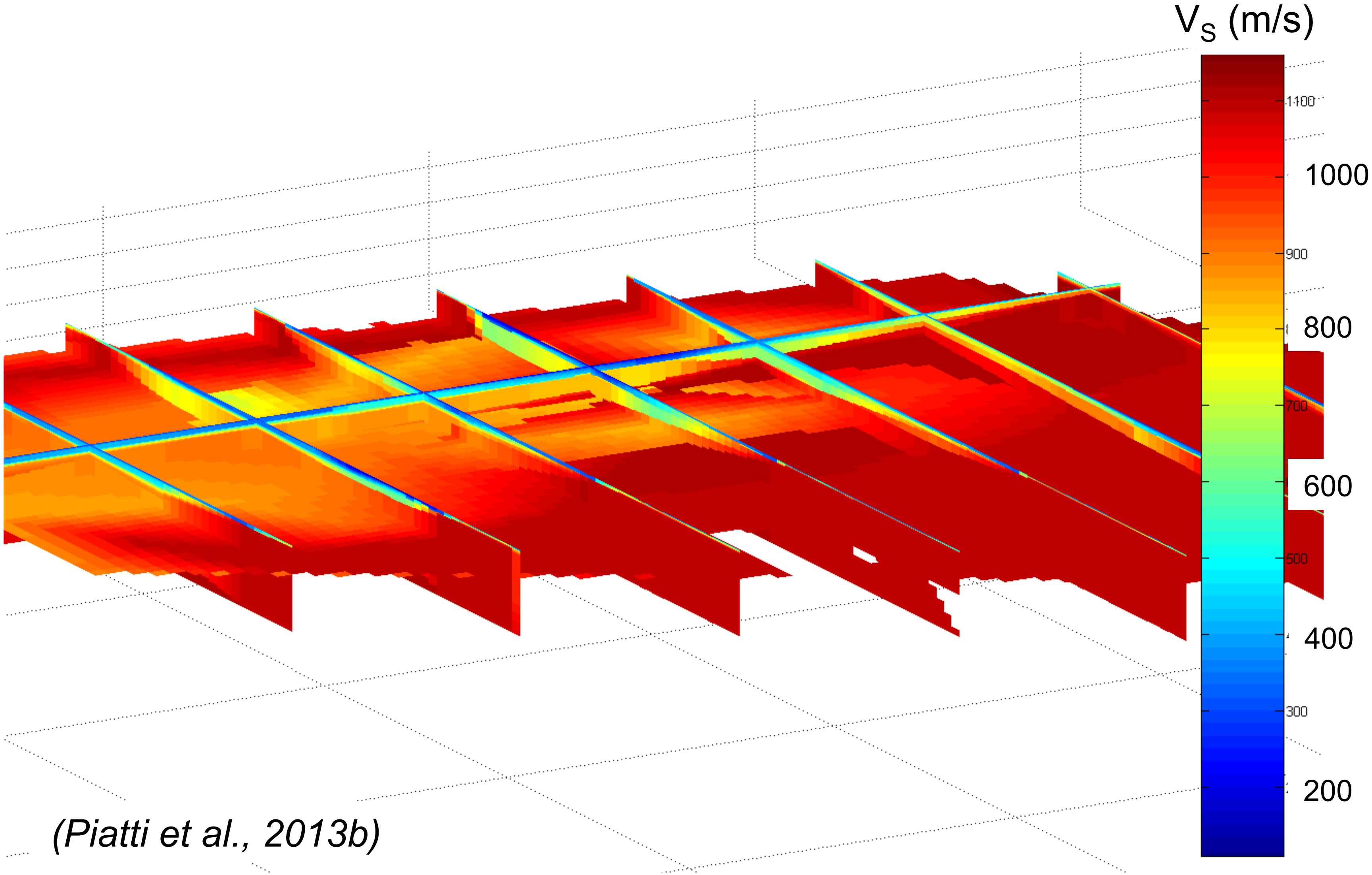
VS profiles from LCI





(Piatti et al., 2013b)

3D V_S model



(Piatti et al., 2013b)

Closing remarks

- Importance of choosing the right technique for the specific application
- Integration of different techniques improve the reliability of the results
- Laboratory experiments can provide a framework and calibration for quantitative interpretation of field tests

Thank you for your attention

Acknowledgments

Guido Musso (DISEG - Politecnico di Torino)

Laura Valentina Socco (DIATI - Politecnico di Torino)

Cesare Comina (University of Torino)

Renato Cosentini (now at University of Pavia)

Flora Garofalo (now at ENI – Italy)

Margherita Maraschini (now at Fugro - UK)

Daniele Boiero (now at Western-Gico - UK)

Claudio Piatti (now at D'Apollonia - Italy)

Claudio Strobbia (now at Western-Gico - UK)

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