

Tutorial: Geophysical Survey Design

From Problem to Practice

How This Tutorial Works

- We will work through some realistic scenarios
- For each scenario, you will be given information about a problem
- You must decide: What to measure? Where? How? Why?

The type of questions

1. What physical property contrast do I expect?
2. What is my target (depth, size, geometry)?
3. What are my constraints?
4. What question am I actually trying to answer?

Case Study 1

Bedrock depth for foundation design

Single method survey

Case 1: What We Know

- You are hired to survey a construction site for a new 10-story building
- The site is a flat, grassy field (50 m × 50 m) in a temperate climate
- Local geology: Quaternary alluvial sediments overlying crystalline bedrock
- The structural engineer needs to know the depth to bedrock for foundation design
- Expected bedrock depth: somewhere between 5 and 30 m
- Budget is limited; the client wants a single survey method if possible
- No buried utilities or metallic objects are expected

What physical property contrast do you expect between the alluvial sediments and the crystalline bedrock?

A. Density contrast only

B. Seismic velocity contrast (sediments slower, bedrock faster)

C. Magnetic susceptibility contrast

D. Electrical resistivity contrast only

E. No significant contrast exists

B. Seismic velocity contrast

- Crystalline bedrock has much higher P-wave velocity (typically 4000-6000 m/s) than unconsolidated alluvial sediments (typically 300-1500 m/s)
- This is one of the strongest and most reliable contrasts in near-surface geophysics
- Density contrast also exists but is smaller in magnitude
- Resistivity contrast exists but is more variable depending on water content

Which geophysical method is most appropriate for mapping the depth to bedrock at this site?

A. Ground Penetrating Radar (GPR)

B. Gravity survey

C. Seismic refraction

D. Electrical Resistivity Tomography (ERT)

E. Magnetic survey

C. Seismic refraction

Seismic refraction

- Seismic refraction is ideal because: (1) strong velocity contrast exists, (2) target depth (5-30 m) is well within the method's range, (3) the method directly measures layer velocities and depths
- GPR would not penetrate deep enough (limited to ~5-10 m in conductive soils)
- Gravity could detect the interface but with poor depth resolution
- ERT could work but would require assumptions about resistivity values
- Magnetics would not detect a bedrock interface (no magnetic contrast)

You decide to use seismic refraction. How should you design the survey to ensure you can detect bedrock at up to 30 m depth?

A. Short spread (30 m), 1 m geophone spacing

B. Long spread (≥ 100 m), 2-3 m geophone spacing

C. Multiple short spreads (20 m each) across the site

D. Single shot point with geophones at 50 m offset

B. Long spread (≥ 100 m)

Long spread (≥ 100 m), 2-3 m geophone spacing

- Rule of thumb: Maximum investigation depth $\approx 1/3$ to $1/5$ of spread length
- To image 30 m depth, you need a spread of at least 90-150 m
- Multiple shot points (at ends and center) improve velocity model accuracy
- 2-3 m geophone spacing provides adequate resolution for this target depth
- Short spreads would not have sufficient offset to record refracted arrivals from deep bedrock

Your seismic refraction survey shows: Layer 1 velocity = 800 m/s (0-12 m), Layer 2 velocity = 4500 m/s (below 12 m). What do you report to the structural engineer?

A. Bedrock is at 12 m depth; P-wave velocity confirms crystalline rock

B. More surveys needed; the contrast could be a gravel layer

C. The survey failed; 800 m/s is too high for alluvium

D. Bedrock depth varies between 5 and 30 m across the site

A. Bedrock at 12 m depth

Bedrock is at 12 m depth; velocity confirms crystalline rock

- Layer 1 (800 m/s): Typical velocity for compacted alluvial sediments
- Layer 2 (4500 m/s): Consistent with crystalline bedrock (granite, gneiss)
- The sharp velocity increase (factor of $\sim 5.5\times$) indicates a real lithological boundary
- You would report: bedrock depth = 12 m, recommend foundation design for this depth
- If lateral variations exist, you would note where additional profiles were acquired

Case Study 2

Locating buried metallic utilities

Single Method Survey

Case 2: What We Know

- An old industrial site is being redeveloped for residential use
- Historical records indicate buried steel pipes and tanks may exist
- The site (100 m × 80 m) is now vacant with grass cover
- You need to locate any buried metallic objects before excavation begins
- Depth of burial is unknown but estimated at 1-5 m
- The client needs rapid coverage of the entire site
- No active utilities; power has been disconnected

What physical property distinguishes buried steel objects from the surrounding soil?

A. Electrical conductivity

B. Seismic velocity

C. Magnetic susceptibility

D. Dielectric permittivity

E. Density

C. Magnetic susceptibility

- Steel and iron have very high magnetic susceptibility compared to soil
- Ferromagnetic materials create local distortions in Earth's magnetic field
- This contrast is typically several orders of magnitude
- Conductivity contrast also exists, but magnetic contrast is stronger and easier to detect
- A buried steel pipe creates a characteristic dipolar magnetic anomaly

Which survey method would be most efficient for rapidly locating buried steel objects across the entire site?

A. Electrical Resistivity Tomography (ERT)

B. Ground magnetics with continuous walking survey

C. Seismic reflection

D. Time-domain electromagnetics (TEM)

E. Gravity survey

B. Ground magnetics

Ground magnetics with continuous walking survey

- Magnetic surveys can cover large areas quickly (walking speed, continuous recording)
- Strong anomalies from ferromagnetic objects are easy to identify
- No ground contact required (sensor carried above surface)
- ERT would be much slower and might miss small objects
- TEM could work but is slower and more complex
- A single operator can survey hectares per day

You plan a magnetic survey. What line spacing and sensor height would you choose?

A. 20 m line spacing, 2 m sensor height

B. 2 m line spacing, 0.5 m sensor height

C. 10 m line spacing, 1 m sensor height

D. 1 m line spacing, 0.1 m sensor height

B. 2 m line spacing, 0.5 m sensor height

- Line spacing should be smaller than expected anomaly width
- Buried objects at 1-5 m depth produce anomalies roughly 2-5 m wide
- 2 m line spacing ensures you do not miss objects between lines
- 0.5 m sensor height maximizes signal strength while allowing comfortable walking
- Closer to the ground = stronger signal, but too close risks hitting obstacles
- 20 m spacing would miss most buried objects

Your magnetic map shows several dipolar anomalies (paired positive/negative peaks). What do these indicate?

A. Measurement errors from the instrument

B. Buried ferromagnetic objects (pipes, tanks)

C. Natural variations in soil magnetization

D. Effects of nearby power lines

B. Buried ferromagnetic objects

- Dipolar anomalies are the characteristic signature of buried ferromagnetic objects
- The positive-negative pair reflects the object's induced magnetization in Earth's field
- The anomaly shape and amplitude depend on object size, depth, and orientation
- Natural soil variations produce much weaker, broader anomalies
- Power line effects are typically linear features, not localized dipoles
- Each dipolar anomaly should be flagged for potential excavation or avoidance

Case Study 3

Mapping a contamination plume

Single Method Survey

Case 3: What We Know

- A chemical spill occurred at an industrial facility 5 years ago
- Groundwater monitoring wells show elevated chloride concentrations downgradient
- You need to map the extent of the contamination plume in 3D
- The aquifer is a sandy gravel layer at 5-15 m depth
- The contaminant is a dissolved salt (high ionic content)
- Regulatory agency requires delineation before remediation planning
- Access is available along existing roads surrounding the site

How does dissolved salt contamination affect the physical properties of groundwater?

A. Increases seismic velocity

B. Decreases electrical resistivity (increases conductivity)

C. Increases magnetic susceptibility

D. Decreases density

E. No measurable effect

B. Decreases resistivity

- Dissolved salts dissociate into ions (Na^+ , Cl^- , etc.)
- Ions are charge carriers that increase electrical conductivity
- Contaminated groundwater can be 10-100× more conductive than clean groundwater
- This creates a strong resistivity contrast with surrounding clean aquifer
- The plume appears as a low-resistivity zone in ERT images

Which method is best suited to map the 3D geometry of a conductive contamination plume at 5-15 m depth?

A. Ground Penetrating Radar (GPR)

B. Seismic refraction tomography

C. Electrical Resistivity Tomography (ERT)

D. Gravity survey

E. Airborne magnetics

C. Electrical Resistivity Tomography

- ERT directly measures resistivity, which is the affected property
- Target depth (5-15 m) is well within ERT's typical range
- Multiple parallel profiles can be combined for 3D visualization
- GPR would fail: high conductivity causes rapid signal attenuation
- Seismic methods would not detect the contamination (no velocity contrast)
- ERT can be repeated over time to monitor plume migration

You design an ERT survey with 5 m electrode spacing and 200 m profile length. What approximate maximum depth can you image?

A. 5 m

B. 15-25 m

C. 50 m

D. 100 m

B. 15-25 m

- Rule of thumb: Maximum depth $\approx 1/5$ to $1/4$ of total profile length
- 200 m profile \rightarrow approximately 40-50 m theoretical maximum, but practical depth is less
- With 5 m electrode spacing, effective depth is typically 15-25 m for good resolution
- This is appropriate for an aquifer at 5-15 m depth
- Deeper imaging would require longer profiles or larger electrode spacing

Your ERT results show a zone of very low resistivity (5-20 Ωm) extending from the spill source toward the southeast, while background resistivity is 100-300 Ωm . What do you conclude?

A. The low-resistivity zone is a clay layer, not contamination

B. The contamination plume extends southeast; the low resistivity is due to dissolved salts

C. The results are inconclusive; more data is needed

D. The spill has been naturally remediated

B. Plume extends southeast

Contamination plume extends southeast

- Factor of 10-20× resistivity reduction is consistent with salt contamination
- The geometry (originating from spill source, extending downgradient) supports this interpretation
- To rule out clay, you would check: (a) borehole logs, (b) spatial correlation with known geology
- If clay layers exist, they would appear as continuous, not plume-shaped anomalies
- Report should include: plume extent (length, width, depth), direction of migration, volume estimate

Case Study 4

Detecting Karst Voids Under a Road

Single Method Survey

Case 4: What We Know

- A highway is planned across a limestone plateau with known karst features
- Surface sinkholes have been observed nearby
- The engineering team needs to detect air-filled voids or solution cavities beneath the road alignment
- Target depth: 0-10 m (within road subgrade and foundation zone)
- The limestone is dry and relatively resistive
- Survey must be conducted along 2 km of planned road corridor
- Speed is important to meet project deadlines

What physical property contrast exists between air-filled voids and limestone bedrock?

A. Seismic velocity (voids have zero velocity)

B. Dielectric permittivity (air ≈ 1 , limestone $\approx 4-8$)

C. Density (voids have zero density)

D. All of the above

D. All of the above

- Air-filled voids create multiple strong contrasts:
 - Seismic: Air cannot transmit P-waves (velocity = 0 in void)
 - Dielectric permittivity: Air $\epsilon \approx 1$ vs. limestone $\epsilon \approx 4-8$ (strong GPR reflection)
 - Density: Air ~ 0 vs. limestone $\sim 2.5 \text{ g/cm}^3$ (gravity anomaly)
- For shallow targets (0-10 m) in dry limestone, GPR typically provides the best resolution
- The permittivity contrast creates strong radar reflections at void boundaries

Given the need for speed (2 km survey) and shallow target depth (0-10 m) in dry limestone, which method would you choose?

A. Gravity microgravity survey

B. Ground Penetrating Radar (GPR)

C. Seismic refraction

D. Electrical Resistivity Tomography (ERT)

B. Ground Penetrating Radar

- GPR is ideal because: (1) very fast acquisition (walking or vehicle-towed), (2) high resolution for shallow targets, (3) dry limestone has low attenuation
- 2 km can be surveyed in one day with vehicle-mounted GPR
- Voids appear as characteristic hyperbolic reflections or reflection-free zones
- Microgravity could detect voids but is slow and requires careful leveling
- ERT could work but would be much slower for 2 km coverage
- Seismic would lose energy at void boundaries (difficult to image)

What GPR antenna frequency would you select for detecting voids at 0-10 m depth in dry limestone?

A. 1600 MHz (very high resolution, very shallow)

B. 400-500 MHz (moderate resolution and depth)

C. 100 MHz (deep penetration, low resolution)

D. 50 MHz (maximum depth)

B. 400-500 MHz

- Trade-off: Higher frequency = better resolution but shallower penetration
- 1600 MHz: Excellent resolution but only penetrates ~1 m in most materials
- 400-500 MHz: Good balance for targets at 0-10 m depth in resistive materials
- 100 MHz: Would penetrate deeper but resolution might miss small voids
- In dry limestone, 400 MHz can achieve 8-15 m penetration with ~0.3 m vertical resolution
- This resolution is sufficient to detect engineering-significant voids (>0.5 m diameter)

Your GPR profile shows a zone with chaotic, disrupted reflections and several hyperbolic diffractions between stations 450-520 m. Surrounding areas show continuous, layered reflections. What does this indicate?

A. Instrument malfunction in that section

B. A zone of disturbed or void-rich limestone (potential karst)

C. A buried utility pipe

D. Change in road surface material

B. Karst zone

- Chaotic reflections indicate disrupted or heterogeneous subsurface (karst dissolution)
- Hyperbolic diffractions are characteristic of point scatterers (void edges, boulders)
- The 70 m lateral extent suggests a significant karst zone, not a single feature
- Continuous reflections elsewhere confirm the instrument was working properly
- Recommendation: Flag this zone for additional investigation (drilling, more detailed survey)
- Engineering implication: Foundation design must account for potential void collapse

Case Study 5

Characterizing an Uncontrolled Landfill

Multi-Method Survey

Case 5: What We Know

- An uncontrolled landfill operated from 1960-1985 with poor records
- The site is now covered with grass and soil; boundaries are uncertain
- Waste content is unknown but may include household waste and industrial debris
- Concern: Potential groundwater contamination from leachate
- You need to: (1) Delineate the lateral extent of the waste body, (2) Estimate waste thickness
- Budget allows for two complementary survey methods
- The site is approximately 200 m × 300 m

An old landfill might contain household waste, metallic debris, and decomposing organic matter. What physical property contrasts might exist?

A. Magnetic contrast (metallic objects) only

B. Resistivity contrast (conductive leachate) only

C. Both magnetic and resistivity contrasts

D. Neither; landfills have no geophysical signature

C. Both contrasts

- Metallic debris (cans, appliances, drums) creates strong magnetic anomalies
- Decomposing organic waste produces conductive leachate (dissolved ions)
- The waste body itself may be more or less resistive than surrounding soil
- Using both properties gives complementary information:
 - Magnetics: Rapid mapping of waste lateral extent (where metal exists)
 - ERT: Vertical structure, depth to base of waste, leachate plumes

Why would using only one method (either magnetics OR ERT) be insufficient for this project?

A. Single methods always fail at landfills

B. Magnetism shows lateral extent but not depth; ERT shows depth but is slow for full coverage

C. Legal requirements mandate two methods

D. One method would be sufficient; two is just for redundancy

B. Complementary strengths

Complementary strengths: lateral extent vs. vertical structure

- Magnetics is fast and excellent for delineating waste boundaries laterally (hours for full site)
- But magnetics provides no depth information (just surface anomaly map)
- ERT provides vertical cross-sections showing waste thickness and base depth
- But full 3D ERT coverage of 200×300 m would take many days
- Strategy: Use magnetics first to map lateral extent, then position ERT profiles across key sections
- This combination is efficient and provides both lateral and vertical characterization

You complete the magnetic survey. Results show a zone of high-amplitude, chaotic anomalies in the central 150 m × 200 m area, with quiet response outside. Where should you position your ERT profiles?

A. Outside the magnetic anomaly zone (in clean areas)

B. Only along the edges of the magnetic anomaly

C. Crossing the entire zone: from outside, through waste, to outside on both sides

D. Randomly distributed across the site

C. Crossing entire zone

Crossing entire zone: outside → through waste → outside

- ERT profiles must extend beyond the waste to establish background resistivity
- This allows you to identify the base and edges of the waste body
- Profiles should cross perpendicular to the long axis for best coverage
- Recommend 3-4 profiles spaced 50 m apart
- Each profile should extend 30-50 m beyond the magnetic anomaly boundary
- This design answers: How thick is the waste? Is there a clay liner? Where is the leachate?

**Your ERT profiles show: Low resistivity (5-30 Ωm) from surface to 8 m depth within the magnetic anomaly zone, underlain by moderate resistivity (100-200 Ωm).
Background soil is 80-150 Ωm . What do you interpret?**

A. Waste body is 8 m thick; underlying layer may be natural clay or liner

B. Contamination extends to 8 m; below that is clean aquifer

C. Results are inconclusive; the waste has no resistivity signature

D. The low resistivity is natural clay, not waste

A. Waste body is 8 m thick

Waste body is 8 m thick; underlying layer may be clay or liner

- Low resistivity in the waste zone is due to conductive leachate from decomposing organics
- The 8 m thickness is consistent with 25 years of uncontrolled dumping
- The moderate resistivity layer below could be: (a) natural clay aquitard, or (b) compacted soil liner
- This is actually good news: it may be limiting downward leachate migration
- Correlation with magnetic anomaly boundaries confirms the interpretation
- Report should include: waste volume estimate ($150 \times 200 \times 8 \text{ m} \approx 240,000 \text{ m}^3$), depth to base

Case Study 6

Archaeological Site Exploration

Multi-Method Survey

Case 6: What We Know

- A potential Roman villa site has been identified from aerial photography
- Surface finds include pottery fragments and building stone
- The site is on a limestone plateau covered by 0.5-2 m of soil
- Archaeological structures may include: stone walls, buried floors, storage pits
- Some structures may be filled with rubble, others with soil or clay
- Excavation budget is limited; geophysics must guide where to dig
- The survey area is 50 m × 50 m

A Roman villa site might contain stone walls, clay floors, rubble-filled pits, and void spaces. What physical property contrasts would you expect?

A. Velocity contrast only (stone vs. soil)

B. Resistivity contrast only (stone vs. clay)

C. No significant contrasts exist at this scale

D. Multiple contrasts: velocity, resistivity, and permittivity

D. Multiple contrasts

- Stone walls: High velocity, high resistivity, strong GPR reflections
- Clay floors/fills: Low resistivity, low GPR reflectivity (absorbs EM energy)
- Rubble/voids: Low velocity, variable resistivity, strong GPR diffractions
- Different features are detectable by different methods
- No single method will reveal all features equally well
- This is exactly why multi-method surveys are valuable in archaeology

You decide to use three methods: Seismic Refraction Tomography (SRT), Ground Penetrating Radar (GPR), and Electrical Resistivity Tomography (ERT). What is each method best suited to detect?

A. All three detect the same features equally well

B. SRT: Layer structure and voids; GPR: Walls and sharp interfaces; ERT: Clay-filled features

C. SRT: Clay features; GPR: Deep structures; ERT: Voids only

D. These methods are redundant and two would suffice

B. Distinct capabilities

Each method has distinct detection capabilities

- SRT: Best for layer structure (soil over bedrock), low-velocity voids, building foundations
- GPR: Best for sharp interfaces (walls), small voids, high-resolution shallow imaging
- ERT: Best for clay-filled features, moisture variations, conductive vs. resistive fills
- Example: A rubble-filled pit might be invisible to GPR (chaotic signal) but clear in SRT (low velocity) and ERT (variable resistivity)
- A mud-brick wall might be invisible to GPR (absorbs signal) but clear in ERT (low resistivity)
- Integration overcomes individual method limitations

How should you design the survey to enable joint interpretation of all three methods?

A. Use different grid orientations for each method to maximize coverage

B. Acquire all methods along the same profiles for direct comparison

C. Use GPR for full coverage, then target ERT and SRT only on anomalies

D. It doesn't matter; the results can be combined regardless of geometry

B. Same profiles for all methods

Acquire all methods along the same profiles

- Co-located data allows direct comparison of anomalies at the same positions
- If GPR shows a reflection at 15 m along the profile, you can check what ERT and SRT show there
- Different grid orientations would make integration confusing and potentially miss correlations
- Practical approach: Cover full area with GPR (fast), then select key profiles for ERT and SRT
- All methods along selected profiles enables rigorous joint interpretation

Your integrated results show: At position 12-18 m, GPR shows low amplitude (signal absorbed); SRT shows low velocity ($V_p < 600$ m/s); ERT shows low resistivity (50-100 Ωm). Background soil is $V_p = 900$ m/s, $\rho = 200-400$ Ωm . What feature do you interpret?

- A. A stone wall (walls have low velocity and low resistivity)
- B. An air-filled void (voids absorb GPR and have low velocity)
- C. A room or pit filled with conductive material (clay, mud brick, or organic fill)
- D. Undisturbed bedrock (consistent with background values)

C. Room/pit with conductive fill

A room or pit filled with conductive material

- Low GPR amplitude: EM energy absorbed by conductive fill (clay or mud brick)
- Low velocity: Loose or soft fill, not compact stone or bedrock
- Low resistivity: Confirms conductive material (clay minerals)
- This triple signature is consistent with a filled room, storage pit, or collapsed structure
- An air-filled void would have HIGH resistivity (air is an insulator)
- A stone wall would have HIGH velocity and HIGH resistivity
- Recommendation: Mark for excavation; likely an archaeological feature of interest

You identify three anomalies with consistent signatures across all methods: A-1 (filled room at 2 m depth), A-2 (possible hall at 1.5 m), A-3 (chamber at 1 m). What do you recommend?

A. Excavate all three simultaneously to maximize efficiency

B. Prioritize based on integrated interpretation; excavate highest-confidence target first

C. Do not excavate; the geophysics is sufficient documentation

D. Recommend more geophysical surveys before any excavation

B. Prioritize highest-confidence target

Prioritize based on integrated interpretation

- Not all anomalies are equally well-constrained or equally significant
- Recommend excavating the highest-confidence anomaly first to validate the geophysical interpretation
- If geophysics is confirmed, proceed to other targets with increased confidence
- This approach is efficient and builds trust in the methodology
- Document the geophysical predictions vs. excavation findings for future reference
- This validation loop improves interpretation of remaining anomalies

Key Takeaways

1. Start with physics: What property contrast exists?
If there is no contrast, no method will work.
2. Match method to target: Depth, size, material, access.
Each method has a "sweet spot" where it excels.
3. Survey design matters: Spacing, length, coverage.
Poor design leads to ambiguous results.
4. Multi-method when needed: Each method sees different things.
Integration overcomes individual limitations.
5. State your interpretation and its basis.
Link geophysical signature to physical properties to geological interpretation.

The Decision Framework

1. Physical Property Contrast

What physical property differs between target and background?
Velocity? Resistivity? Density? Susceptibility?
Permittivity?

2. Target Characteristics

What is the target?
Depth, size, geometry, orientation.
This determines survey parameters.

3. Practical Constraints

What are the limitations?
Access, budget, time, heritage protection.
These shape what is possible.

4. The Actual Question

What do you need to know?
"Where is it?" differs from "What is it?"
Define your deliverable.

Apply this framework to every survey you design.