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Target-Driven Integrated Near-Surface Geophysics: A Framework for Method Selection and Multi-Method Interpretation

Michael Arvanitis

sales@geomorphimaging.com

Geomorph Imaging Solutions Ltd

Method Article

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Abstract

Near-surface geophysics provides non-invasive tools for characterising the shallow subsurface across geotechnical, environmental, infrastructure, archaeological, and security-related applications. Yet the shallow subsurface is highly heterogeneous, and no individual method is universally capable of resolving all relevant targets, depths, and physical properties under all site conditions.

This narrative review compares three major methodological families used in shallow subsurface investigations: seismic methods, ground-penetrating radar (GPR), and electromagnetic (EM) methods including transient electromagnetics (TEM) and electrical resistivity tomography (ERT). Their physical sensitivities, acquisition characteristics, processing and inversion approaches, resolution scales, and site-specific failure modes are examined with emphasis on the complementary information provided by elastic, dielectric, and electrical-property contrasts.

Building on this comparison, a seven-step target-driven framework is proposed for method selection, integrated survey design, co-registration, joint interpretation, validation, and uncertainty reporting. The framework is operationalised through a decision matrix that maps target type, physical contrast, site conditions, and investigation depth to recommended method combinations, integration levels, and known failure modes. Five levels of integration rigour are distinguished, from side-by-side display to full probabilistic joint inversion, enabling practitioners to select the approach appropriate to the available data quality, computational resources, and decision context. The paper also discusses the limitations of multi-method integration, including scale mismatch, co-registration errors, structural coupling assumptions, petrophysical model uncertainty, and the risk of artificial agreement in joint inversion results. Representative application domains — cavity detection, archaeological prospection, seawater intrusion, geotechnical site investigation, and infrastructure assessment — are discussed with explicit reference to the framework. Recent advances in full-waveform inversion, joint petrophysical inversion, passive seismic methods, multi-channel GPR, and machine learning are reviewed. The central conclusion is that integrated near-surface geophysics is most effective when method combinations are selected from the expected target physics and site constraints, interpreted within a common spatial and uncertainty framework, and validated against independent ground truth rather than simply compared post hoc.

1. Introduction

The shallow subsurface — broadly defined as the interval from the ground surface to depths of a few tens of metres — is one of the most geophysically and geotechnically consequential domains in applied geoscience. Within this relatively narrow depth range, geological complexity, anthropogenic disturbance, variable moisture conditions, buried objects, fractures, voids, utilities, stratigraphic discontinuities, and construction materials may coexist. The reliable imaging and interpretation of near-surface targets is therefore inherently challenging, and the difficulty is compounded by the wide range of spatial scales, target types, and geological settings encountered across different application domains.

Near-surface geophysics has progressively evolved into a major scientific field because it offers non-invasive, minimally disruptive tools for the investigation of shallow formations and buried targets. These tools are now routinely applied across a remarkably diverse range of disciplines: geotechnical site characterisation before construction, foundation engineering, road and pavement assessment, pipeline and cable mapping, cavity and sinkhole detection, environmental contamination surveys, cultural heritage and archaeological prospection, and defence-related subsurface sensing (Everett, 2013; Reynolds, 2011; Butler, 2005; Parsekian et al., 2015; Binley et al., 2015). The discipline is further driven by the growing demand for quantitative, reproducible, and uncertainty-aware subsurface models that can support engineering decisions, regulatory compliance, and scientific interpretation.

A fundamental practical reality persists: no single geophysical method is universally optimal for near-surface investigations. Seismic methods are particularly valuable when the target problem relates to elastic properties, stratigraphic layering, stiffness contrasts, or mechanical characterisation. Ground-penetrating radar offers exceptional shallow resolution

and is highly effective when dielectric contrasts are strong and ground conditions permit adequate signal penetration. Electromagnetic methods — including transient electromagnetic (TEM) methods and electrical resistivity tomography (ERT) — are especially useful in problems governed by conductivity and resistivity contrasts, fluid content, or subsurface heterogeneity in settings where radar may be attenuated. Each method images the subsurface differently because each responds to a different physical property of the medium.

This physical specialisation creates both a challenge and an opportunity. The challenge lies in the fact that isolated interpretation from a single method can be incomplete, ambiguous, or overconfident. The opportunity lies in the fact that the combined use of multiple methods, designed around the physics of the target problem, can provide a substantially more robust and defensible subsurface image by integrating complementary physical information. What has often been missing is a structured, physically motivated logic for deciding how and why to combine specific methods, under which geological and operational conditions, and for which target type — including conditions under which integration is unlikely to provide benefit or may introduce spurious results.

Several methodological developments have strengthened the case for integrated near-surface geophysics. Improvements in probabilistic inversion, full-waveform modelling, joint inversion, multi-channel acquisition, and georeferencing increasingly allow datasets with different spatial scales and physical sensitivities to be compared within common spatial and uncertainty frameworks (Virieux and Operto, 2009; Gallardo and Meju, 2004; Doetsch et al., 2010; Qin et al., 2022, 2024; Moorkamp, 2022). Bayesian treatments of seismic-model uncertainty (Arvanitis and Vlamos, 2009), alternative ray-tracing formulations for strongly heterogeneous media (Arvanitis, 2009), and high-density georeferenced GPR acquisition (Arvanitis and Frey, 2025) are considered here as representative components of a wider integration strategy rather than as universally applicable solutions. Their specific contributions and limitations in the context of near-surface integration are discussed explicitly.

The present contribution differs from existing practitioner guides and method-specific reviews in three ways. First, it proposes an explicit decision matrix linking target type, physical contrast, site conditions, and investigation depth to recommended method combinations, integration levels, and known failure modes — a level of prescription absent from most prior frameworks. Second, it distinguishes five levels of integration rigour (Section 4.1), which the existing literature often conflates. Third, it explicitly addresses conditions under which multi-method integration is unlikely to be beneficial or may introduce artefacts (Section 4.6). Together, these elements are intended as a practical bridge between method-specific expertise and problem-oriented subsurface characterisation.

This paper first compares the physical basis and practical characteristics of seismic, GPR, and EM methods, including a critical discussion of failure modes and site-specific limitations. It then examines the scientific rationale for multi-method integration, distinguishes integration levels, and discusses integration limitations. A seven-step target-driven framework is proposed and supported by a decision matrix. Representative application domains, recent methodological advances, and open research challenges are subsequently discussed.

Review methodology. This is a narrative review. The literature was identified through systematic searches of Web of Science, Scopus, and Google Scholar using the following keyword combinations: "near-surface geophysics", "integrated geophysics", "joint inversion", "seismic tomography", "ground-penetrating radar", "transient electromagnetics", "electrical resistivity tomography", "Bayesian inversion", "uncertainty quantification", "machine learning geophysics", "hydrogeophysics", and "archaeological geophysics". The time range covered is 1987–2025, with particular emphasis on publications from 2019 onwards for topics related to methodological advances. Additional references were identified through citation tracing. Selection prioritised peer-reviewed journal articles reporting field or synthetic validation of integration strategies; papers reporting only single-method or purely theoretical results were included where they provide essential physical background.

2. Physical Basis and Practical Limitations of the Main Method Families

2.1 Seismic Methods

Seismic methods investigate the subsurface through the generation, propagation, and recording of elastic waves. In the near-surface domain, the most commonly applied approaches include refraction surveying, reflection profiling, surface-wave methods — most notably MASW (Park et al., 1999) — seismic refraction tomography, and full-waveform inversion (FWI). Seismic refraction exploits critically refracted P-waves to estimate velocity structure. MASW provides shear-wave velocity (Vs) profiles directly linked to soil stiffness, site amplification, and liquefaction susceptibility. The physical basis of seismic methods lies in the sensitivity of elastic wave velocities to the mechanical properties of the medium: P-wave velocity is controlled by the bulk and shear moduli and density; S-wave velocity is controlled by shear modulus and density alone, rendering it insensitive to pore fluid properties.

Three-dimensional seismic travel-time tomography is particularly challenged by the strong lateral and vertical heterogeneity common in the near surface. Large velocity contrasts, sparse or uneven ray coverage, near-surface noise, and non-uniqueness may cause instability or excessive smoothing, depending on the forward solver, regularisation, and starting model (Zelt and Barton, 1998; Tarantola, 1987). In crustal studies, velocity contrasts between layers are typically small and gradients smooth, so that standard ray-tracing algorithms converge reliably. At engineering or archaeological scales, however, inter-layer velocity contrasts may be large, causing conventional ray-tracing algorithms to become unstable and produce tomograms that are physically unrealistic, overly smooth, or incapable of resolving key anomalies (Arvanitis, 2009). The practical implication is that solver choice — conventional ray-tracing, finite-difference eikonal solvers, or alternative formulations — should follow the acquisition geometry, data quality, target scale, and expected velocity structure, rather than being applied routinely.

Alternative forward-modelling formulations have been proposed for strongly heterogeneous settings. One example is Finsler-geometry-based ray tracing, in which the travel-time metric is formulated within a direction-dependent Lagrangian framework on the tangent bundle of the velocity field (Arvanitis, 2009). Synthetic and field examples reported in that study indicated improved recovery of low-velocity and channel-shaped anomalies relative to the conventional ray-tracing implementation tested, with chi-square values converging from 13.83 to 1.1 after six inversions. Such approaches are potentially useful where standard forward solvers perform poorly, but their broader applicability relative to modern eikonal solvers and finite-difference schemes remains to be systematically evaluated across a wider range of geological settings.

A second major issue in seismic tomography is the treatment of model and data uncertainty. Seismic inverse problems are non-unique, and residual misfit alone does not fully describe model reliability. Bayesian formulations provide one route for combining prior information with observed travel-time data and expressing the result as a posterior probability distribution (Tarantola, 1987). In a near-surface travel-time tomography example, Arvanitis and Vlamos (2009) compared Bayesian and frequentist estimators on first-break picks from 200 shot records and reported lower residual measures (RMS approximately 1.0 vs. 1.56; chi-square 1.1 vs. approximately 2.0) and improved agreement with independent excavation information for the tested dataset. The Bayesian approach also completed the analysis in approximately half the computational time of the frequentist approach. The wider lesson is that uncertainty should be represented explicitly and, where feasible, propagated into subsequent integrated interpretation. However, the validity of the chosen prior model, which strongly influences the posterior in high-dimensional near-surface problems, must be justified for each application (Fig. 1).

Seismic full-waveform inversion (FWI) seeks to minimise the misfit between observed and modelled seismograms to recover spatially continuous elastic-property models at higher resolution than travel-time-only approaches (Virieux and Operto, 2009). Its near-surface application remains demanding because of strong heterogeneity, cultural noise, source and receiver coupling, and cycle-skipping risk. Accordingly, no single inversion or ray-tracing strategy is universally optimal; solver choice should follow the acquisition geometry, data quality, target scale, and expected velocity structure. Key failure modes of seismic methods in the near-surface domain include: velocity inversions that cannot be resolved by refraction tomography; velocity-depth ambiguity in shallow refraction surveys; noise contamination from traffic and wind in urban environments; and over-smoothing caused by insufficient ray coverage at the edges of tomographic sections.

2.2 Ground-Penetrating Radar (GPR)

Ground-penetrating radar operates through the transmission and recording of electromagnetic waves. Propagation velocity is primarily controlled by dielectric permittivity, whereas reflection amplitude depends on contrast in electromagnetic properties across an interface and attenuation is strongly influenced by electrical conductivity (Annan, 2005; Daniels, 2004). Dry, low-conductivity materials commonly favour signal penetration, while conductive clays and saline pore fluids may strongly attenuate radar energy and restrict investigation depth to centimetres in extreme cases. This fundamental limitation is among the most important site-specific failure modes of GPR: the method cannot be reliably applied in marine clays, saturated salt-contaminated soils, or environments where the near-surface conductivity exceeds approximately 30–50 mS/m, depending on frequency and target depth requirements.

Modern archaeological and engineering GPR surveys increasingly use densely sampled grids, GNSS or total-station positioning, and three-dimensional depth-slice visualisation. The Sanctuary of Poseidon at Isthmia, Greece, provides one example of georeferenced grid acquisition used to map rectilinear anomalies and guide archaeological interpretation (Arvanitis and Frey, 2025). Using a 450 MHz MALÅ system across 14 grids encompassing 588 two-dimensional profiles over very dry soils, the survey achieved consistent signal penetration to 3 m. Post-processing included time-zero correction, automatic gain, bandpass filtering, background removal, migration, topographic correction, and Finsler imaging techniques for data optimisation (Arvanitis, 2009). Depth-slice visualisation at 1.15 m revealed rectilinear structures consistent with buried wall remnants oriented along east–west and north–south axes; an unexpectedly dense group of anomalies at 0.8 m depth east of the Roman bath complex — previously assumed to be open space — indicated that targeted excavation may be warranted. Critically, the geophysical interpretations were treated as hypotheses to be tested against known excavation data and three-dimensional scans of exposed architectural remains, rather than as definitive conclusions.

GPR full-waveform inversion (FWI) represents the most quantitatively advanced GPR application: rather than interpreting reflection kinematics alone, GPR-FWI matches the complete electromagnetic waveform to recover spatially continuous models of dielectric permittivity and electrical conductivity at sub-wavelength resolution. Deep learning-guided GPR-FWI has demonstrated near-real-time quantitative inversion in field conditions (Zhang et al., 2024). The limitations of GPR beyond conductivity attenuation include: depth–resolution trade-off (higher frequency yields better resolution but less penetration); clutter from surface reflections and near-field effects; the difficulty of quantifying wave velocity in heterogeneous media without calibration targets or common-midpoint surveys; and the computational cost of FWI for large 3D datasets.

2.3 Electromagnetic Methods

Electromagnetic methods investigate the subsurface through the induction and measurement of secondary electromagnetic fields generated by the interaction of primary fields with electrically conductive or resistive subsurface features. The primary physical parameter of interest is electrical conductivity (sigma, S/m) or its reciprocal, resistivity (rho, Ohm.m). Different materials — water-bearing sediments, dry sands, clays, metallic pipes, saline intrusions, and air-filled voids — have characteristically different conductivity or resistivity signatures, making EM methods sensitive to a wide range of targets that are invisible or ambiguous in seismic or GPR data.

The transient electromagnetic (TEM) method is a time-domain technique in which a primary field is generated and then rapidly terminated, inducing secondary currents whose decay reflects subsurface electrical structure. TEM is particularly valuable where investigation depth or conductivity conditions limit GPR. Its response depends on source geometry, time window, host resistivity, target size and contrast, and system characteristics. The TEM response of a resistive underground cavity embedded in a more conductive host may be reduced relative to the background during diagnostic portions of the decay; the opposite sense of anomaly is observed for a conductive target. The timing and amplitude of these anomalies are not universal signatures: they depend on geometry, host conductivity, source-receiver configuration, and the measured field

component (Xue et al., 2010). Forward modelling using analytical or numerical solutions is therefore an essential part of TEM interpretation, particularly for cavity detection (Fig. 2).

A large-loop TEM field example from a coal-mine setting in Shanxi Province, China, illustrates the potential of the method for deeper void detection (Xue et al., 2010). High-resistivity anomalies interpreted as air-filled workings were compared with subsequent drilling information: the drill confirmed a tunnel top at 48 m depth with a thickness of 22 m, closely matching the geophysical estimate. The example is useful as field validation of TEM sensitivity to resistive cavities, but the transferability of any anomaly criterion to other geological settings requires site-specific modelling and independent verification, as the TEM response is strongly dependent on host conductivity and source-loop geometry. Key limitations of TEM include: equivalence between models of different conductivity-thickness products; resolution decreasing with depth as the secondary field spreads laterally; electromagnetic noise from power lines and metallic infrastructure; and the need for open access for loop deployment.

Electrical resistivity tomography (ERT) provides complementary 2D or 3D resistivity imaging through the injection of controlled DC current between electrode pairs and measurement of the resulting voltage distribution. ERT is particularly powerful for time-lapse monitoring of subsurface hydrological changes, contaminant plume mapping, and characterisation of fluid-bearing formations (Binley et al., 2015). Frequency-domain EM (FDEM) methods offer rapid non-contact conductivity profiling well-suited to large-area reconnaissance surveys. The integration of TEM and ERT provides complementary sensitivity to both deep resistive structures (better resolved by TEM) and shallow lateral heterogeneity (better resolved by ERT).

3. Comparative Analysis of Near-Surface Methods

The method families differ fundamentally in physical sensitivity, practical depth of investigation, spatial resolution, acquisition density, and vulnerability to site-specific noise. Table 1 provides a qualitative comparison. Figure 3 presents a qualitative matrix illustrating the complementarity of method sensitivities across six dimensions. The ratings in the figure are qualitative and configuration-dependent; they should not be interpreted as universal or site-independent performance rankings.

Table 1
Comparative summary of near-surface geophysical method families. Depth and resolution values are configuration-dependent and should be treated as order-of-magnitude guidance rather than fixed limits.

Method	Physical Sensitivity	Typical Depth / Resolution	Key Strengths	Key Limitations	Main Applications
Seismic refraction / tomography	Elastic wave velocity (Vp); velocity contrasts	Metres to tens of metres; resolution depends on source–receiver geometry and wavelength	Bedrock/regolith mapping; velocity structure; tomographic imaging of velocity contrasts	Non-uniqueness; velocity inversions; logistics; cultural noise; conventional ray-tracing unstable in > ~ 70% inter-layer contrast (Arvanitis, 2009)	Geotechnical; geohazard; mining; geoarchaeology
MASW / surface waves	Shear-wave velocity (Vs); stiffness; dispersion	0–30 m; 1–3 m vertical resolution typical	Vs profiling; liquefaction assessment; direct link to geotechnical parameters	Lateral averaging; sensitive to heterogeneity; may miss velocity inversions	Site characterisation; urban geotechnics
Ground Penetrating Radar (GPR)	Dielectric permittivity; electromagnetic contrast	Centimetres to several metres; strongly frequency- and site-dependent	Very high shallow resolution; dense 3D grid acquisition; GNSS-synced; non-invasive	Attenuated by conductive media (clay, saline water); depth–resolution trade-off	Archaeology; utilities; pavement; void detection; forensics
Transient Electromagnetic (TEM)	Electrical resistivity/conductivity; time-domain decay	Metres to hundreds of metres, depending on source geometry, time window, host conductivity, and noise	Depth-sensitive resistivity; no galvanic contact; scalable source; detects resistive and conductive anomalies	EM noise; equivalence/non-uniqueness; resolution decreases with depth	Mining; hydrogeology; cavity detection; deep engineering
Electrical Resistivity Tomography (ERT)	Electrical resistivity; fluid content; saturation	Shallow to tens of metres in common surveys; array- and resistivity-dependent	Fluid mapping; contaminant plumes; time-lapse monitoring	Requires electrode contact; resolution decreases with depth; labour-intensive	Environmental; hydrogeological; geotechnical
EM induction (FDEM)	Apparent conductivity; soil/bedrock contrast	Shallow to intermediate depth, strongly instrument- and frequency-dependent	Rapid profiling; no ground contact; multi-depth sounding	Calibration drift; near-surface noise; temperature sensitivity	Agriculture; environmental; utility mapping

Note: Depth and resolution values depend on acquisition design, target-host contrast, instrument configuration, and site conditions, and should not be applied without site-specific modelling.

Complementarity is best understood through target physics rather than fixed method rankings. A shallow dry void may produce seismic, radar, and resistivity contrasts, although detectability depends on target size, depth, host properties, and survey geometry. A saline groundwater plume may strongly attenuate GPR while producing a pronounced electrical conductivity anomaly amenable to ERT or TEM investigation (Binley et al., 2015). A deeper air-filled excavation may lie beyond the practical range of high-frequency GPR but remain detectable with TEM or ERT under favourable resistivity contrast (Xue et al., 2010). Method selection should therefore be based on expected contrast, scale, and site conditions, with forward modelling used where detectability is uncertain.

Several conditions commonly lead to method failure in the near-surface context. Seismic refraction fails to resolve velocity inversions and produces unrealistically smooth tomograms in high-contrast settings unless an appropriate forward solver is used. GPR fails in electrically conductive soils and cannot penetrate beneath the water table in saline environments. TEM and ERT face equivalence problems, particularly in layered settings where thin conductive or resistive layers can produce responses indistinguishable from those of thicker layers with different conductivity. MASW yields poor lateral resolution in strongly heterogeneous settings because of the implicit one-dimensional assumption in dispersion-curve inversion. Recognising these failure modes is a prerequisite for assessing whether integration is likely to resolve an ambiguity or merely aggregate two ambiguous results.

4. The Scientific Case for Multi-Method Integration

4.1 Levels of Multi-Method Integration

The literature on integrated geophysics does not always distinguish between different levels of integration rigour, which can lead to confusion about the strength of evidence that a multi-method result provides. Five levels can be usefully distinguished, following the typology developed in Linde and Doetsch (2016) and applied in the context of near-surface and hydrogeophysical applications (Parsekian et al., 2015; Binley et al., 2015):

- Level 1 — Side-by-side display: geophysical sections or maps from different methods are plotted adjacent to one another and interpreted subjectively. No formal spatial co-registration is required. This is the most common level of integration in practice; it reduces overconfidence in any single-method result but provides no formal constraint on the joint solution.
- Level 2 — Co-registered overlay interpretation: datasets are spatially co-registered to a common coordinate system and interpreted simultaneously, typically by identifying corresponding anomalies across methods. This is more rigorous than Level 1 because it requires spatial consistency, but the coupling between datasets remains qualitative.
- Level 3 — Structural joint inversion: a formal inversion is performed in which structural features (interfaces, gradients, boundaries) are required to be consistent across datasets, typically through cross-gradient constraints (Gallardo and Meju, 2004). No petrophysical relationship between the inverted physical parameters is assumed. This level is appropriate when the physical parameters are structurally correlated but not quantitatively related.
- Level 4 — Petrophysical joint inversion: the inversion is formulated in terms of common petrophysical parameters (porosity, saturation, fluid content) that link multiple geophysical observables through rock-physics models such as Gassmann's equations, Archie's law, or the CRIM model (Qin et al., 2022, 2024). This level yields quantitative subsurface characterisation but requires reliable petrophysical models, which are a major source of uncertainty.
- Level 5 — Full probabilistic joint inversion: a Bayesian formulation is used in which the posterior probability distribution over all model parameters, given all datasets simultaneously, is computed or approximated (Tarantola, 1987; Arvanitis and Vlamos, 2009; Moorkamp, 2022). This level provides the most complete uncertainty characterisation but is computationally demanding and requires well-justified priors.

The appropriate integration level for a given investigation depends on the data quality, the available petrophysical information, the computational resources, and the decision context. Higher integration levels are not always warranted or

achievable; practitioners should select the level consistent with the evidence available rather than defaulting to the most sophisticated technique.

4.2 Reduction of Interpretational Ambiguity

The most fundamental argument for multi-method integration is the reduction of interpretational ambiguity inherent in all geophysical inverse problems. Because each method responds to a different physical property, the set of subsurface models consistent with one dataset will generally differ from the set consistent with another. The intersection of these solution spaces — the models consistent with both datasets simultaneously — is substantially smaller and more geologically meaningful than either individually. This principle is well established theoretically (Gallardo and Meju, 2004; Doetsch et al., 2010) and confirmed empirically across a wide range of field studies.

4.3 Scale Linkage and Complementary Spatial Resolution

Different methods operate at different spatial scales. GPR provides centimetre-to-decimetre resolution at depths of up to several metres; seismic refraction tomography resolves structures at the metre-to-decametre scale over depths of tens of metres; and TEM provides depth-sensitive resistivity information over ranges from a few metres to several hundred metres. In an integrated survey, these different resolution scales can be combined to build a multi-scale subsurface characterisation that no single method can achieve (Parsekian et al., 2015). However, the different support volumes of different methods — the volume of ground to which a single measurement is sensitive — must be accounted for when comparing or jointly inverting datasets, as apparent agreement between results at different scales may reflect averaging rather than genuine corroboration.

4.4 Resilience to Site-Specific Method Failures

In a single-method workflow, site-specific degradation of that method may leave critical aspects of the subsurface unresolved. In a multi-method workflow, the degradation of one method can be compensated by the diagnostic power of another, provided the target produces a detectable contrast in at least one of the available physical domains. For example, a conductive clay layer that blocks GPR signals may produce a strong ERT anomaly that confirms the layer depth and conductivity, allowing the combined result to be more reliable than either dataset alone. The value of redundancy diminishes, however, when all selected methods fail to detect the target for different reasons — a situation that forward modelling before survey design can help identify.

4.5 Formalised Joint Inversion

Cross-gradient joint inversion (Level 3; Gallardo and Meju, 2004) promotes structural similarity between models derived from different datasets without prescribing a direct petrophysical relationship. Indirect joint petrophysical inversion (Level 4; Qin et al., 2022, 2024), in which geophysical models are transformed to common parameters through rock-physics relations, offers a different route to integration that yields hydrogeologically interpretable results. Probabilistic methods (Level 5; Arvanitis and Vlamos, 2009; Moorkamp, 2022) can complement both strategies by characterising uncertainty, but the validity of coupling assumptions and petrophysical relations must be tested for the specific near-surface materials under investigation.

4.6 Limitations and Failure Modes of Multi-Method Integration

The scientific case for integration should not obscure the conditions under which multi-method approaches fail to improve, or may even degrade, subsurface characterisation. Several failure modes are well recognised in the literature but are underemphasised in practitioner guidance:

- Scale mismatch: different methods interrogate different support volumes. Seismic tomographic cells, ERT pixels, and GPR traces all represent averages over different spatial scales. When co-registered results are compared, apparent agreement may reflect independent averaging of a spatially heterogeneous subsurface rather than mutual

corroboration of a common model. This effect is especially pronounced when comparing surface-wave Vs profiles with GPR depth slices at the same nominal depth.

- Co-registration errors: positioning inaccuracies in one or more datasets propagate as interpretation artefacts when overlaying datasets at different spatial resolutions. In archaeological applications, sub-metre positioning errors may shift a GPR anomaly relative to an ERT anomaly sufficiently to suggest non-correspondence where genuine correspondence exists.
- Temporal differences between acquisition campaigns: time-lapse changes in soil moisture, frost, or fluid content between GPR and seismic or ERT surveys may be misinterpreted as spatial structure if datasets acquired at different times are co-registered without accounting for temporal variability.
- Inappropriate structural or petrophysical coupling: cross-gradient joint inversion assumes that structural boundaries in resistivity and velocity coincide. Where this assumption does not hold — for example, where a lithological boundary produces a strong velocity contrast but no resistivity contrast — the cross-gradient constraint biases both inversions toward a spurious common structure. Petrophysical coupling through rock-physics models carries additional uncertainty when models calibrated for clean sands are applied to clay-bearing, partially saturated, or anthropogenically altered near-surface materials.
- Artificial agreement in joint inversion results: the apparent improvement in a joint inversion relative to separate inversions — lower residuals, smoother interfaces, reduced uncertainty bounds — does not guarantee that the result is geologically more accurate. Joint inversion can produce a model that satisfies all datasets simultaneously but corresponds to no physical reality if the coupling assumptions are violated or if one dataset is poorly conditioned. Independent validation against borehole, excavation, or laboratory data is therefore essential before attributing accuracy to a jointly inverted model (Doetsch et al., 2010).

Recognising these limitations does not argue against integration; it argues for thoughtful integration design, explicit forward modelling, and rigorous independent validation.

4.7 Defensibility of Practical Decisions

In applied geophysics, survey outputs often inform decisions with financial, heritage, or safety consequences. Converging evidence from physically independent datasets can strengthen an interpretation, but multiple methods do not automatically eliminate ambiguity. Defensibility depends on transparent processing, verified co-registration, explicit uncertainty analysis, and independent validation. This is especially important in void detection, where a single-method false negative can have severe safety consequences (Xue et al., 2010), and in archaeological prospection, where false positives leading to unnecessary excavation waste finite and irreplaceable resources (Arvanitis and Frey, 2025).

5. A Target-Driven Framework for Integrated Survey Design

The comparative analysis and integration rationale developed in the preceding sections are operationalised in a seven-step, target-driven framework for integrated near-surface geophysical survey design and interpretation. The framework is illustrated in Fig. 4. A decision matrix (Table 2) provides a concise reference for method selection and integration level for common investigation scenarios.

Step 1: Define the target problem and investigation objectives. The starting point is a precise, written statement of the investigation objective, identifying the type of target, the level of spatial resolution and positional accuracy required, and the decision context in which results will be used. Without this explicit definition, method selection inevitably defaults to convention rather than physical reasoning.

Step 2: Characterise the expected depth, geometry, and size of the target. Prior to method selection, the practitioner should quantify, even approximately, the expected depth range, lateral extent, and aspect ratio of the primary target. These parameters directly control the resolution, frequency content, and receiver geometry requirements for each method under

consideration. Where no prior information exists, preliminary single-method reconnaissance may be used to constrain these parameters before a full integrated survey is designed.

Step 3: Identify the dominant physical contrast. The practitioner must identify which physical contrast — elastic, dielectric, or conductivity/resistivity — is most likely to exist between the target and its host medium under anticipated geological and hydrological conditions. Where multiple contrasts are expected, the method combination should be selected to address each independently. Where no single contrast is clearly dominant, forward modelling should be used to assess detectability before committing to a survey design.

Step 4: Evaluate site conditions and operational constraints. Site conditions — soil conductivity, surface accessibility, cultural noise levels, vegetation cover, existing infrastructure, survey area extent, and budget — directly affect method performance and must be assessed before finalising survey design. For each candidate method, the practitioner should explicitly identify any site condition that could degrade its performance below the detection threshold for the target, and select the method combination accordingly.

Step 5: Select method combination and integration level from the decision matrix (Table 2). Given the target characterisation and site assessment of Steps 1–4, the appropriate method combination and integration level can be identified from Table 2. The selected combination should maximise independent sensitivity to the target while remaining compatible with the required resolution, investigation depth, access, and budget. The decision matrix lists known failure modes for each combination to guide practitioners in identifying conditions where integration may not provide the expected benefit.

Step 6: Integrated acquisition, processing, and interpretation at the selected level. Data should be acquired in a temporally and spatially coordinated manner to ensure common spatial coverage and minimise time-lapse variability effects. Processing should produce co-registered data products on a common georeferenced coordinate system. Interpretation should be applied at the integration level selected in Step 5 (Levels 1–5, Section 4.1) rather than defaulting to a higher level that the data quality and petrophysical information do not support. Formal joint inversion should be accompanied by explicit assessment of the coupling assumptions, as discussed in Section 4.6.

Step 7: Validate, quantify uncertainty, and report with confidence bounds. Every integrated survey should include explicit uncertainty assessment appropriate to the integration level applied: at Level 1–2, qualitative statements of agreement and inconsistency; at Level 3, resolution analysis and sensitivity testing; at Levels 4–5, posterior uncertainty bounds or ensemble spread. Independent validation should draw on whatever ground-truth information is available — boreholes, excavation, exposed structures, laboratory data, or repeat surveys — and should be planned as part of the survey design rather than treated as an afterthought. Reported results should clearly distinguish observed anomalies from inferred targets and state confidence and limitations explicitly.

Table 2
Decision matrix for integrated near-surface geophysical survey design. Integration levels (†) follow the typology of Section 4.1 (1 = side-by-side display; 2 = co-registered interpretation; 3 = structural joint inversion; 4 = petrophysical joint inversion; 5 = probabilistic joint inversion). The table lists common scenarios; site-specific modelling is recommended for all novel configurations.

Target type	Depth range	Dominant contrast	Primary method	Secondary method	Integration level†	Caution
Bedrock interface	5–30 m	Elastic + resistivity	Seismic refraction	ERT	2–3	Verify Vp–resistivity correlation with borehole data
Shallow void / cavity	0–5 m	Dielectric + resistivity	GPR	ERT or FDEM	2–3	GPR fails in conductive soils; confirm with forward modelling
Deep void / cavity	> 5 m	Resistivity	TEM	ERT	3	Strong host-contrast required; verify with drilling
Buried masonry / wall	0–3 m	Dielectric ± elastic	GPR	Magnetics	2	Weak seismic contrast common in rubble backfill
Seawater intrusion	5–50 m	Resistivity (strong)	ERT / TEM	Seismic	3–4	Archie law only valid in clean sand; clay complicates inversion
Vadose zone hydrology	0–10 m	Dielectric + elastic	GPR	Shallow seismic	4	JPI requires accurate rock-physics model; validate with TDR
Pavement / slab NDT	0–0.5 m	Dielectric	GPR	–	1–2	Single-method often sufficient; ERT/FDEM for deep voids
Buried threat / landmine	0–0.3 m	Dielectric + metal	GPR	Metal detector	1–2	Cultural clutter severe; false alarm rate critical metric
Archaeological feature	0–3 m	Dielectric ± resistivity	GPR	Magnetics or ERT	2	Hypothesis-driven; integrate with excavation context
Geotechnical site	0–30 m	Elastic + resistivity	Seismic (MASW)	ERT	2–3	Calibrate Vs–Su relation with CPT or SPT testing

Note: All combinations require co-registration (Step 6) and independent validation (Step 7). "–" in Secondary method column indicates that single-method coverage is typically sufficient for first-pass investigation but should be supplemented if anomalies are ambiguous.

6. Framework Application to Representative Domains

The seven-step framework of Section 5 is applied here to five representative investigation scenarios to illustrate how method selection, integration level, and validation strategy vary with target type, depth, and site conditions. These examples draw on published field studies and established practice; they are intended as illustrative rather than prescriptive, and site-specific forward modelling remains essential for each new application.

6.1 Geotechnical and Engineering Site Investigations

Geotechnical site characterisation requires estimates of subsurface layering, stiffness, velocity structure, saturation, and heterogeneity (Steps 1–2: bedrock/regolith interface at 5–30 m depth, lateral extent of tens to hundreds of metres). The

dominant physical contrasts are elastic (velocity structure) and electrical (saturation, lithology), supporting a primary seismic/MASW with secondary ERT combination (Step 5; Table 2, Level 2–3). MASW provides Vs profiles linked to shear stiffness and liquefaction susceptibility (Xia et al., 2003); ERT provides saturation and lithology information that seismic velocities alone cannot resolve. Integration is most productive at Level 2–3 when a robust petrophysical relationship between Vs and resistivity cannot be independently calibrated. The critical Step 7 action is cross-referencing inversion results against borehole or CPT data to validate Vs–strength relationships before the survey is used for engineering design.

6.2 Infrastructure Diagnostics and Non-Destructive Testing

Infrastructure assessment — pavement condition monitoring, bridge deck inspection, tunnel lining evaluation, utility mapping — requires very shallow (0–1 m) and rapid investigation (Step 2). The dominant contrast is dielectric (GPR, Step 3), making GPR the natural primary method (Step 5; Table 2, Level 1–2). Vehicle-mounted multi-channel GPR arrays provide areal coverage at survey speeds of several kilometres per hour. TEM or ERT can supplement GPR where voids or saturation beneath concrete exceed GPR penetration depth (Step 4: conductivity of near-surface materials may limit GPR). Validation (Step 7) against cores, window openings, or reference sections is essential to calibrate layer-thickness and dielectric estimates.

6.3 Environmental and Hydrogeophysical Investigations: Seawater Intrusion

Seawater intrusion in coastal aquifers represents a major geoenvironmental hazard affecting groundwater resources worldwide (Binley et al., 2015). Target characterisation (Step 2): freshwater–saltwater interface at 5–50 m depth with a strong resistivity contrast (Step 3: saline water, rho approximately 0.5–5 Ohm.m vs. fresh, > 20 Ohm.m). GPR is typically ineffective in saline environments (Step 4: conductivity constraint), making ERT or TEM the primary method, supported by FDEM for rapid reconnaissance (Step 5; Table 2, Level 3). Joint petrophysical inversion (Level 4) using Archie's law to relate resistivity to saturation and salinity is technically feasible but requires validation against water chemistry data, as clay content strongly affects the petrophysical relationship. The principal caution (Table 2) is that clay-bearing sediments violate simple Archie's law, leading to overestimation of freshwater extent; this must be addressed in Step 7 through hydrochemical sampling alongside the geophysical survey (Binley et al., 2015).

6.4 Cavity and Void Detection

Cavity detection spans a range of depths and geological contexts. Step 2 determines whether GPR, TEM, or both are appropriate: for shallow (0–5 m) voids in dry resistive soils, GPR is the primary method supported by ERT or FDEM (Table 2, Level 2–3); for deeper voids (> 5 m) or in conductive soils, TEM is the primary method. The dominant contrast is resistive for air-filled voids (Step 3), but the magnitude of the contrast relative to noise must be assessed through forward modelling before survey deployment. TEM has demonstrated reliable sensitivity to resistive voids in coal-mine environments at depths to 50 m (Xue et al., 2010), but its success depends critically on favourable host conductivity and loop geometry. A key limitation (Section 4.6) is that TEM, ERT, and GPR each respond to any resistive or reflective body, not only cavities; geological context, forward modelling, and independent validation (Step 7: drilling) are therefore essential to avoid false positives. In an integrated workflow, TEM may provide depth-sensitive resistivity constraints while GPR resolves shallower geometry and seismic methods constrain mechanical contrasts, reducing the range of plausible subsurface models.

6.5 Archaeological and Cultural Heritage Prospection

Archaeological prospection places a premium on non-destructive investigation and often involves targets with variable geometry, material composition, and preservation (Step 2: buried walls, floors, graves, typically at 0–3 m depth). The dominant contrast in dry conditions is dielectric (Step 3), making GPR the natural primary method, supplemented by magnetics or ERT for clay-rich sites where GPR attenuation is problematic (Step 5; Table 2, Level 2). At Isthmia, Greece, georeferenced GPR grids were used to map rectilinear anomalies and investigate spatial relationships between excavated and unexcavated zones (Arvanitis and Frey, 2025). The wider lesson from archaeological applications is that integrated

interpretation should be hypothesis-driven: geophysical anomalies are tested against known architecture, stratigraphy, excavation records, historical mapping, and other remote-sensing datasets (Step 7). Conversely, areas with low anomaly density may also be archaeologically informative when survey coverage and signal quality are sufficient to exclude a methodological artefact. Multi-method design should be guided by the archaeological question and the expected physical contrast of the target rather than by default application of a fixed instrument set.

6.6 Defence and Dual-Use Sensing

GPR is the primary technology for shallow buried threat detection, owing to its sensitivity to the dielectric contrast between explosive casings and surrounding soil. Recent realistic numerical simulations of GPR landmine response have incorporated full antenna models, frequency-dependent soil dispersion, and heterogeneous background clutter (Stadler and Igel, 2024), providing a rigorous basis for automated detection algorithm development. The combination of GPR with metal detectors (Level 1–2) exploits the complementary sensitivity of the two methods to dielectric and metallic targets respectively. The integration of GPR with seismic and EM methods on unmanned platform systems represents an emerging frontier for rapid standoff subsurface sensing in high-risk environments. The key Step 7 challenge in this domain is managing false alarm rates rather than uncertainty quantification in the conventional geophysical sense; the relevant metric is receiver operating characteristic (ROC) performance evaluated against a ground-truth test grid.

7. Recent Methodological Advances

7.1 Full-Waveform Inversion in the Near-Surface Domain

Full-waveform inversion (FWI) represents the most quantitatively ambitious application of seismic and GPR data in the near-surface context. Seismic FWI minimises the misfit between observed and modelled full seismograms to recover spatially continuous models of elastic properties at higher resolution than travel-time-only approaches (Virieux and Operto, 2009). Near-surface seismic FWI remains challenging due to strong heterogeneity, cultural noise, cycle-skipping at high velocity contrasts, and the difficulty of accurate source and receiver characterisation. GPR-FWI matches the complete electromagnetic waveform to recover dielectric permittivity and conductivity at sub-wavelength resolution; deep learning-guided GPR-FWI has demonstrated near-real-time quantitative inversion in field conditions (Zhang et al., 2024). Neither FWI approach removes the need for detectability analysis and independent validation: high-resolution FWI results may still be non-unique, and artefacts introduced by imperfect source modelling or unresolved near-surface heterogeneity are difficult to identify without ground truth.

7.2 Joint Petrophysical Inversion

Joint petrophysical inversion (JPI) of seismic and GPR data represents one of the most significant recent advances in integrated near-surface geophysics, enabling simultaneous quantification of porosity and water saturation — parameters of direct relevance to hydrogeological, environmental, and geotechnical applications. Indirect JPI schemes, in which seismic and GPR wavefields are individually inverted for their respective geophysical parameters and then jointly transformed to petrophysical parameters using rock-physics models including Gassmann's equations, Archie's law, and the CRIM model, have demonstrated improved accuracy and robustness compared to separate inversion (Qin et al., 2022, 2024). A subsequent study applied simultaneous JPI that updates petrophysical parameters at each iteration step of the iterative process, accounting for non-negligible clay fractions and rock matrix conductivity to reduce petrophysical model error (Domenzain et al., 2022). The Bayesian probabilistic framework provides a natural complementary approach for propagating petrophysical model uncertainty into the posterior distribution of the jointly inverted parameters (Arvanitis and Vlamos, 2009; Moorkamp, 2022), though the computational cost of full Bayesian JPI remains prohibitive for many practical near-surface problems.

7.3 Passive Seismic and Ambient Noise Methods

Passive seismic methods exploit the ambient seismic noise field generated by natural and anthropogenic sources. Ambient noise tomography (ANT) and passive MASW extract surface-wave dispersion information from cross-correlations of noise records, enabling the construction of subsurface Vs models without controlled seismic sources. These methods are particularly valuable in urban environments where active source acquisition is logistically difficult, and in large-area investigations where the cost of source deployment would be prohibitive. The combination of active and passive MASW — exploiting controlled sources for high-frequency shallow resolution and traffic noise for lower-frequency deeper penetration — is increasingly used in geotechnical and urban subsurface characterisation. Distributed acoustic sensing (DAS), in which optical fibre cables deployed in boreholes or along trenches serve as spatially continuous seismic receivers, is extending the operational reach of passive seismic methods in near-surface applications, potentially enabling large-area shallow imaging at costs and spatial densities previously unattainable. The integration of passive seismic with active seismic and GPR at Level 2–3 provides multi-scale Vs information that can constrain the elastic component of a petrophysical model without additional active-source deployment.

7.4 Multi-Channel GPR Array Systems

Multi-channel and multi-frequency GPR array systems have significantly expanded the operational capabilities of GPR in high-throughput near-surface investigations. Vehicle-mounted systems with multiple transmitter-receiver pairs simultaneously acquire closely spaced parallel profiles, enabling three-dimensional subsurface data volumes at survey speeds of several kilometres per hour over areas of thousands of square metres. This operational mode, combined with automated data processing workflows for time-slicing, migration, and attribute extraction, has made large-scale 3D GPR a practical tool for road network assessment, bridge deck inspection, archaeological landscape investigation, and utility corridor mapping. GNSS synchronisation, as employed in the Isthmia survey (Arvanitis and Frey, 2025), is now standard practice for georeferenced depth-slice visualisation and multi-method data fusion. The principal remaining challenges are processing speed and quality control for large volumes of automatically acquired data, and the development of reliable automated anomaly detection algorithms with documented false-alarm rates.

7.5 Machine Learning and Deep Learning Applications

Machine learning (ML) and deep learning (DL) methods have begun to transform several key workflows in near-surface geophysics, including data quality control, anomaly detection, inversion, and integrated interpretation (Yu and Ma, 2021; Khosro Anjom et al., 2024). Convolutional neural networks (CNNs) have been applied to automatic detection and classification of buried utilities, voids, and other subsurface anomalies from GPR radargrams, demonstrating performance competitive with experienced human operators in controlled settings. Deep learning-based clutter removal has improved signal-to-noise ratios in complex urban GPR environments (Li et al., 2023). In seismic data analysis, DL has been applied to first-break picking, surface-wave dispersion extraction, and automated classification of seismic facies in near-surface tomographic images. The prediction of Vs models directly from surface-wave records using DL, bypassing the conventional dispersion-curve extraction and inversion workflow, has been demonstrated on synthetic and field datasets.

In multi-method integration contexts, unsupervised learning methods such as self-organising maps have been applied to the joint classification of archaeological features from heterogeneous multi-layer geophysical datasets, demonstrating the potential for ML-assisted integrated interpretation that goes beyond the capabilities of sequential single-method analysis. However, several challenges limit the operational deployment of ML in near-surface geophysics: the scarcity of labelled training data from heterogeneous real geological settings; the domain-shift problem that reduces performance when models trained on one site are applied to another; and the difficulty of quantifying prediction uncertainty in neural network models. Physically informed ML approaches that incorporate governing equations of wave propagation or electromagnetic induction as constraints offer a promising route to improved generalisation (Yu and Ma, 2021; Khosro Anjom et al., 2024).

7.6 Uncertainty Quantification: A Taxonomy

Effective uncertainty quantification in integrated geophysics requires distinguishing between at least six qualitatively different types of uncertainty, which propagate differently and require different mitigation strategies:

- Measurement uncertainty: instrument noise, coupling losses, positioning errors, and timing jitter. This is typically characterised statistically from repeat measurements or manufacturer specifications and propagated as data variance in inversion.
- Processing uncertainty: variability of results attributable to choices of filter parameters, gain functions, migration aperture, or picking algorithms. This uncertainty is often not quantified in routine workflows; sensitivity analysis (repeating key processing steps with perturbed parameters) provides a practical estimate.
- Inversion uncertainty: the inherent non-uniqueness of the geophysical inverse problem — the existence of multiple models that fit the data within measurement uncertainty. Bayesian inversion (Arvanitis and Vlamos, 2009; Tarantola, 1987) characterises this as a posterior distribution; regularisation-based approaches typically report only the smoothest or minimum-norm model without uncertainty.
- Petrophysical uncertainty: errors in the rock-physics models used to relate geophysical parameters to subsurface material properties. This is frequently the dominant source of error in Level 4–5 joint inversion and is difficult to quantify without independent laboratory or in situ measurements.
- Spatial resolution uncertainty: the smoothing and bandwidth limitations of geophysical imaging mean that the true spatial distribution of physical properties is always recovered at lower resolution than the data would suggest in the absence of noise and model approximations. Resolution matrices or point-spread function analysis can quantify this component.
- Interpretation uncertainty: the subjective step of mapping geophysical anomalies to geological or engineering features. This uncertainty is inherently qualitative and can only be reduced by integrating geophysical results with geological mapping, boreholes, excavation, or other independent data.

Integrated geophysical reporting should distinguish these uncertainty sources explicitly. The common practice of reporting a single preferred model with no uncertainty measure conflates all six types and significantly overstates the reliability of the result.

8. Open Challenges and Research Directions

Despite significant progress in integrated near-surface geophysics, several important challenges remain genuinely unresolved. The following discussion focuses on open scientific and practical problems rather than summarising the conclusions of preceding sections.

The development of reliable, site-independent petrophysical models for near-surface materials remains the principal unsolved problem in quantitative joint inversion. Models calibrated for clean, unconsolidated sands — Gassmann's equations, Archie's law, the CRIM model — perform poorly in clay-bearing, partially saturated, or anthropogenically disturbed materials that are common at the engineering and archaeological scales where near-surface geophysics is most frequently applied. The development of improved rock-physics models calibrated against co-located laboratory and in situ measurements, covering a wider range of near-surface material types and conditions, is a research priority with direct implications for the accuracy and reliability of Level 4–5 integration.

Scalable probabilistic inversion methods for high-dimensional 3D and multi-physics near-surface problems remain computationally inaccessible for most routine applications. Full Bayesian inversion provides the most complete uncertainty characterisation but is currently feasible only for problems with a small number of model parameters or with simplified forward operators. Ensemble methods, reduced-order models, and Bayesian neural network approaches offer potential routes to scalable probabilistic inversion for larger near-surface problems, but their accuracy in multi-physics contexts has not been systematically evaluated.

The formal quantification and communication of interpretation uncertainty (Section 7.6, type 6) is largely absent from current practice. Geophysical reports typically present a preferred interpretation without characterising the range of

alternative geological explanations consistent with the data. Decision frameworks that explicitly account for interpretation uncertainty — for example, by associating each geophysical anomaly with a probability distribution over target types — would substantially improve the defensibility and practical utility of integrated surveys, particularly in high-stakes engineering, environmental, and heritage applications.

The integration of near-surface geophysics with complementary data streams — drone-based topographic and multispectral surveys, satellite-based InSAR deformation monitoring, direct geotechnical testing, and laboratory analysis — remains largely qualitative. Formal data fusion frameworks that quantitatively combine these disparate information sources within a unified subsurface model, while accounting for the different spatial and temporal resolutions and uncertainty characteristics of each data type, represent an important and largely undeveloped area of methodological research.

The deployment of machine learning in near-surface geophysics faces a critical data challenge: the lack of publicly available, well-labelled, geologically diverse training datasets limits the generalisability of models trained in one setting to others. Community-level initiatives to develop and curate open benchmark datasets for key near-surface applications — utility detection, void identification, archaeological feature mapping, hydrogeological characterisation — would substantially accelerate progress in ML-based interpretation and inversion. The development of physically informed ML approaches that incorporate wave propagation and electromagnetic induction physics as constraints remains an active research priority (Yu and Ma, 2021).

Finally, the translation of integrated geophysical methods into routine professional practice is hampered by the absence of accessible, well-documented, and validated open-source software for multi-method survey design, co-registration, joint inversion, and uncertainty quantification. The scientific literature on integration methodology is technically demanding and sometimes inaccessible to practitioners without advanced quantitative training. Investment in software infrastructure — including graphical tools for the decision matrix of Table 2, modular joint inversion codes, and uncertainty visualisation — is essential for realising the practical potential of the research advances documented in this review.

9. Conclusions

This paper has proposed a target-driven framework for integrated near-surface geophysical survey design and interpretation. Its principal contribution, relative to existing method-specific practitioner guides, is threefold: it explicitly links the choice of method combination to target physics, site conditions, and a defined integration level; it provides a decision matrix that operationalises this logic for ten common investigation scenarios while identifying known failure modes; and it distinguishes five levels of integration rigour — from side-by-side display to full probabilistic joint inversion — to clarify the strength of evidence that different integration approaches provide and to guide practitioners in selecting the level appropriate to the available data quality and petrophysical knowledge.

The review has demonstrated that the three major method families — seismic, GPR, and EM/TEM — each provide physically distinct and inherently incomplete views of the shallow subsurface. Seismic methods, equipped with Bayesian uncertainty quantification (Arvanitis and Vlamos, 2009) and adapted forward solvers for high-contrast settings (Arvanitis, 2009), address elastic and mechanical characterisation. GPR, as demonstrated by the Isthmia archaeological survey (Arvanitis and Frey, 2025), provides unmatched shallow resolution for dielectric-contrast targets in favourable site conditions. TEM and ERT, as exemplified by the coal-mine cavity detection case study (Xue et al., 2010), are uniquely capable of imaging resistivity structures at depths from metres to hundreds of metres. No method universally outperforms the others; method selection must be driven by target physics and validated by independent ground truth.

The framework also highlights conditions under which multi-method integration may not deliver its expected benefits — including scale mismatch, co-registration errors, temporal differences, inappropriate coupling assumptions, and the risk of artificial agreement in joint inversion results. Recognising these limitations is as important as understanding the scientific rationale for integration. The six-category uncertainty taxonomy proposed here provides a basis for more rigorous and

informative reporting of integrated geophysical results, distinguishing measurement, processing, inversion, petrophysical, spatial-resolution, and interpretation uncertainties.

Open challenges include the development of reliable petrophysical models for heterogeneous near-surface materials, scalable probabilistic inversion methods for multi-physics high-dimensional problems, formal frameworks for integrating geophysics with remote sensing and geotechnical data, community benchmark datasets for machine learning development, and accessible open-source software for integrated survey design and uncertainty quantification. Progress on these challenges will determine whether the quantitative and methodological advances documented in this review translate into improved routine practice across the broad range of near-surface geophysical applications.

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Author Contribution

One author wrote the whole paper.

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Figures

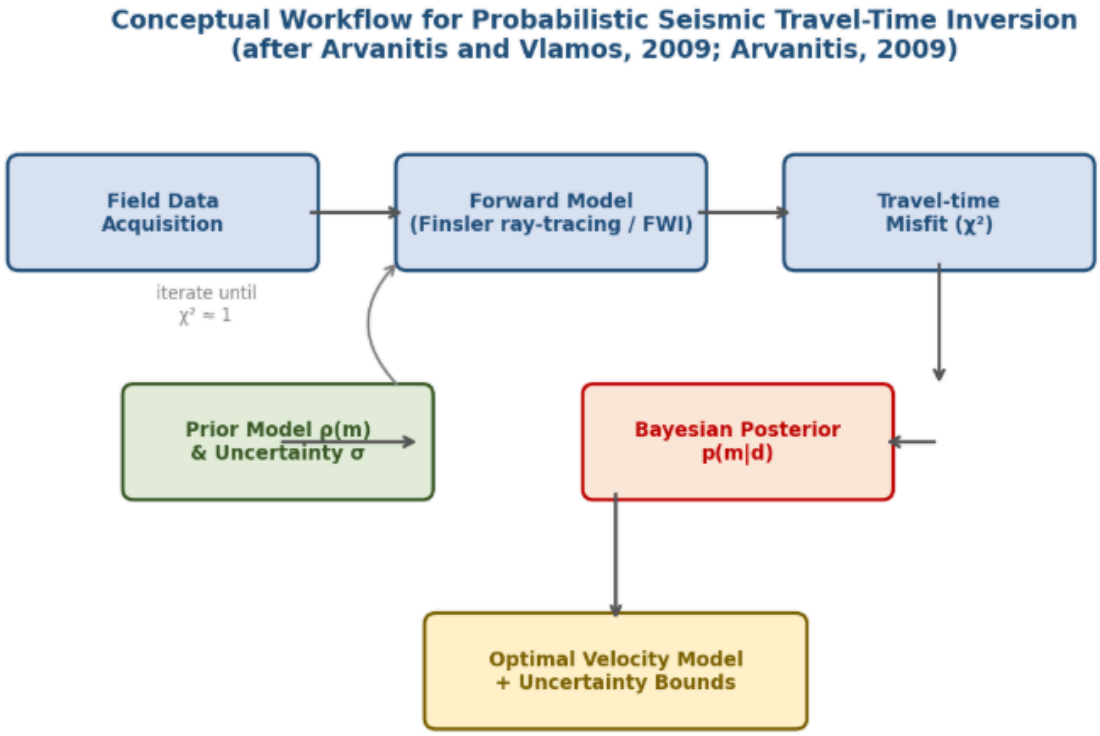


Figure 1

Conceptual workflow for probabilistic seismic travel-time inversion. A prior model and its uncertainty are updated using observed data and forward modelling to obtain a posterior model distribution and uncertainty bounds. Finsler-geometry ray tracing is shown as one possible forward solver (adapted from Arvanitis and Vlamos, 2009; Arvanitis, 2009).

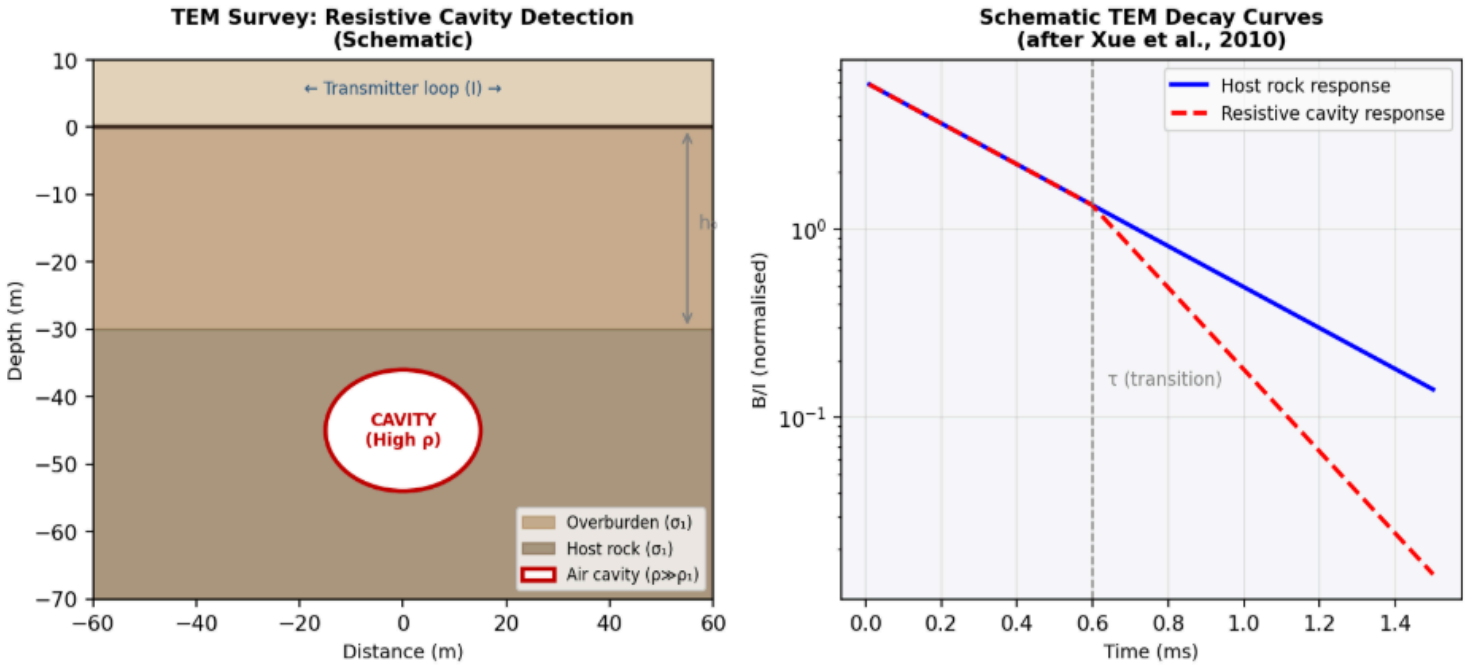


Figure 2

Conceptual TEM survey over a resistive underground cavity and schematic transient responses for host and cavity conditions. The figure illustrates the principle of a conductivity-contrast-dependent TEM anomaly rather than a universal response curve (adapted from Xue et al., 2010). The characteristic transition time tau depends on host conductivity and cavity radius.

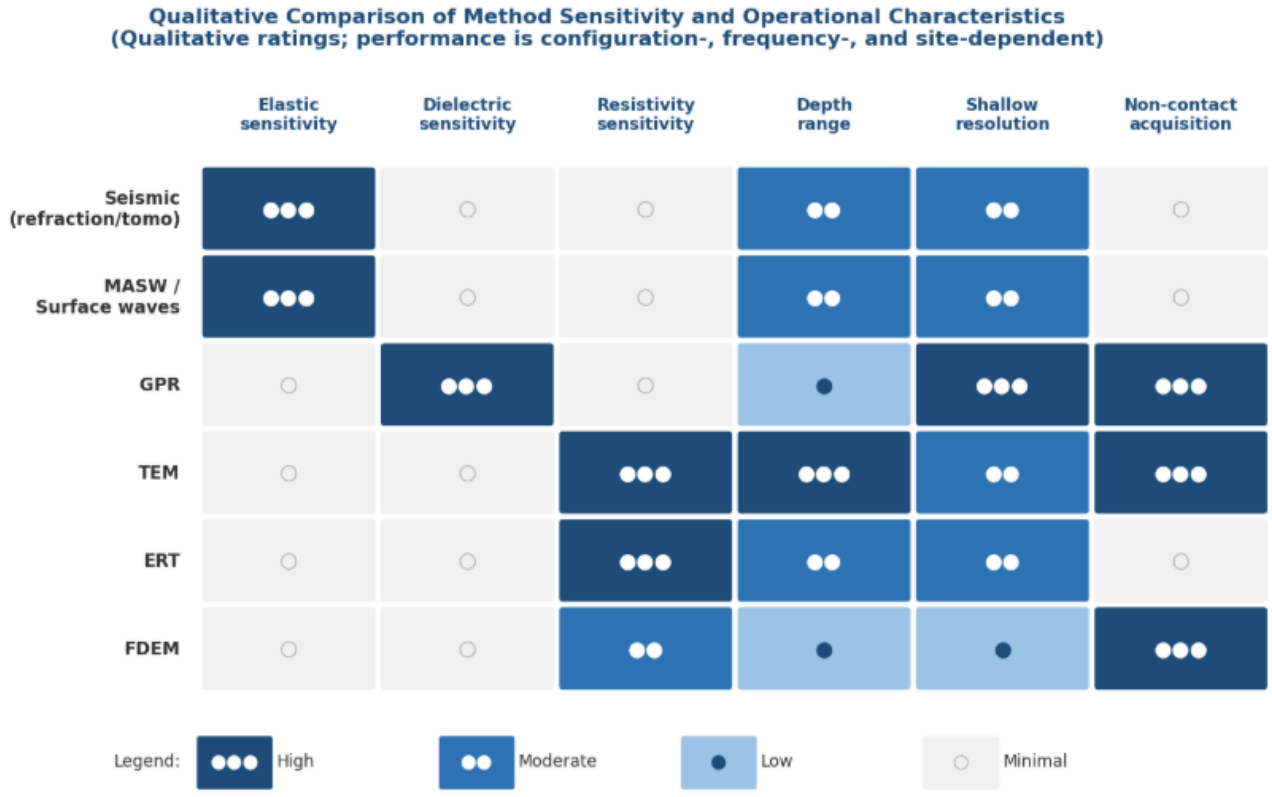


Figure 3

Qualitative comparison matrix of relative sensitivities and operational characteristics of the six main near-surface geophysical methods across six dimensions. Ratings (High, Moderate, Low, Minimal) are qualitative and depend strongly on acquisition design, target properties, instrument configuration, frequency, and site conditions. The matrix is intended to illustrate complementarity rather than to provide fixed performance benchmarks.



Figure 4

Seven-step target-driven framework for integrated near-surface geophysical survey design and interpretation. The framework proceeds from problem definition through method selection (supported by the decision matrix, Table 2), co-

registered acquisition and joint interpretation at the appropriate integration level, to validated models with quantified uncertainty bounds.