Electrical Resistivity

Tutorial Session

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Resistivity, conductivity & Ohm's Law

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How current propagates through the subsurface

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Electrode Configurations

Wenner, Schlumberger & Dipole-Dipole

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Data Interpretation

Reading apparent resistivity curves

Key quantities in resistivity methods

Resistivity ρ

Unit: Ω·m

$$\rho = R \times A / L$$

Measures how strongly a material opposes electrical current flow

Increases with dryness & mineral content

Typical range: ~1 (clays) → 10^6 Ω·m (granite)

Conductivity σ

Unit: S/m or mS/m

$$\sigma = 1 / \rho$$

Inverse of resistivity

Higher when more dissolved ions or more water-saturated pores

Often preferred in near-surface studies

Apparent Resistivity ρ_a

What you measure in the field

$$\rho_a = k \times (\Delta V / I)$$

k = geometric factor (depends on electrode array geometry)

ΔV = measured voltage difference

Bulk response of the subsurface, not a single layer

Exercise 1:

Problem Statement

A cylindrical rock core sample is measured in the lab. You are given the following values:

Parameter	Symbol	Value
Electrical resistance	R	**250 Ω**
Cross-sectional area	A	**0.01 m^2**
Sample length	L	**0.5 m**

Your Tasks:

(1) Write down the formula linking resistivity ρ to resistance R, cross-sectional area A, and length L.

(2) Substitute the values and calculate ρ in Ω·m.

(3) Based on typical rock resistivity values, what geological material might this sample represent?

Hint: ρ has units of Ω·m (check: Ω × m^2 / m = Ω·m ✓)

Resistivity

Geomaterial	Resistivity [Ωm]
Clay	1–20
Sand, wet to moist	20–200
Shale	1–500
Porous limestone	100–10^3
Dense limestone	10^3–10^6
Metamorphic rocks	50–10^6
Igneous rocks	10^2–10^6

Solution:

(1) Formula

$$\rho = R \times A / L$$

(2) Calculation

$$\rho = 250\ \Omega \times 0.01\ m^2 / 0.5\ m = 5\ \Omega\cdot m$$

Result: $\rho = 5\ \Omega\cdot m$

(3) Rock Identification

5 Ω·m falls in the typical range of saturated sediments, shales, or clay-rich formations (1-100 Ω·m).
It is far too conductive to be dry igneous or metamorphic rock (10^3-10^6 Ω·m).
A likely candidate: water-saturated alluvial sediment or marine clay.

Recap 2: Current flow in the subsurface

What carries the current?

Rocks and dry soils are poor conductors. Electrical current flows primarily through water in pore spaces and fractures, dissolved ions (Na^+, Cl^-, etc.) carry charge under the applied field.

Current streamlines & equipotentials

Current radiates outward from the injection electrode as streamlines. Equipotential surfaces are everywhere perpendicular to streamlines. The two fields are orthogonal.

Why does a voltage difference arise?

As current crosses layers of different resistivity, the electric field adjusts, creating measurable ΔV between two surface electrodes.

Apparent resistivity at field scale

$\rho_a = k \times (\Delta V / I)$. The geometric factor k encodes the electrode geometry. ρ_a is a weighted average of all subsurface resistivities at that electrode spacing.

Exercise 2: Apparent resistivity with Wenner array

Setup

A survey team deploys a Wenner array with electrode spacing $a = 3$ m.
They inject a current $I = 50$ mA and measure a voltage difference $\Delta V = 0.75$ V.

Wenner geometric factor: $k = 2\pi a$ Apparent resistivity: $\rho_a = k \times (\Delta V / I)$

Tasks:

(A) Calculate the geometric factor k for this Wenner array.

(B) Calculate the apparent resistivity ρ_a.

(C) The spacing is now doubled to $a = 6$ m. With the same ΔV and I recorded, how does ρ_a change? What does this suggest about the subsurface structure?

Solution 2: Apparent resistivity with Wenner array

(A) Geometric Factor

$k = 2\pi \times a = 2\pi \times 3\text{ m} = 18.85\text{ m}$

(B) Apparent Resistivity

$\rho_a = k \times (\Delta V / I) = 18.85 \times (0.75 / 0.05) = 18.85 \times 15 = 282.7\ \Omega\cdot\text{m}$

(C) Doubling the spacing (a = 6 m)

$k = 2\pi \times 6 = 37.70\text{ m}$

$\rho_a = 37.70 \times 15 = 565.5\ \Omega\cdot\text{m}$

ρ_a nearly doubled → the deeper material now sampled is MORE resistive.

Interpretation: resistivity increases with depth, perhaps a drier or more consolidated layer below.

Recap 3: Electrode configurations

Wenner

$k = 2\pi a$

C1 · P1 · P2 · C2 (equal spacing a)

✓ Strengths

- High signal strength
- Simple setup & calculation
- Good horizontal resolution

✗ Limitations

- All 4 electrodes move for depth
- Limited depth penetration

Schlumberger

$k = \pi (L^2 - l^2) / (2l)$

C1 ··· P1 · P2 ··· C2 (C much wider than P)

✓ Strengths

- Greater depth penetration
- Fewer electrode movements
- Good for Vert. Electr. Sound. (VES)

✗ Limitations

- Weaker signal/more noise
- More complex processing

Dipole-Dipole

$k = \pi n (n+1) (n+2) a$

C1·C2 ···n··· P1·P2

✓ Strengths

- High lateral sensitivity
- Ideal for 2D/3D imaging
- Good for fault mapping

✗ Limitations

- Weakest signal, noise prone
- Complex data interpretation

Exercise 3: choosing the right electrode configuration

For each field campaign below, select the most appropriate electrode configuration and justify your choice:

Scenario A

Groundwater Exploration

Determine the depth and thickness of an unconfined aquifer (~30-80 m deep) beneath a flat agricultural plain. The team has only one day on site.

Your choice + reason:

Scenario B

Fault Mapping

Detect and map the lateral trace of a suspected fault zone along a 300 m transect. Sharp lateral resistivity contrasts are expected.

Your choice + reason:

Scenario C

Landfill Boundary Detection

Delineate a contamination plume near a former landfill. Both depth and lateral extent are unknown, full 2D characterisation is needed.

Your choice + reason:

Solution 3: choosing the right electrode configuration

Scenario A · Groundwater

= Schlumberger → VES

Best for depth profiling with minimal electrode movement. Expanding the current electrodes while fixing the centre probes increasing depths. Ideal for detecting horizontal layering like an aquifer top and base.

Scenario B · Fault Mapping

= Dipole-Dipole

Highest sensitivity to lateral resistivity contrasts. Accepts lower signal for much better horizontal resolution. Ideal for detecting the sharp discontinuity of a fault plane along a profile.

Scenario C · Landfill Contamination

= ERT (2D imaging)

Multi-electrode ERT combines both sounding and profiling in one pass, delivering a 2D resistivity section. Dipole-dipole or Wenner arrays within ERT give both lateral extent and depth of the plume.

Recap 4: sounding vs. profiling

SOUNDING (VES)

Vertical Electrical Sounding

→ Goal: How does ρ vary with depth?

→ Method: Expand electrode spacing; keep centre point fixed

→ Penetration depth increases with separation

→ Output: 1D depth profile at one location

→ Application: Aquifer depth, bedrock depth, layer thickness

PROFILING

Electrical Resistivity Profiling

→ Goal: How does ρ vary laterally?

→ Method: Fixed spacing; move entire array along transect

→ Same depth range sampled along the line

→ Output: Lateral resistivity map along profile

→ Application: Faults, cavities, contamination mapping

Exercise 4: sounding vs. profiling

Read each field procedure. Identify whether it describes Sounding, Profiling, or ERT, and explain your reasoning.

A A team drives four Wenner electrodes at spacing a = 10 m. After each reading, all four stakes are pulled and re-driven 5 m further along the transect. They repeat this 40 times.

B Two potential electrodes are fixed at a central point. The current electrodes begin 5 m apart; after each reading, only the outer electrodes move further out (10 m, 20 m, 40 m, 80 m…) keeping the centre fixed.

C A 64-electrode cable (2 m spacing, 126 m long) is laid out. A resistivity meter automatically cycles through hundreds of electrode combinations, logging ΔV and I for each — all in one hour.

Solution 4: sounding vs. profiling

A

PROFILING

The entire array moves with fixed spacing along the transect. This samples a fixed depth while scanning laterally, the defining characteristic of resistivity profiling.

B

SOUNDING (VES)

The array centre stays fixed while only the outer current electrodes expand. Increasing separation = increasing depth penetration at one location (classic Schlumberger VES).

C

ERT / 2D Imaging

Multi-electrode systems cycle through all combinations, performing sounding and profiling simultaneously. Data is processed into a 2D resistivity pseudosection (Electrical Resistivity Tomography).

Recap 5: refraction at resistivity interfaces

Why does current bend at an interface?

Continuity of normal current density (J_n) and tangential electric field (E_t) must both be satisfied simultaneously, forcing current lines to change angle.

Governing equation (Resistivity Snell's Law)

$\tan(\theta_1) / \tan(\theta_2) = \rho_2 / \rho_1$ where θ is measured from the normal to the interface (vertical for horizontal layers).

Conductive-to-resistive boundary ($\rho_1 < \rho_2$)

$\tan(\theta_2) = \tan(\theta_1) \times \rho_1 / \rho_2 < \tan(\theta_1) \rightarrow \theta_2 < \theta_1$. Current bends toward the normal, more vertical penetration in the resistive layer.

Resistive-to-conductive boundary ($\rho_1 > \rho_2$)

$\tan(\theta_2) = \tan(\theta_1) \times \rho_1 / \rho_2 > \tan(\theta_1) \rightarrow \theta_2 > \theta_1$. Current bends away from the normal, spreads laterally in the conductive layer.

Exercise 5: refraction at resistivity interfaces

Current flows from a conductive clay layer (Layer 1: $\rho_1 = 5\ \Omega\cdot m$) into a resistive dry sandstone (Layer 2: $\rho_2 = 500\ \Omega\cdot m$). In Layer 1, the current lines make an angle $\theta_1 = 45°$ with the vertical.

Resistivity Snell's Law: $\tan(\theta_1) / \tan(\theta_2) = \rho_2 / \rho_1 \rightarrow \tan(\theta_2) = \tan(\theta_1) \times (\rho_1 / \rho_2)$

Tasks:

(1) Calculate the refracted angle θ_2 in the sandstone layer. Show your steps.

(2) Does the current bend toward or away from the vertical? Explain physically why.

(3) What does this extreme bending imply for the detectability of deep resistive layers in a VES survey?

Solution 5: refraction at resistivity interfaces

(1) Calculate θ_2

$\tan(\theta_2) = \tan(45°) \times (\rho_1 / \rho_2) = 1.000 \times (5 / 500) = 0.01$

$$\theta_2 = \arctan(0.01) \approx 0.57°$$

(2) Direction of bending

$\theta_2 \approx 0.6° \ll \theta_1 = 45°$ → Current bends strongly toward the vertical (toward the normal).
In a resistive medium, ions cannot migrate laterally, they are funnelled almost straight down through the layer.

(3) Implication for VES surveys

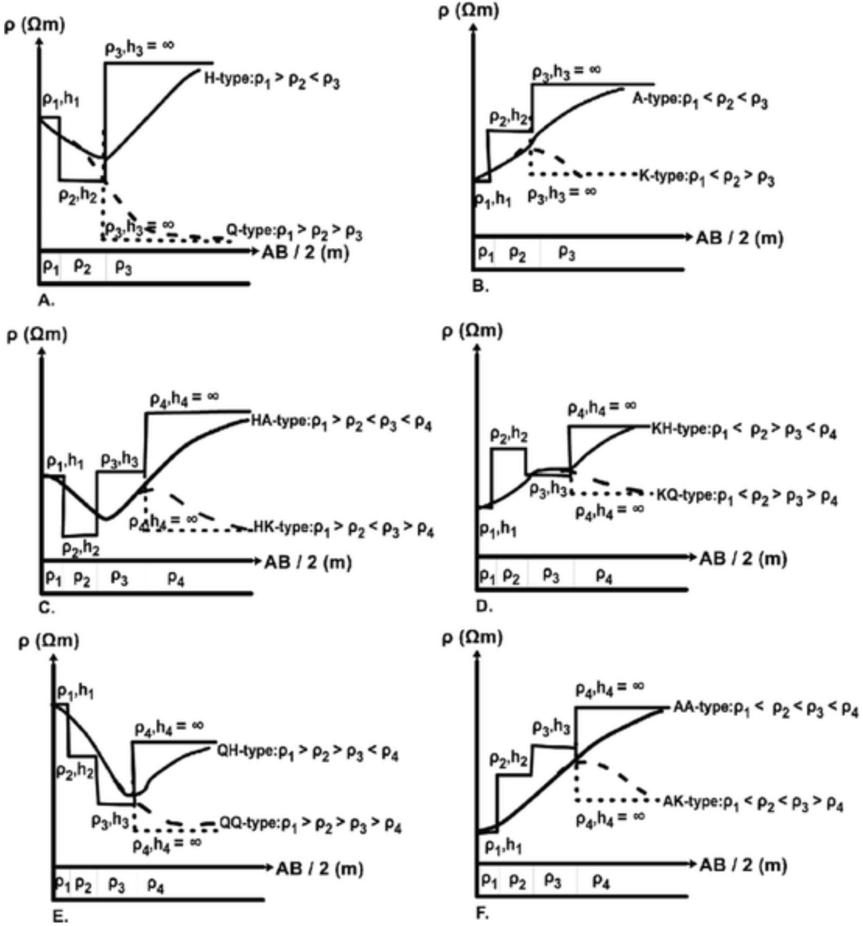
Almost no energy is scattered sideways in a resistive layer, making the surface measurement insensitive to its thickness. This is the T-equivalence problem: very thick resistive layers and very thin ones can produce nearly identical sounding curves.

Recap 6: Interpreting VES apparent resistivity curves

In a log-log VES plot (ρ_a vs electrode spacing), small spacing → shallow layers; large spacing → deep layers. The shape of the curve encodes the number of layers and their relative resistivities.

Curve Shape	Resistivity Pattern	Typical Geological Setting
▲ Monotonically rising	ρ increases with depth	Soil over dry basement or crystalline rock (A-type)
▼ Monotonically falling	ρ decreases with depth	Dry surface over saline water / marine clay (Q-type)
▲▼ Bell-shaped (rise–fall)	Resistive intermediate layer	E.g. limestone between two clays (K-type)
▼▲ Basin-shaped (fall–rise)	Conductive intermediate layer	Saturated clay / aquifer between dry layers (H-type)
Flat line	Uniform half-space	Homogeneous sediment (rare in practice)

Recap 6: Interpreting VES apparent resistivity curves



Exercise 6: Interpret a VES Curve (coastal site)

A Schlumberger VES survey in a coastal area yields the following apparent resistivity vs. half-electrode-spacing (L/2) data:

L/2 (m)	**1**	**2**	**5**	**10**	**20**	**50**	**100**
ρ_a (Ω·m)	50	48	20	**8**	**9**	80	180

Tasks:

(1) Describe the shape of this curve qualitatively. Name the curve type (e.g. K, Q, H, A).

(2) How many subsurface layers does the curve suggest? Estimate ρ_1, ρ_2, and ρ_3.

(3) Propose a geological interpretation. What material might each layer represent? (Coastal context!)

(4) Bonus: What limitation of resistivity inversion is most relevant here?

Solution 6: Interpret a VES Curve (coastal site)

(1) Curve shape

Basin-shaped / H-type: ρ_a starts ~50 Ω·m, drops sharply to a minimum ~8 Ω·m at L/2 ≈ 10–20 m, then rises to ~180 Ω·m at large spacing.

(2) Layer count & resistivities

Three-layer model: $\rho_1 \approx 50$ Ω·m (shallow) · $\rho_2 \approx 8$ Ω·m (intermediate) · $\rho_3 \approx 180$ Ω·m (deep).
Pattern: $\rho_1 > \rho_2$, $\rho_3 > \rho_2$ - conductive sandwich.

(3) Geological interpretation (coastal context)

Layer 1 (~50 Ω·m): Dry to partially-saturated coastal sand or soil.
Layer 2 (~8 Ω·m): Saline-water-saturated sediment or marine clay — low ρ due to dissolved salts.
Layer 3 (~180 Ω·m): Resistive limestone or compacted coastal bedrock.

(4) Limitation (bonus)

Equivalence principle: many different combinations of layer thickness and ρ_2 can reproduce the same basin curve. Additional data (borehole logs, EM surveys) are needed to uniquely constrain the model.