



SAPIENZA
UNIVERSITÀ DI ROMA

Environmental Geophysics

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6. Data integration and conclusions

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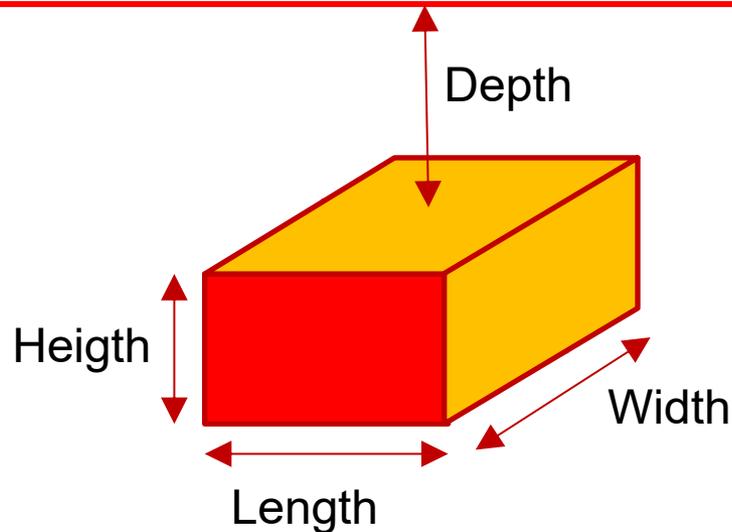
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Remember...

We can locate buried targets without any damage to the subsoil (non-invasive method)

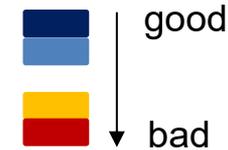
To this end we should get shape, type, depth and size (3-D) of the buried target (6 unknowns)

Earth's surface



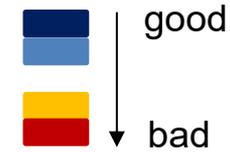
+ Shape and type of buried target

Wave-propagation methods



Method	Type	Cost	Resolution	DOI	Environmental Target
Seismic	Down-hole	medium-high	medium-high	medium	stratigraphy geotechnical properties and $v_{s,eq}$
	Cross-hole	high	high	high	detailed stratigraphy contamination geotechnical properties and $v_{s,eq}$
	Refraction (5 shots)	low	low	medium	first-approx. stratigraphy groundwater level
	Tomography	medium-low	medium	medium	detailed stratigraphy groundwater level cavity geotechnical properties contamination
	Sub-bottom profiling	very high	ultra-high	high	stratigraphy (below sea/river/lake bed)
SONAR	Multibeam	very high	ultra-high	high (only down to sea/river/lake bed)	bathymetry (sea/river/lake bed) anthropogenic features contamination plumes
HFEM	GPR	medium	ultra-high	low (generally) high (only for glaciers)	Glaciers (high DOI) cavity, buried bodies, pipes, utilities shallow stratigraphy shallow contamination

Field methods



Method	Type	Cost	Resolution	DOI	Environmental Target
LFEM	Slingram (fixed coil spacing)	very low	low	medium	leachate buried bodies, pipes, utilities (only metal) contamination
DC electrical	ERT	low	medium	high	detailed stratigraphy groundwater level salinization cavity, buried bodies leachate contamination gas plumes
	IP	medium-low	medium	medium	leachate contamination clay/silt layers

Integration of geophysical data

Which are the issues arising when using a geophysical method standalone?

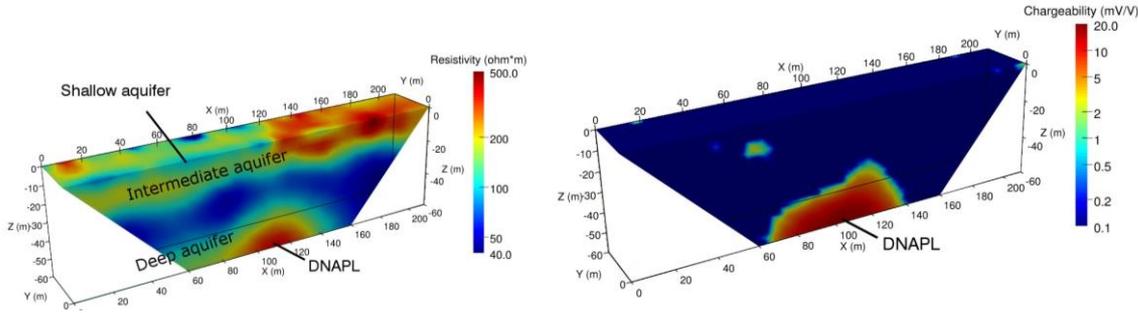
1. **The same values** of the studied parameter **can correspond to different soils/rocks/anthropogenic materials**
2. Some methods **do not work in certain environmental conditions** (i.e. GPR for conductive soils, ERT for insulators, seismic methods for high noise levels, etc.)
3. One method can allow the reconstruction of the depth of the target but not its shape or type, since **it does not have a sufficient resolution** (i.e. LFEM) **or vice versa it does not reach a sufficient DOI** (p.es. GPR)
4. The best method, in terms of resolution and DOI is too expensive and/or not affordable for the project (i.e. Multibeam or seismic reflection).



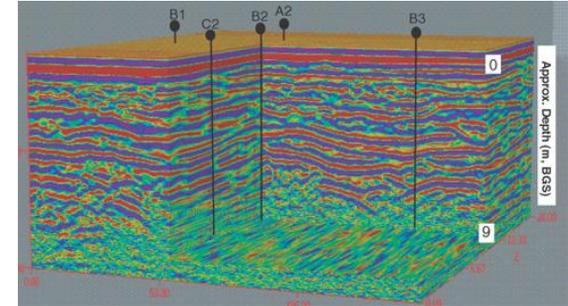
INTEGRATION OF GEOPHYSICAL DATA

Data fusion

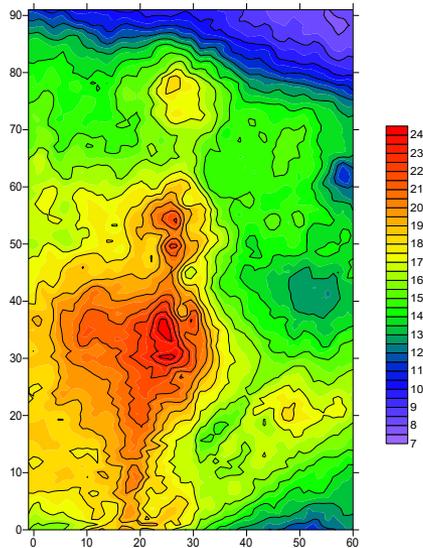
ERT and IP models



GPR



LFEM



If we combine more information coming from different techniques we can:

1. **Reduce the uncertainty** associated with the target parameters (dimension, depth, shape, type)
2. **Allow a prediction/estimation of the physical parameters** employed for environmental engineering (porosity, saturation, permeability, elastic moduli)

Data fusion and interpretation

Data fusion and interpretation

Qualitative

Visual comparison of different models/maps

Semi-quantitative

Correlation between geophysical and physical parameters

Empirical relationships (i.e. Archie, Wyllie, Topp) or constitutive equations to switch from geophysical to **petrophysical models** (saturation, porosity, permeability, etc.)



Our exercises

Quantitative

Joint inversion

Merge together all observations (i.e. travel times + apparent resistivities)

$$\mathbf{d}_{\text{TOT}}^{\text{obs}} = \begin{Bmatrix} \boldsymbol{\rho}_a^{\text{obs}} \\ \mathbf{t}_{\text{TOT}}^{\text{obs}} \end{Bmatrix}$$

After joint inversion we achieve a multi-parameter model:

$$\mathbf{m} = (\rho_i; v_i; G)$$

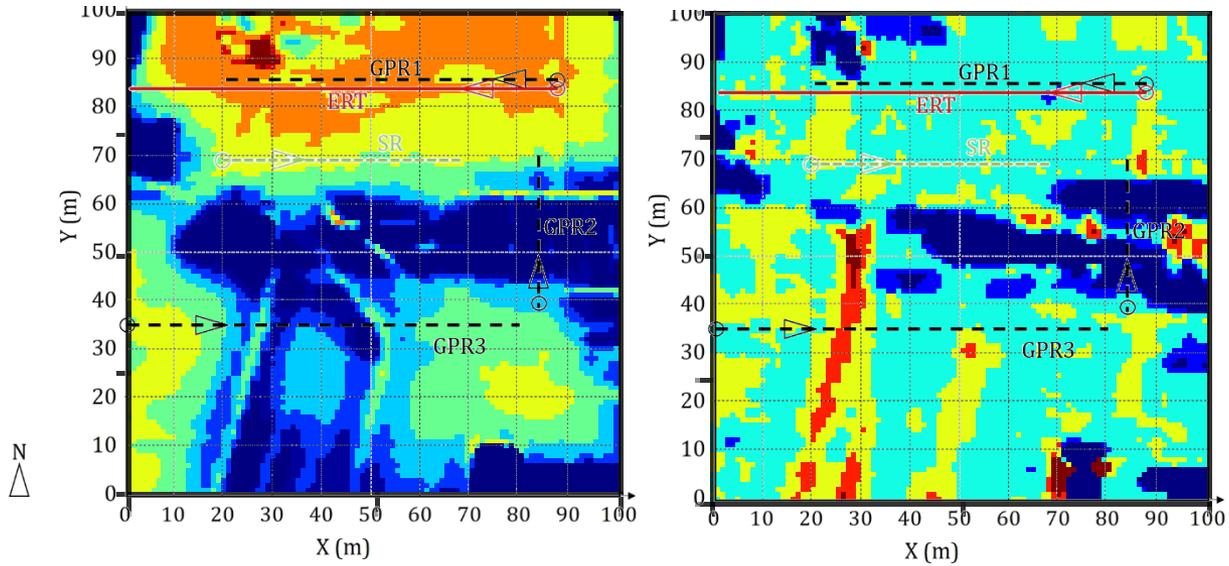
with $i = 1, 2, \dots, N$
 N = number of pixels
 G = mesh geometry

Machine Learning-based

Clustering

Define groups (clusters) sharing similar properties in terms of the investigated parameters (i.e. resistivity, chargeability, velocity of seismic waves, etc.)

Qualitative – Contaminated site



LFEM

ERT

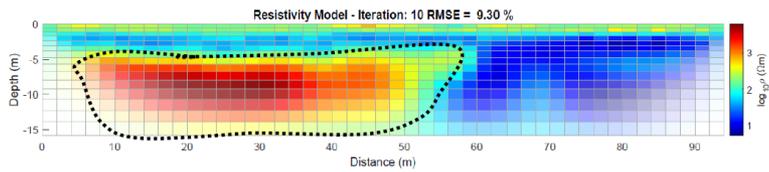
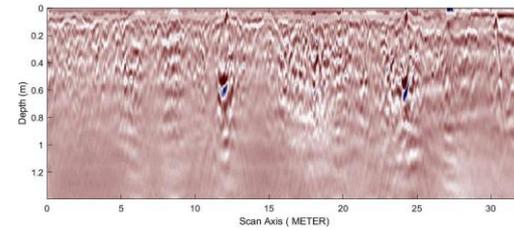
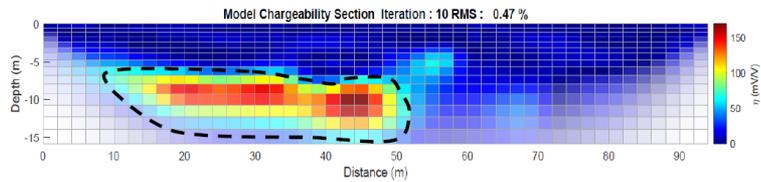
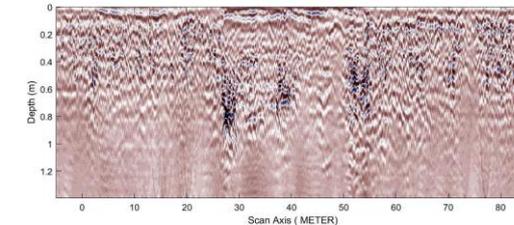


Figura 18 ERT-Individuazione dell'area contaminata nel modello di resistività

TDIP

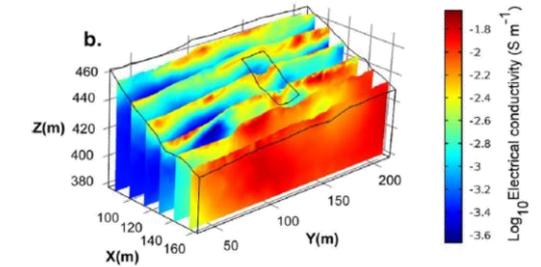
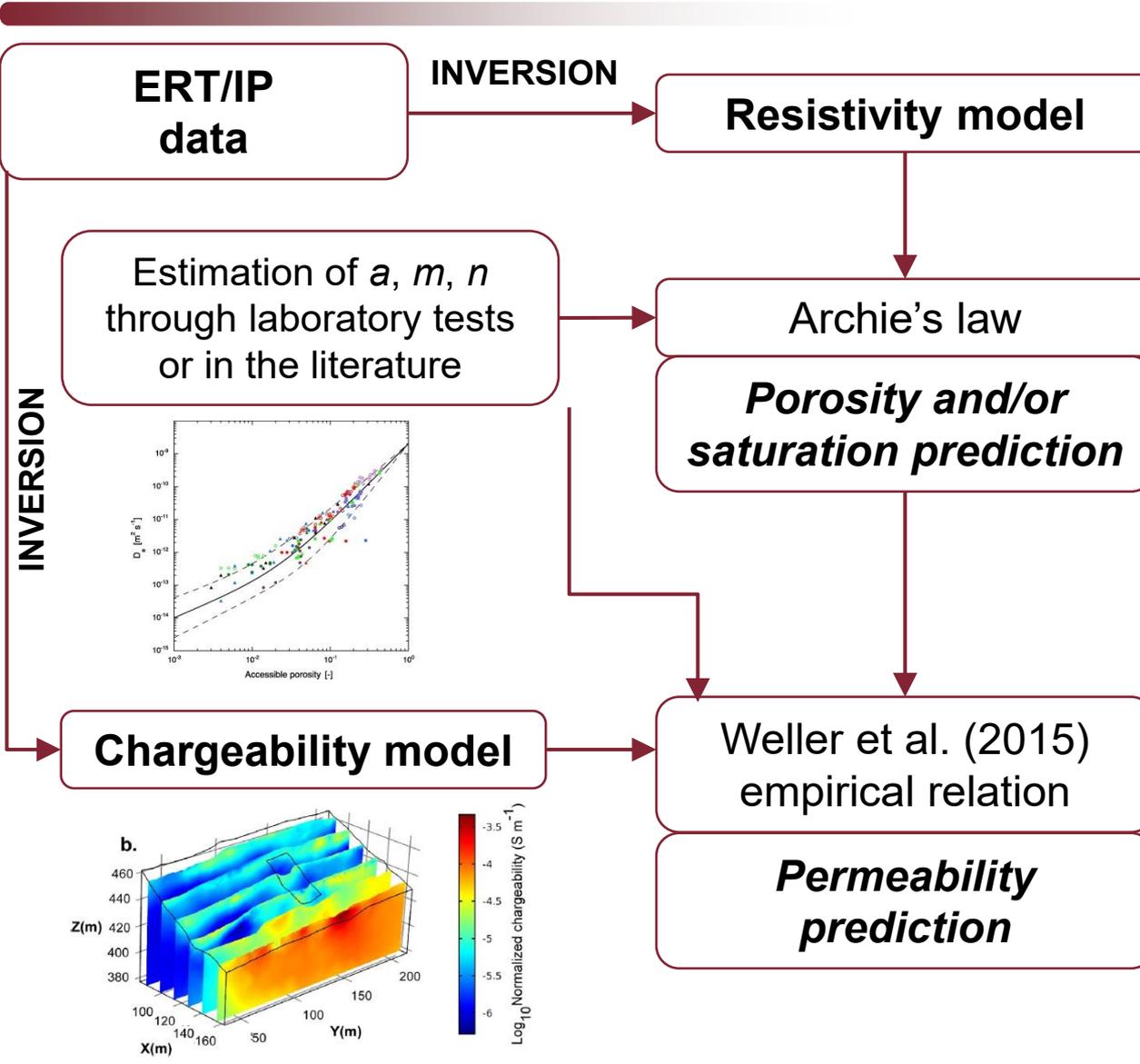


GPR2

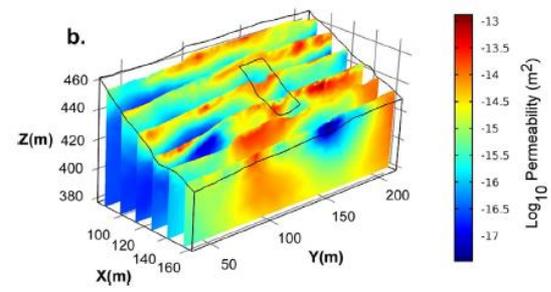
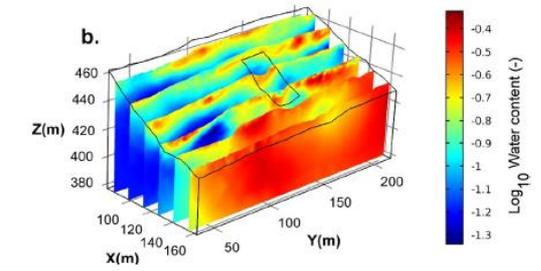


GPR3

Semi-quantitative (Revil et al. 2020)



$$\rho = a\phi^{-m}S_w^{-n}\rho_w$$



Semi-quantitative: *low-strain geotechnical parameters* (Ulhemann et al. 2016)



INVERSION

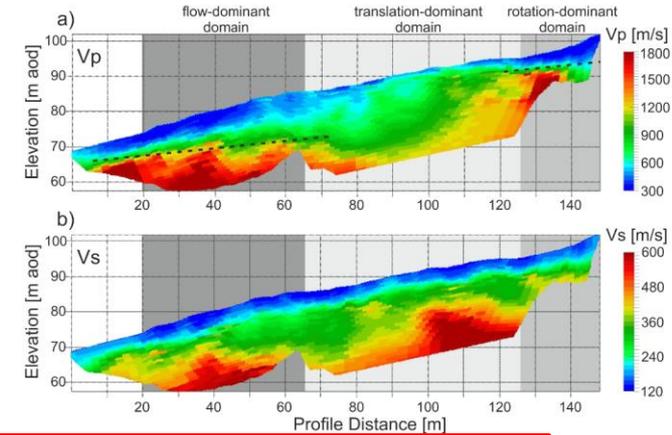
Travel times

P- and S-wave velocity models

Borehole data (density δ)

Constitutive equations

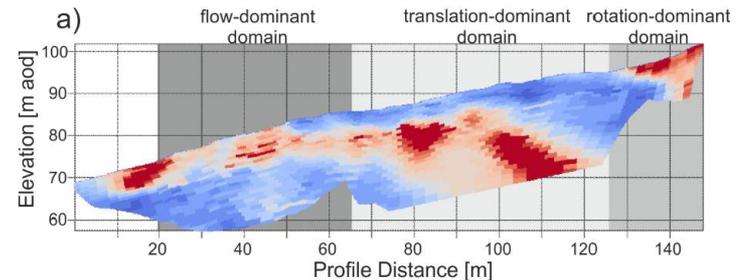
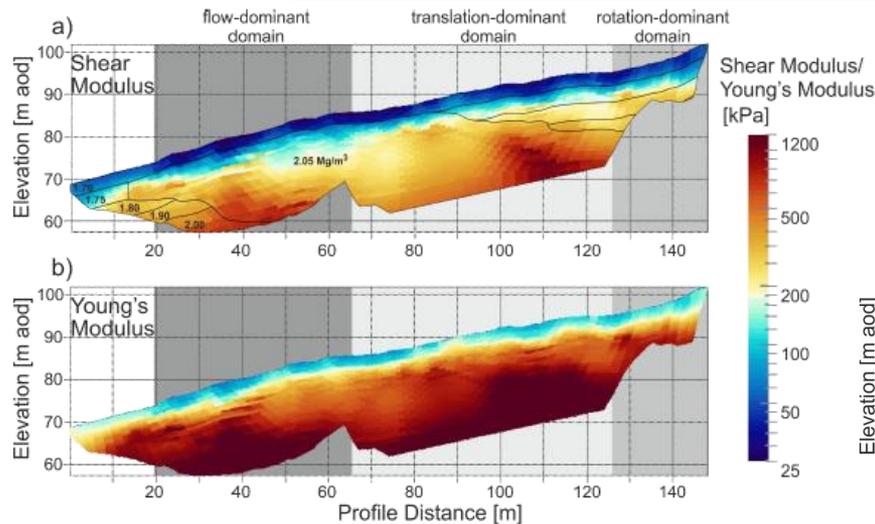
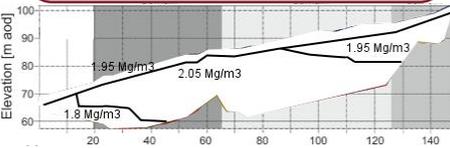
Low-strain geotechnical parameters (E_0 , G_0 , ν , etc.)



$$E_0 = \frac{\delta v_S^2 (3v_P^2 - 4v_S^2)}{v_P^2 - v_S^2}$$

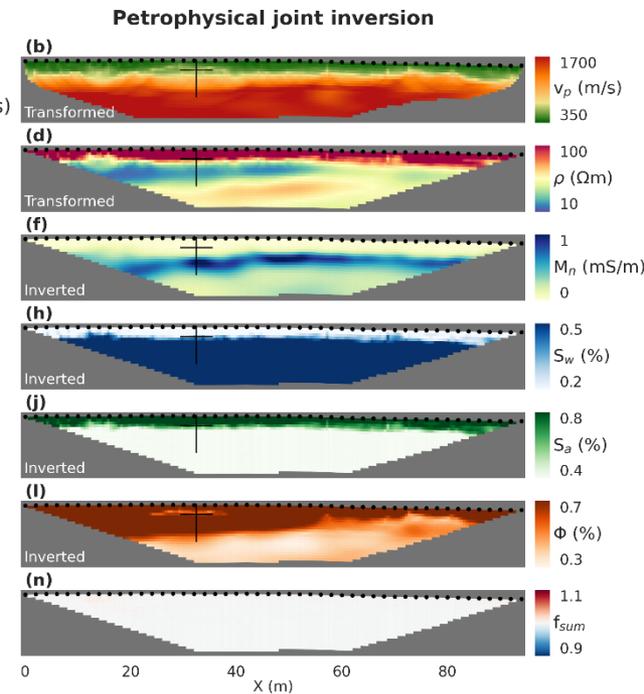
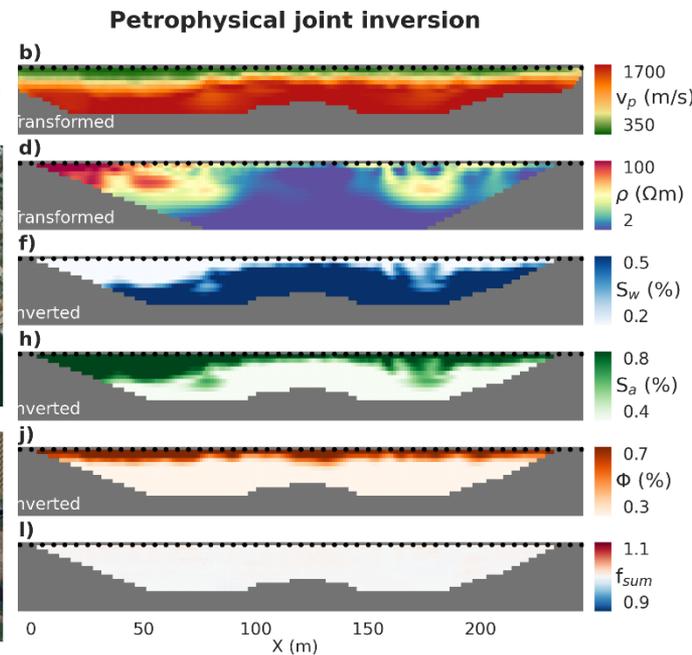
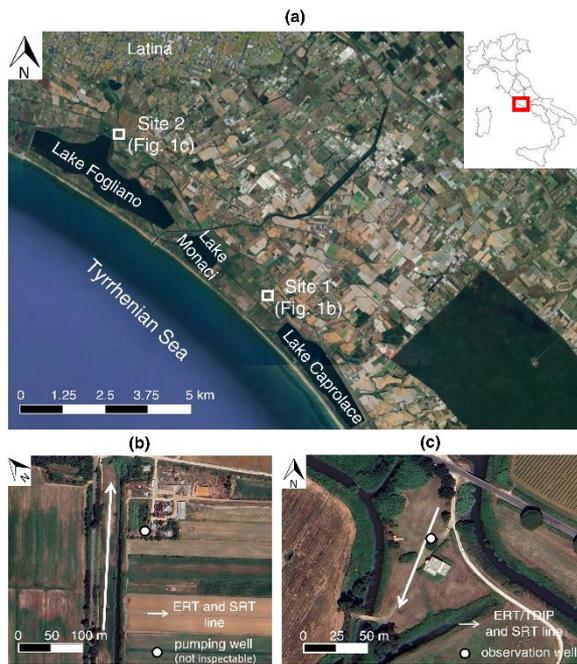
$$G_0 = \delta v_S^2$$

$$\nu = \frac{v_P^2 - 2v_S^2}{2(v_P^2 - v_S^2)}$$



Petrophysical joint inversion

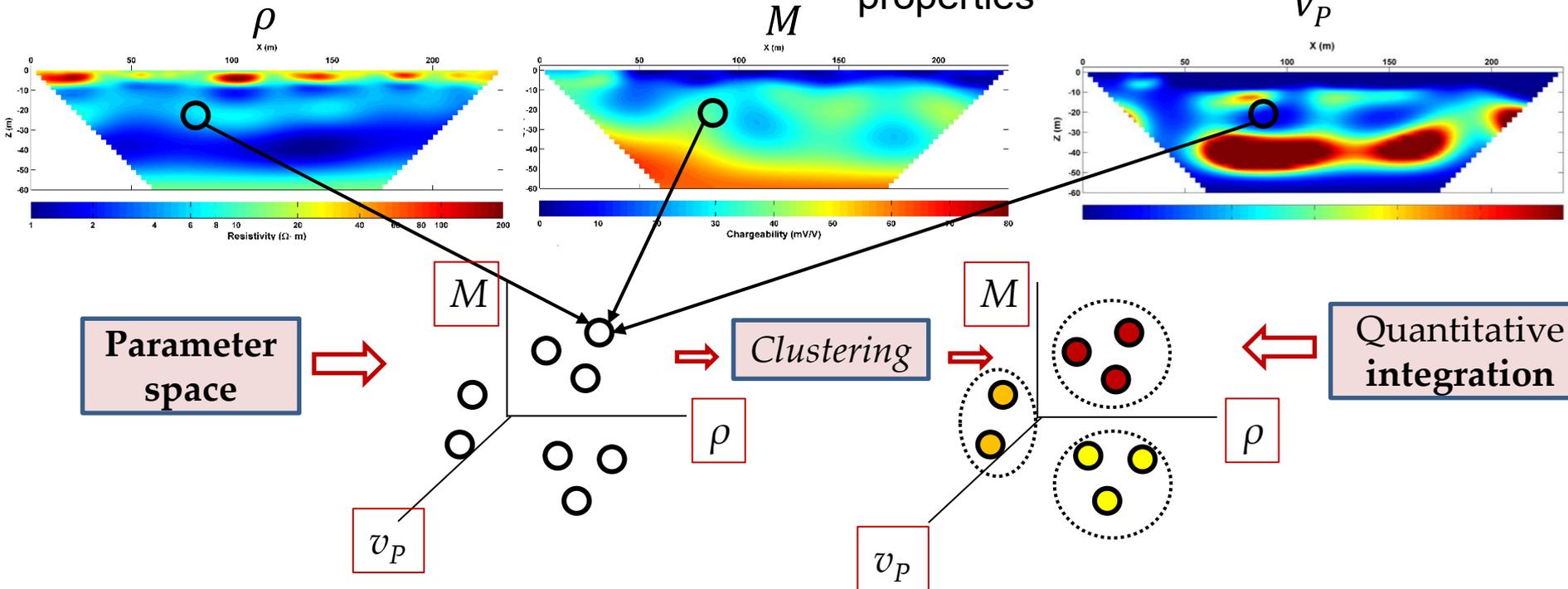
Joint inversion of seismic and electrical tomography for the three fractions (phases): air, water, matrix, based on the Archie's and Wyllie's equations



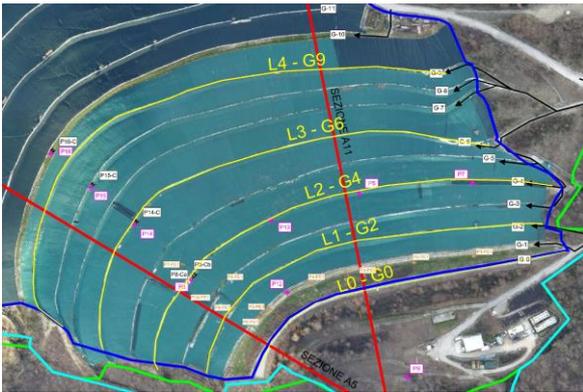
ML-based integration

Machine Learning (ML) is a programmed system capable of autonomously learning information if correctly trained to

Clustering algorithms are unsupervised ML techniques based on **spatial distances**, creating groups which share similar properties

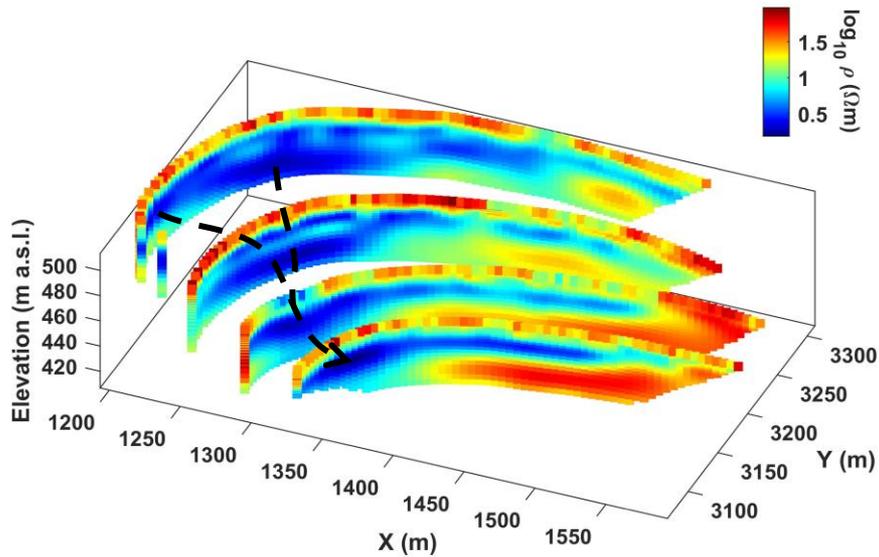


ML-based integration – Urban waste landfill

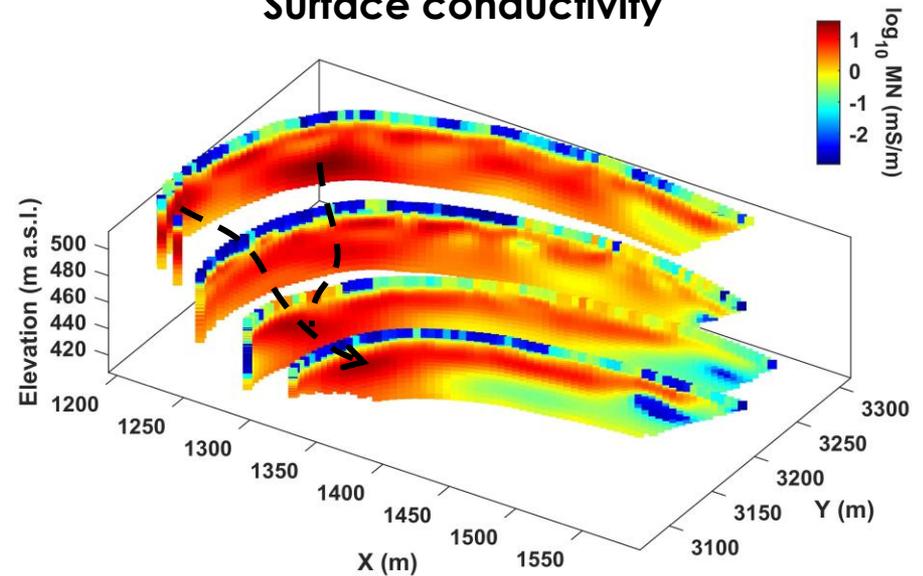


Inverted models - 3D view

Resistivity



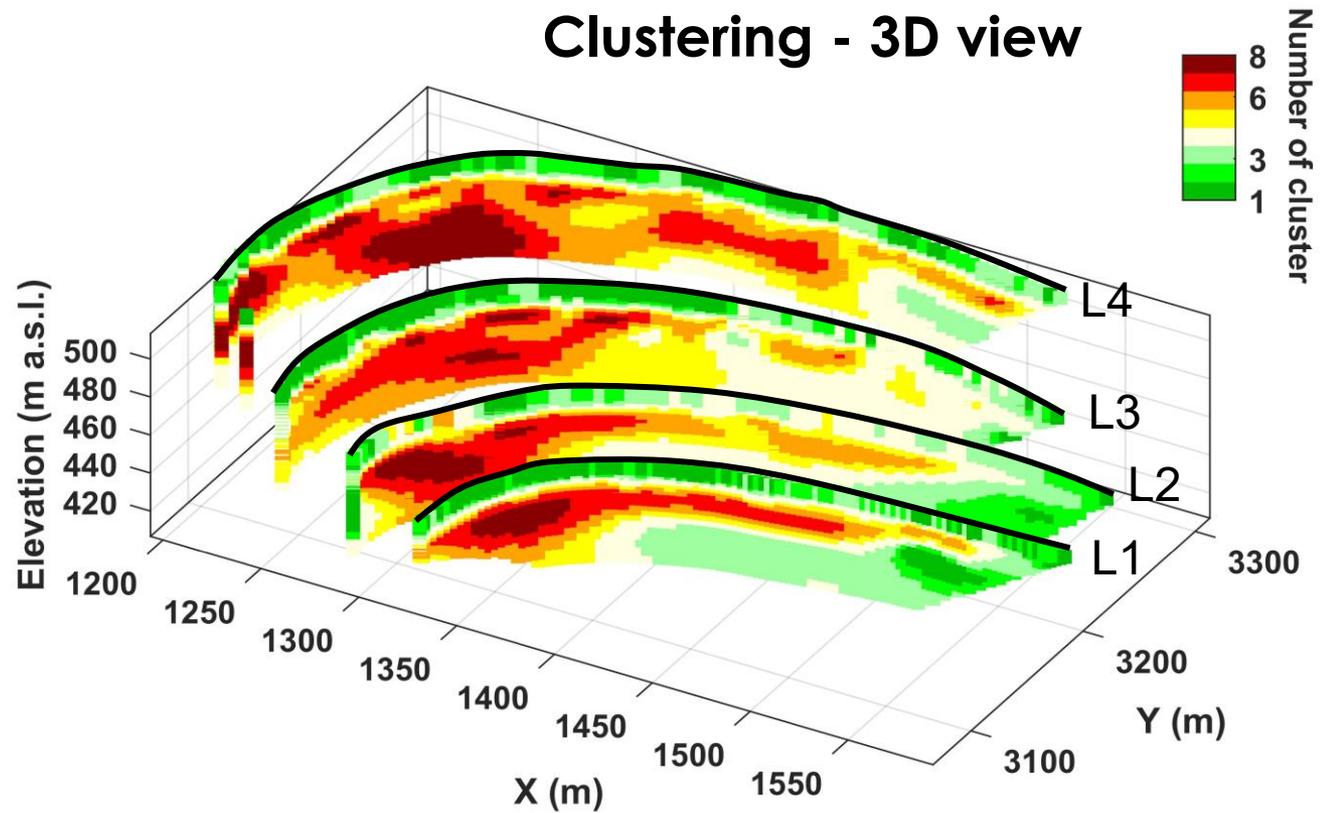
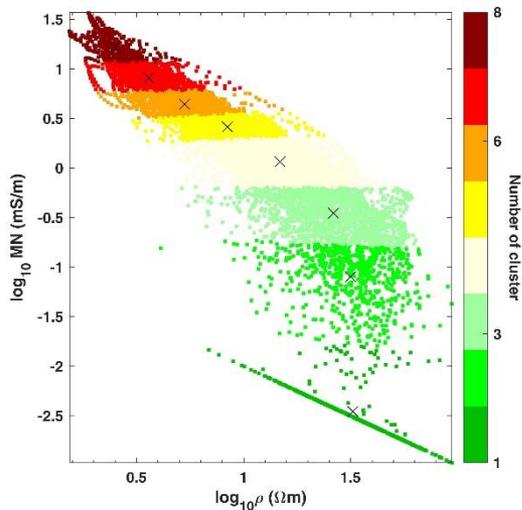
Surface conductivity



--> Leachate preferential path

Clustering algorithm (K-means)

Clustering - 3D view

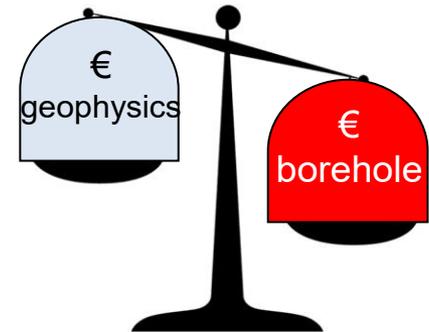


Geophysical reconstruction and direct information

However, **geophysical methods should be validated by direct measurements** (boreholes, direct inspections, piezometers).

The integrated application of direct (scattered and invasive) and geophysical (areal and non-invasive) methods allows to:

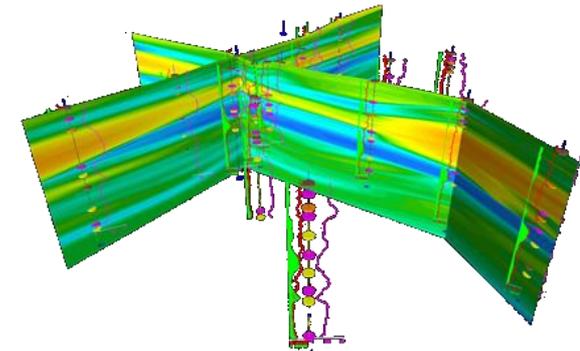
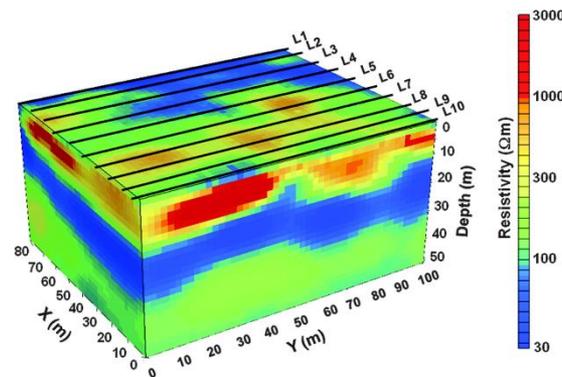
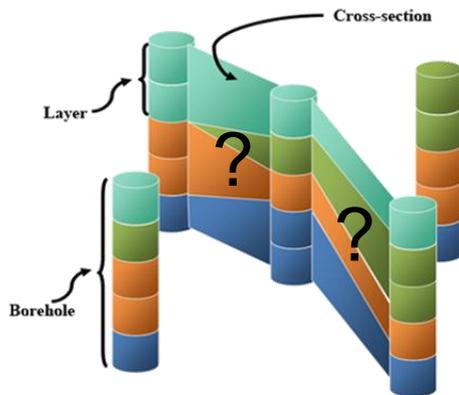
- **Reduce the costs of direct investigations** (i.e. boreholes location is chosen according to the results of the geophysical campaign);
- **Improve accuracy and resolution of geotechnical, hydrogeological and environmental models** often based only on scattered points;
- **Validate geophysical results** to reduce the uncertainty associated with the geophysical reconstruction.



Please remember that the cost difference between boreholes and surface geophysics is of **one order of magnitude for unit area**

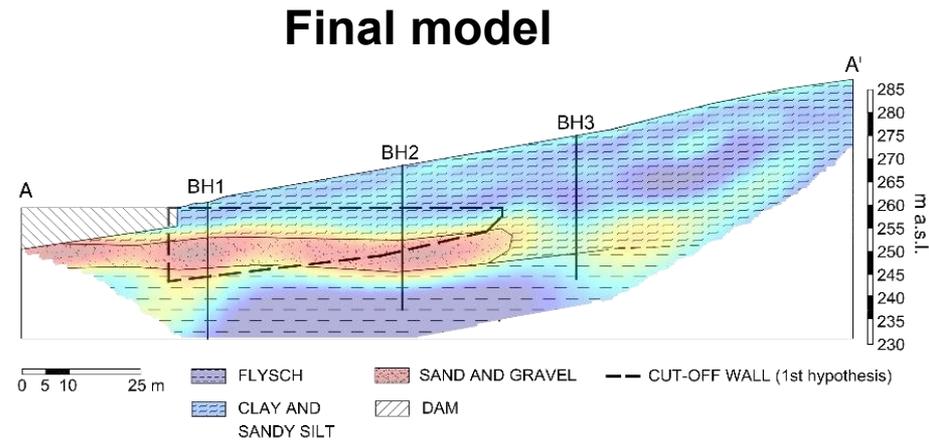
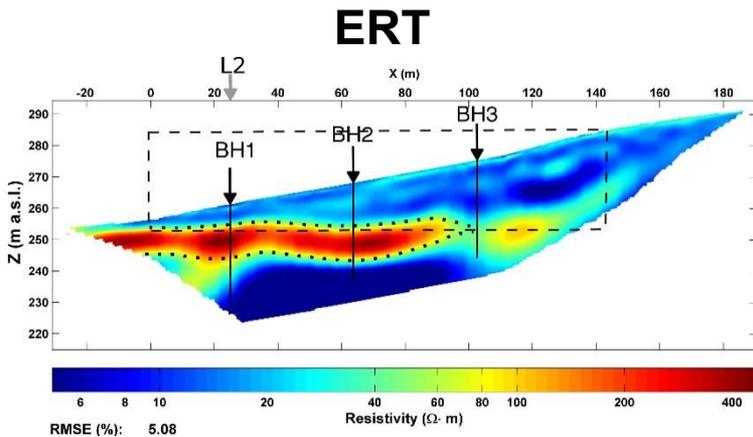
Geophysical reconstruction and direct information

	Model based only on direct information	Model based only on geophysics	Model based on integration between geophysics and direct information
Resolution	low	high	high
Uncertainty	0 on measured points ∞ elsewhere	low near surface but increasing with depth and correlation with physical parameters needed	low

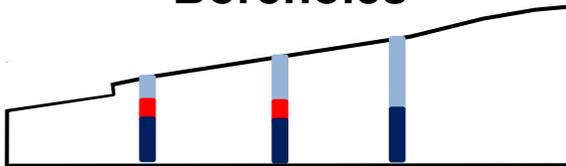


A final example...

The integrated approach should be always applied for reconstruction of a 2D/3D model for environmental applications (mapping and monitoring)



Boreholes



- silt and clay
- sand and gravel
- flysch