

REVIEW ARTICLE OPEN ACCESS

Geophysical Methods for Geotechnical Parameters' Estimation in Shallow Subsurface Investigations: A Review

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ABSTRACT

Geotechnical investigations have traditionally relied on invasive methods, such as boreholes and laboratory tests. However, these techniques can be time-consuming, expensive and spatially limited, often resulting in discontinuous subsurface characterisation that fails to capture the full extent of soil heterogeneity. Geophysical methods are becoming increasingly integrated into conventional geotechnical investigations to overcome these spatial and economic constraints. This review examines how seismic, electrical resistivity and electromagnetic surveys provide rapid, nondestructive and spatially continuous subsurface data that can be used to infer geotechnical information across a range of shallow infrastructure and environmental applications, typically within the upper 30 m of the subsurface, at site-specific scale. Methods such as multichannel analysis of surface waves (MASW) estimate shear-wave velocity profiles, which can be related to soil stiffness and small-strain shear modulus through appropriate constitutive assumptions and site-specific calibration. Electrical resistivity tomography (ERT) is well suited to mapping moisture content distributions and detecting seepage anomalies in embankments and slopes. A key finding of this review is that the reliability of geophysical–geotechnical correlations is strongly parameter-dependent: Relationships grounded in physical theory, such as that between shear-wave velocity and small-strain shear modulus, are more robust and transferable than empirical correlations such as those between resistivity and SPT-N values, which tend to be highly site-specific. In all cases, reliability depends on integration with complementary geophysical methods and calibration against direct geotechnical measurements, since soil heterogeneity and environmental conditions can make interpretation ambiguous. Advanced data fusion approaches, including belief function theory and geostatistical interpolation, show practical potential for combining heterogeneous datasets and managing spatial uncertainty. Emerging techniques such as machine learning and Full waveform inversion (FWI) offer further possibilities for quantitative parameter estimation, though their routine application remains constrained by computational demands and the current lack of standardised field validation datasets. This review identifies current knowledge gaps and outlines directions for developing more reliable, quantitative frameworks for geophysical–geotechnical integration in infrastructure assessment and environmental applications.

1 | Introduction

The integrity of civil engineering infrastructures strongly depends on the accurate characterisation and description of soil behaviour, whether as foundation material or as the construction

medium for earthworks. Although standard geotechnical investigation methods have served as essential tools for several decades, their inherent limitations, including invasive sampling procedures, discrete data collection and difficulties in assessing spatially variable ground, typically result in discontinuous

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subsurface evaluations [1]. These limitations can lead to severe engineering problems, particularly for critical or linear structures such as road and railway embankments and riverbanks, where continuous spatial characterisation is required both for initial design and for monitoring throughout the operational lifespan of the structure. Emerging developments in geophysical techniques offer new prospects for overcoming these limitations through nondestructive testing and spatially continuous subsurface profiling [2].

Soil forms the physical basis for the foundations of buildings and, in the case of civil engineering works such as levees and transportation networks, constitutes the primary construction material [3]. Structural weaknesses or failures within these systems, particularly those caused by flooding, seepage and foundation instability, continue to cause catastrophic loss of property, environmental damage and loss of life. Recent flood events have demonstrated how levee failures can devastate communities, whereas structural failures caused by uneven settlement led to costly repairs and significant safety hazards [4].

Soil behaviour is a critical factor in river levee failures during flood events and in building damage caused by foundation settlement [5–8]. River levees, which are essential to flood control, are prone to failure during extreme weather events, often revealing weaknesses in both design and monitoring practise. Such failures are frequently attributed to inadequate subsurface characterisation, whereby standard methods fail to detect zones of weakness or to predict hydraulic loading performance [6]. Foundation settlements similarly arise from inaccurate soil characterisation, leading to differential settlement, structural cracking, increased seismic vulnerability and costly rehabilitation [7].

Conventional methods such as SPT and CPT do not work effectively in heterogeneous soils, where spatial variability undermines their representative value [7]. In general terms, conventional geotechnical investigation is constrained by its invasive nature, high cost relative to spatial coverage, time demands and the disturbance it may introduce to the soil being tested ([1, 9–11]). An alternative approach to addressing these spatial-coverage limitations, operating at a markedly different scale, is the use of geostatistical and spatial interpolation techniques, such as inverse distance weighting and kriging, to generate continuous geotechnical soil maps from discrete borehole records [12, 13].

In only a limited number of cases, geophysical and geotechnical parameters are directly related or identical. The term “geotechnical parameter” is used throughout this review in a broad sense, encompassing both qualitative descriptors of subsurface conditions (i.e., textural properties, cementation, etc.), state variables (water content, porosity, etc.) and quantitative engineering properties (i.e., cohesion, shear modulus, etc.), depending on what a given geophysical method can resolve in a particular case. For most applications, relating geophysical measurements to geotechnical properties requires the use of empirical or theoretically derived equations, and the reliability of such relationships varies considerably depending on the physical basis of the correlation, the soil type and the degree of site-specific calibration available [14]. This review is based on a thorough analysis of

published scientific literature in peer-reviewed, internationally recognised journals specialising in geotechnical engineering, applied geophysics, geoenvironmental engineering, geosciences and earth sciences, focusing specifically on the use of geophysical methods for the estimation of geotechnical parameters in shallow soil deposits, typically within the upper 30 m of the subsurface. This review presents a synthesis of published studies examining the applicability of geophysical methods for estimating geotechnical parameters across a range of shallow near-surface geotechnical applications. Here, ‘shallow’ is used in the engineering sense, typically referring to investigations within the upper approximately 30 m of the subsurface. Both field-scale investigations and laboratory-scale experiments are considered, as the former demonstrate integrated approaches in practical geotechnical characterisation, whereas the latter establish the underlying physical correlations under controlled conditions. It is emphasised throughout that geophysical methods serve as complementary tools to conventional geotechnical investigation rather than as replacements for it. By examining existing correlation methodologies and identifying current knowledge gaps, this review is aimed at contributing to the development of more reliable approaches for infrastructure assessment and design.

This article is organised as follows. Section 2 describes the methodology for this review. Section 3 presents different applications of relationships between geophysical data and geotechnical parameters from previously published studies. Section 4 discusses the key findings of the review and highlights existing research gaps. Section 5 presents the conclusions and recommendations for future work.

2 | Materials and Methods

To ensure high scientific quality, priority was given to articles published in indexed journals, including *Near Surface Geophysics*, *Surveys in Geophysics*, *Journal of Applied Geophysics*, *Geotechnical Testing Journal* and *Journal of Environmental and Engineering Geophysics*, among others. Conference proceedings were also considered, where the methodological content was sufficiently detailed. The search was conducted between November 2024 and April 2025 using the Scopus, ResearchGate and Google Scholar databases, with the following search strings: ‘geophysical geotechnical correlation’, ‘geotechnical parameters from electrical and seismic measurement’, ‘integrated geophysical methods for geotechnical assessments’, ‘ERT versus CPT’ and ‘shallow soil geophysical characterisation’. In addition to the database search, supplementary references were identified through the reference lists of previously retrieved studies, including prior review works on related topics such as Romero-Ruiz et al. [11] and Plati et al. [2]. Consulting such synthesis works proved valuable in identifying additional method-specific studies relevant to the present review.

Studies were considered eligible if they presented direct empirical correlations or theoretically derived relationships between geophysical parameters, such as shear-wave velocity (V_s), electrical resistivity or dielectric constant and geotechnical parameters, such as shear strength, stiffness, porosity or saturation. Experimentally tested or field-verified studies

were preferred, with priority given to those reporting statistically valid results relevant to shallow geotechnical research. Studies addressing exclusively deep subsurface exploration or presenting purely theoretical geophysical modelling without any geotechnical parameter estimation or validation were excluded.

The initial search returned 100 articles. These were filtered through a three-stage screening process, as illustrated in Figure 1. In the first stage, titles and abstracts were screened for relevance against the eligibility criteria described above, reducing the pool to 59 articles. In the second stage, full texts were assessed for methodological quality and data quality, excluding studies that lacked sufficient detail on measurement procedures, calibration or reported results and reducing the pool to 34 articles. In the third stage, a final selection was made based on alignment with the review objectives and on ensuring representative coverage across geophysical methods and application domains, yielding a final list of 25 articles, with 19 of them published after 2010. These articles form the core framework of the review and provide the basis for the results and discussion that

follow. A complete list of all 100 initially identified articles, with the 25 selected studies highlighted, is provided in Appendix A.

3 | Results

3.1 | Levee and Embankment Assessment Using Geophysical Methods

Inazaki and Sakamoto [15] support levee integrity assessment by the illustration of the capability of integrating several geophysical methods, including multichannel analysis of surface wave (MASW) dispersion measurement, capacitively coupled (CC) resistivity measurement, multifrequency electromagnetic (EM) surveys, high-resolution S-wave seismic reflection and traditional direct current (DC) resistivity surveys, to overcome the shortcomings of traditional inspections. Key contributions include recommending MASW and CC resistivity as optimal for the evaluation of key levee parameters such as permeability and stiffness, with a focus on field efficiency of land streamer-based seismic reflection and EM surveys in the acquisition of rapid, high-resolution

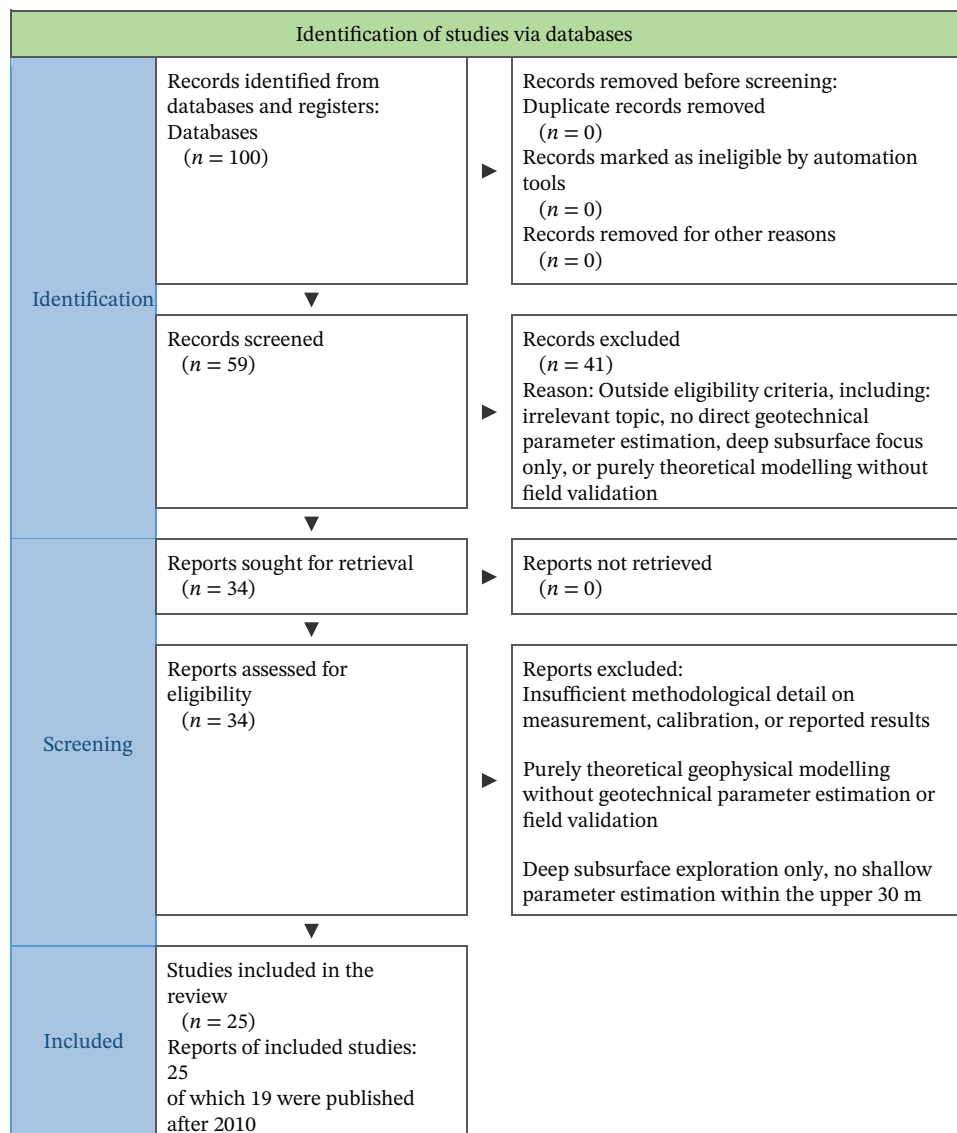


FIGURE 1 | Three-stage screening flow diagram showing reduction from 100 identified records to 25 final included studies.

subsurface images. Field testing on two case studies in the region of Kanto in central Japan validates these methods' sensitivity to structural anomaly detection, even if the study recommends further confirmation in other test sites. The findings point out that a combined approach, namely CC resistivity or EM surveys and MASW, offers an effective and scalable solution for continuous levee monitoring, significantly improving safety assessments under flood or seismic conditions.

Chen et al. [16] investigated the use of geophysical methods in finding hidden flaws in the Yangtze River embankment, motivated by the 1998 catastrophic flooding and the need for efficient embankment inspections. The study focuses on the use of seismic and electrical resistivity methods in embankment condition inspection with an emphasis on identifying weak areas and potential seepage zones. The Laocheng test site in Hubei Province in China is founded on Holocene-aged deposits and seepage-resistant construction materials. Soil parameters, including Vs, compressional wave velocity (Vp), electrical resistivity, porosity and moisture content, were mainly estimated from laboratory measurements complemented by resistivity variations with multiple moisture contents. The study employed seismic reflection, MASW and resistivity sounding for structural integrity characterisation of the embankment. Results demonstrated a consistent spatial association between zones of elevated moisture content, reduced Vs and elevated seepage potential index values, a relationship that is physically grounded but whose quantitative thresholds remain site-specific and dependent on local calibration of the empirical coefficients in the seepage potential index formula. The research concludes that the use of seismic and resistivity data enhances the safety evaluation of embankments.

Weller et al. [17] presented detailed research on the design, installation and long-term monitoring of a levee monitoring system (LMS) in Vietnam with a focus on levee stability and flood protection. The system components include a permanent multielectrode resistivity-imaging array, borehole drilling rigs, frequency-domain reflectometry (FDR) probes, tensiometers and an observation well. The geoelectrical surveys combined with geotechnical sensors provide critical data on changes in conductivity and water level response to rainfall and flooding events. The hydraulic modelling, employing a transient finite element approach, demonstrates the importance of time-dependent analysis in seepage estimation. The study concludes with practical recommendations for a typical LMS configuration and its incorporation into early warning systems.

Rahimi et al. [18] compared the effectiveness of reference Vs curves for soil classification in the Melvin Price Reach of the Wood River Levee, using MASW. The research identifies the limitations of broad Vs ranges for classifying soils and proposes more accurate reference Vs curves with respect to confining stress. Results showed that whilst reference Vs curves had good agreement with boring log data at depths greater than 5 m, they deviated at shallow depths below 5 m due to low confining stress. The authors proposed a critical depth value and determined new reference curves for loose sand and soft clay at shallow depths.

Karl et al. [19] discussed the application of MASW in determining the structural health of earth-fill dams. The study

presents the advantages of seismic approaches in deriving S-wave velocity profiles integral to dyke stability analysis. Field tests were conducted at two levee sites on the River Mulde near Bitterfeld in Germany. Results demonstrate strong correlations between clay consistency and S-wave velocity, with resolution limits depending on wavelength and material contrast.

Niederleithinger et al. [20] evaluated ERT, electromagnetic approaches (EM31 and RMT), MASW and GPR for the identification of soil inhomogeneities within river embankments at a 100-year-old test area along Germany's Mulde River. ERT with 1–2 m electrode spacing performed best. EM31 and RMT showed limitations due to metallic interference, whereas GPR was restricted by clayey soil attenuation. MASW was useful in the indirect classification of soil through correlation with CPT data.

Arato et al. [21] introduced a new seismo-electric streamer to effectively image linearly extended earth structures, including a river embankment in Turin, Italy. The method enables simultaneous recording of electrical resistivity and seismic data, enabling rapid data acquisition. Results showed good agreement between the anomalies identified by the proposed system and those detected by the reference surveys. Three-dimensional influences on data interpretation were identified as a limitation requiring further development.

Across the reviewed levee and embankment investigations, MASW and ERT consistently emerge as the most effective and complementary pairing, supported by studies conducted across Japan, China, Germany, Vietnam, the United States and Italy. In terms of correlation classification, the Vs-stiffness relationship is physics-based, grounded in elastic wave propagation theory ($G = \rho V_s^2$) and represents the most robust and transferable correlation in this domain. The resistivity-moisture relationship is Semi-Empirical, physically motivated through Archie's law but requiring site-specific calibration due to sensitivity to clay content, pore fluid chemistry, saturation state and temperature. Composite indices such as the seepage potential index proposed by Chen et al. [16] are purely empirical, with no guaranteed transferability without local recalibration. Quantitative validation evidence across these studies is limited: Most studies rely on qualitative agreement with borehole or CPT data rather than formal statistical metrics such as R^2 or RMSE, and this absence of standardised reporting is a recurring limitation of the current evidence base, discussed further in Section 4. EM methods, including EM31 and RMT, consistently underperformed relative to ERT in near-surface resolution and reliability [20].

3.2 | Soil Characterisation Using Seismic and Electrical Resistivity

Cosentini and Foti [22] discussed issues with the measurement of physical properties of coarse-grained soils using standard laboratory testing, promoting geophysical testing where a large volume of soil can be examined in its natural state. A new method was proposed to quantify porosity and degree of saturation in unsaturated soils by integrating seismic and electrical resistivity measurements, grounded in Archie's law and wave propagation equations. Laboratory tests on saturated uniform quartz sand

validated the technique. Further development is required to enhance precision in water retention curve estimates.

Vagnon et al. [23] explored the application of noninvasive geophysical techniques, combining seismic Vs and electrical resistivity, for preliminary assessment of earth structures. The study explored seven retaining structures selected based on different materials and the availability of independent geotechnical data. Three methods, theoretical, statistical and field-based, were used to estimate soil properties. The theoretical approach demonstrated flexibility and calibration potential, whereas the statistical approach was found to be extremely site-specific.

Khalil and Hanafy [24] used seismic refraction and first-arrival travel time tomography to quantitatively assess subsurface rock quality. By correlating Vp, Vs and density mathematically, seven geotechnical parameters were deduced: concentration index, material index, density gradient, stress ratio, N-value, an index the authors term bearing capacity and reaction modulus. Two case studies in Egypt and Saudi Arabia demonstrated effectiveness in regional and site-specific investigations.

McCarter [25] investigated the electrical resistivity characteristics of clay-water electrolyte systems using Cheshire and London clays. Results showed a characteristic resistivity-water volume relationship for each clay type and an inverse relationship between resistivity and saturation, establishing fundamental physical principles for resistivity-moisture correlations.

Islam et al. [26] investigated the correlation between electrical resistivity and significant geotechnical soil properties in the Peshawar basin of Pakistan. Results showed resistivity ranges of 40–250 Ωm for three subsurface layers, with inverse quadratic correlations with cohesion and water content, and positive quadratic correlations with internal friction angle and SPT-N values.

Salas-Romero et al. [27] demonstrated the successful application of MASW to characterise a high-risk quick-clay landslide site in south-west Sweden. Results presented very low near-surface Vs values, often below 180 m/s and as low as 60–100 m/s, typical of very soft, sensitive materials. The interpretation was strengthened by integrating Vs models with previous resistivity and geotechnical data.

Ozcep et al. [28] discussed the relationship between electrical resistivity and soil water content in earthquake-prone regions in Turkey. Results provided a predictive model of resistivity as a function of water content, distinguishing between volume and surface conduction mechanisms.

Alshameri and Madun [29] investigated the correlation between seismic data and geotechnical characteristics in kaolin-sand mixtures using bender element testing. Moduli and seismic wave velocities exhibit a nonlinear relationship with fines content: increasing from 20% to 40% raises wave velocities, whereas increases from 40% to 70% reduce them.

When the soil characterisation studies are compared across methods, parameters, soil types and validation approaches, a consistent hierarchy of correlation reliability emerges. The Vs-shear modulus relationship ($G = \rho V_s^2$) is physics-based

and applies across soil types and geological settings. The electro-seismic model of Cosentini and Foti [22] and the integrated Vs-resistivity approach of Vagnon et al. [23] are Semi-Empirical, theoretically motivated but requiring site-specific calibration. The resistivity-SPT, resistivity-cohesion and resistivity-friction angle correlations of Islam et al. [26] and Ozcep et al. [28] are purely empirical, valid only within the specific geological contexts from which they were derived. Islam et al. [26] reported specific resistivity ranges of 40 to 250 Ωm correlating via quadratic functions, providing quantitative relationships but derived from a single geological setting. McCarter [25] confirmed that resistivity responds simultaneously to moisture content, clay mineralogy and saturation, limiting the transferability of single-variable calibrations. The nonlinear soil composition effects demonstrated by Alshameri and Madun [29] further underscore the importance of soil-specific factors before applying any resistivity-geotechnical correlation beyond its original derivation context. Formal statistical metrics such as R^2 remain inconsistently reported across studies, limiting rigorous cross-site comparison.

3.3 | Advanced Data Integration and Uncertainty Management

Dezert et al. [30] examined the integration of geophysical and geotechnical data using belief functions as the mathematical tool for managing uncertainty. Geophysical data from ERT were processed using Wasserstein distances to quantify uncertainty, whereas discrete CPT data were extrapolated using an exponential decay function. A synthetic two-layer variable-thickness model and a controlled physical model were used to validate the data fusion algorithm. The belief function-based framework was confirmed as a useful method for combining geophysical and geotechnical data, with conflict regions indicating anomalies requiring further investigation.

Di Buccio et al. [31] provided an integrated approach to estimating fines content for liquefaction assessment in the Po Plain basin of northern Italy. A workflow incorporating Glover's equation and the Hashin–Shtrikman model was used to image horizontal fines content variability. Fines content prediction methods were calibrated at two sites in Ferrara, Italy, showing high agreement between predicted and measured values. Calibrated correlations were applied at the San Carlo test field to image the spatial arrangement of liquefiable layers.

Hen-Jones et al. [32] discussed the use of ERT in monitoring slope stability through the examination of relationships between resistivity and soil properties under seasonal moisture cycling at the BIONICS embankment test field in Northumberland, United Kingdom. Key findings determined hysteresis in water content-resistivity and shear strength-resistivity relationships, triggered by soil fabric deterioration and suction loss due to dry-wet cycles.

Rezaei et al. [33] applied integrated geotechnical and geophysical technologies for landslide estimation in Nargeschal Village, Iran, combining ERT and ambient noise Vs analysis with borehole drilling and SPT-N. Spearman's rank correlation and least

squares regression revealed significant correlations between electrical resistivity and soil moisture content, and between Vs and SPT-N values.

Cosenza et al. [34] developed quantitative and qualitative relationships between electrical and geotechnical data at the Garchy site in France, employing ERT, GPR and seismic refraction alongside in situ vane shear and dynamic cone penetration tests. Qualitative ERT-geotechnical consistency was satisfactory, whereas quantitative resistivity-cone resistance correlations were limited by heterogeneity in the upper layer.

The studies in this subsection address the challenge of combining geophysical and geotechnical datasets with fundamentally different spatial sampling characteristics. Dezert et al. [30] addressed this most rigorously through belief function theory, demonstrating that fusion quality depended primarily on borehole placement rather than measurement magnitude. Di Buccio et al. [31] demonstrated a Semi-Empirical petrophysical integration workflow for fines content estimation, with high agreement between predicted and measured values representing some of the strongest quantitative validation evidence in the reviewed literature. Hen-Jones et al. [32] made the important observation that hysteresis in resistivity-moisture and resistivity-shear strength relationships arises from soil fabric changes during dry-wet cycling, meaning that a single static calibration curve cannot reliably represent these relationships across seasonal cycles. Cosenza et al. [34] confirmed that qualitative ERT-cone resistance correlations are more reliably achieved than quantitative ones in heterogeneous upper layers. Across all studies, formal uncertainty management is essential for producing geotechnically reliable outputs from combined geophysical-geotechnical investigations.

3.4 | High-Resolution Imaging and Anomaly Detection

Liu et al. [35] explored subsurface obstruction detection at a trial site in Changi East, Singapore. MASW was used for stratigraphic interpretation but was not effective in accurately delineating obstruction boundaries. Cross-hole seismic methods including full waveform inversion (FWI) yielded high-resolution images, with FWI precisely mapping obstructions to a horizontal range of 14–26 m and a vertical range of 7.5–11.0 m, closely aligning with penetration and borehole data. FWI, though computationally intensive, is a feasible technique for high-resolution subsurface imaging.

Accaino et al. [36] conducted a comprehensive geophysical investigation of Quaternary sediments of the Bibione coastal plain in north-east Italy, integrating P-, SH- and SV-wave seismic tomography and ERT. K-means clustering was used to segment regions of equivalent soil composition, and simulated annealing inversion was used to image brine saturation, clay fraction and porosity. Cross-comparison with borehole stratigraphy confirmed the existence of a saltwater wedge at approximately 20 m depth.

Cho and Yeom [37] presented crossline resistivity tomography for detecting anomalous seepage pathways in an embankment dam in Korea. A field experiment identified two

irregular seepage channels, with one subsequently confirmed by geotechnical investigation through trenching and visual inspection.

Braga et al. [38] examined the correlation between geoelectrical parameters and SPT blow counts using DC resistivity and induced polarisation at a site near Rio Claro in Brazil. Resistivity and longitudinal conductance showed strong correlations with SPT values, whereas chargeability lacked any significant relationship.

The studies in this subsection address high-resolution imaging and anomaly detection across diverse engineering objectives. Liu et al. [35] provided the most direct comparison of competing seismic methods, demonstrating that FWI outperformed MASW in delineating obstruction boundaries, mapping them to a horizontal range of 14–26 m and a vertical range of 7.5–11.0 m in close agreement with borehole data. Accaino et al. [36] demonstrated that multicomponent seismic tomography combined with ERT, k-means clustering and petrophysical inversion can produce quantitative estimates of brine saturation, clay fraction and porosity validated against borehole stratigraphy. Cho and Yeom [37] provided physical confirmation of a geophysically identified seepage anomaly through trenching, one of the methodologically strongest validation examples in the entire reviewed literature. Braga et al. [38] established a purely empirical but practically useful correlation between longitudinal conductance and SPT blow counts, noting the absence of any useful relationship with chargeability. Across this subsection, the trade-off between resolution, computational cost and calibration requirements is consistent: high-resolution methods provide the most precise spatial characterisation but require the most demanding calibration and computational investment.

4 | Discussion

Geotechnical characterisation of shallow soil deposits is fundamental to infrastructure development, environmental assessment and hazard mitigation [39]. The reviewed studies demonstrate that integrating geophysical techniques with conventional geotechnical investigations provides a more comprehensive characterisation of subsurface conditions by extending the spatial representativeness of inherently discrete borehole and in-situ measurements ([10]). Rather than replacing conventional geotechnical investigations, geophysical methods complement direct testing by providing spatially continuous information that supports site characterisation, optimises borehole placement and improves the interpretation of geotechnical conditions.

Geophysical methods, including seismic, electrical, EM and spontaneous potential measurements, offer noninvasive, rapid and cost-effective means of investigating subsurface properties [40]. These methods can provide continuous spatial data, detect heterogeneities of the soil and complement conventional geotechnical methods [11]. A combination of geophysical and geotechnical data has proved effective in increasing the accuracy of soil characterisation, particularly in applications involving transportation facilities, flood protection systems and foundation stability assessment [41].

TABLE 1 | Key findings from reviewed studies.

Geophysical method	Primary applications	Derived geotechnical information	Correlation type	Validity conditions and ground truth required	Advantages	Limitations and uncertainty	Key studies
MASW	Vs profiling, soil classification, levee and embankment stiffness assessment, landslide and geohazard characterisation	Shear modulus ($G = \rho V_s^2$), liquefaction potential, small-strain stiffness and soil consistency	Physics-based (Vs–G); Semi-Empirical (Vs–soil class, Vs–SPT–N)	Reliable below 5 m depth; stress correction required above 5 m in soft soils; borehole or CPT validation recommended	Noninvasive, cost-effective, good depth resolution, transferable across soil types	Resolution limited in heterogeneous media; mode misidentification at shallow depth (< 5 m); density assumption required for modulus	Rahimi et al. [18]; Karl et al. [19]; Niederleithinger et al. [20]; Inazaki and Sakamoto [15]; Chen et al. [16]; Salas-Romero et al. [27]; Rezaei et al. [33]; Liu et al. [35]
ERT	Moisture mapping, seepage detection, slope monitoring, clay content estimation, embankment and dam assessment	Moisture content, porosity, hydraulic conductivity, clay content, SPT–N (via empirical regression)	Semi-Empirical (resistivity–moisture via Archie's law); purely empirical (resistivity–SPT, resistivity–strength parameters)	Requires site-specific calibration; unreliable in clay-rich or saline environments without ground truth; borehole or lab data essential; seasonal fabric changes affect calibration	High sensitivity to water content variations; spatially continuous; suitable for time-lapse monitoring	Nonunique inversion; ambiguous in conductive or clay-rich soils; simultaneous sensitivity to clay, salinity, saturation and temperature limits single-parameter interpretation	Hen-Jones et al. [32]; Chen et al. [16]; Islam et al. [26]; Weller et al. [17]; Cho and Yeom [37]; McCarter [25]; Ozcep et al. [28]; Cosenza et al. [34]; Rezaei et al. [33]; Karl et al. [19]; Niederleithinger et al. [20]; Di Buccio et al. [31]; Accaino et al. [36]
Cross-hole seismic	High-resolution obstruction detection, stiffness profiling at specific sites	Vs and Vp profiles, shear modulus, soil stiffness distribution and layer boundary delineation	Physics-based (velocity–stiffness); density assumption required for modulus derivation; FWI velocity models require independent validation	Requires boreholes at known separation; most reliable where borehole logs provide independent validation; FWI sensitive to starting model	Precise imaging of lateral heterogeneities; superior resolution compared with surface methods	Expensive; requires boreholes; FWI sensitive to starting model and may converge to local minima; anomalies at source and receiver locations affect results	Liu et al. [35]

(Continues)

TABLE 1 | (CONTINUED)

Geophysical method	Primary applications	Derived geotechnical information	Correlation type	Validity conditions and ground truth required	Advantages	Limitations and uncertainty	Key studies
EM surveys	Large-scale levee and embankment screening, rapid site reconnaissance and qualitative soil mapping	Qualitative conductivity distribution; indirect indicators of moisture and clay content	Qualitative only; no reliable quantitative geotechnical correlation without supplementary ERT or borehole calibration	Appropriate for screening and reconnaissance only; not suitable for quantitative parameter estimation in conductive environments or near metallic infrastructure	Rapid data acquisition; wide spatial coverage; no electrode contact required	Poor near-surface resolution; wide susceptible to metallic interference and conductive environments; limited to qualitative interpretation without calibration	Niederleithinger et al. [20]; Inazaki and Sakamoto [15]; Cosenza et al. [34]
Seismoelectric	Combined Vs and resistivity imaging along linear structures such as levees and embankments	Soil layering, stiffness, saturation and electrical resistivity	Semi-Empirical; combines Physics-based Vs-stiffness with Semi-Empirical resistivity-moisture correlation	Efficient for linearly extended structures; borehole validation still required; 3D effects may distort 2D interpretation; limited published field validation	Simultaneous seismic and electrical acquisition reduces survey time for extended linear structures	3D effects may distort 2D interpretation; limited published validation across diverse geological settings; emerging technology with few field applications	Arato et al. [21]
FWI	High-resolution subsurface velocity modelling, obstruction detection	Vs and Vp models, shear modulus, soil stiffness profile	Physics-based velocity models; modulus derivation requires a density assumption; sensitive to starting model conditions	Most reliable where independent borehole and penetration data are available for validation; not suitable for routine investigations, given computational cost	Superior spatial resolution compared with MASW; precise delineation of lateral boundaries	Computationally intensive; sensitive to starting model assumptions; may converge to local minima, producing plausible but incorrect solutions	Liu et al. [35]

(Continues)

TABLE 1 | (CONTINUED)

Geophysical method	Primary applications	Derived geotechnical information	Correlation type	Validity conditions and ground truth required	Advantages	Limitations and uncertainty	Key studies
Resistivity-SPT correlations	Soil strength estimation, site characterisation in layered sedimentary formations	SPT-N values, longitudinal conductance	Purely empirical; site-specific regression without transferable physical basis; chargeability shows no reliable relationship with SPT	Valid only within derivation geology; requires local SPT and resistivity measurements for calibration; not applicable across different lithologies without recalibration	Rapid field assessment; useful where direct SPT is impractical; longitudinal conductance, more reliable than transverse resistance in layered profiles	Purely empirical; no physical basis; requires local calibration; chargeability not correlated with SPT; results not transferable without site-specific regression	Braga et al. [38]; Islam et al. [26]
Integrated seismic-resistivity	Porosity and saturation estimation, soil layering, fines content, hydraulic conductivity, geotechnical characterisation of earth structures	Void ratio, water content, porosity, fines content, hydraulic conductivity, soil type	Semi-Empirical; physically motivated through Archie's law and elastic wave theory; statistical regression approach is purely empirical and highly site-specific	Most reliable when calibrated against independent borehole, CPT or laboratory data; theoretical approach more transferable than statistical regression; validated across seven retaining structures by Vagnon et al. [23]	Overcomes single-method limitations; simultaneous estimation of mechanical and hydrological properties; reduces interpretation ambiguity	Complex interpretation; calibration against independent geotechnical data essential; statistical approach highly site-specific; induced polarisation recommended in clay-rich environments	Cosentini and Foti [22]; Vagnon et al. [23]; Chen et al. [16]; Salas-Romero et al. [27]; Cosenza et al. [34]; Di Buccio et al. [31]; Alshameri and Madun [29]

(Continues)

TABLE 1 | (CONTINUED)

Geophysical method	Primary applications	Derived geotechnical information	Correlation type	Validity conditions and ground truth required	Advantages	Limitations and uncertainty	Key studies
Belief function fusion	Uncertainty management in combined geophysical and geotechnical data interpretation	Material classification (e.g. clay, silt, ...); confidence indices for subsurface condition assessment	Framework-based; does not produce geotechnical parameters directly but quantifies confidence in combined ERT and CPT interpretations	Requires expert knowledge for implementation; most effective when borehole placement is optimised relative to ERT coverage; validated on synthetic and physical laboratory models	Rigorous quantification of uncertainty; identifies conflict zones as anomaly indicators; handles datasets with different spatial sampling characteristics	Requires expert knowledge and specialist implementation; validated primarily on synthetic and laboratory-scale models; limited field applications published to date	Dezert et al. [30]
Multimethod clustering and inversion	Petrophysical characterisation, fluid distribution imaging, coastal aquifer and sediment characterisation	Porosity, clay fraction, brine saturation, subsurface lithology	Semi-Empirical; petrophysical models, including CRIM, Archie's law and Hashin-Shtrikman bounds, provide physical motivation; site-specific calibration is required	Requires borehole stratigraphy for calibration and validation; most applicable in sedimentary coastal environments; complex petrophysical modelling expertise needed	Translates geophysical images into quantitative geotechnical and hydrogeological parameters; methodology is replicable; k-means clustering enables objective zonation	Requires calibration data and complex petrophysical modelling; currently demonstrated in specialist coastal investigations; not yet validated across diverse geological settings	Accaino et al. [36]

Note: Correlation type key: Physics-based = grounded in established physical theory, transferable across sites, Semi-Empirical = physically motivated but requires site-specific calibration. Purely empirical = site-specific regression without a transferable physical basis.
Abbreviations: ρ , bulk density; CPT, cone penetration test; CRIM, complex refractive index model; EM, electromagnetic; ERT, electrical resistivity tomography; FWI, full waveform inversion; G, shear modulus; MASW, multichannel analysis of surface waves; SPT, standard penetration test; Vp, compressional wave velocity; Vs, shear-wave velocity.

Table 1 lists significant results of the reviewed studies.

4.1 | Cross-Study Synthesis: Comparing Methods, Parameters and Validation Quality

When the reviewed studies are compared across common parameters, methods, soil types, depth ranges and validation approaches, several consistent patterns emerge. MASW and ERT emerge consistently as the most widely deployed and complementary pairing. Integrated approaches combining both methods consistently outperformed single-method investigations, as demonstrated across studies conducted in Japan, China, Germany, Vietnam, the United States and Italy. EM methods, including EM31 and GPR, consistently underperformed relative to ERT in near-surface resolution and were more susceptible to interference in conductive environments, limiting their suitability for quantitative geotechnical parameters' estimation [20].

4.2 | Classification of Correlations: Physics-Based, Semi-Empirical and Purely Empirical

A critical finding of this review is that the reliability and transferability of geophysical-geotechnical correlations depend fundamentally on their physical basis. The Vs-shear modulus relationship ($G = \rho V_s^2$) is physics-based and transferable across soil types and geological settings, representing the most robust correlation identified across all reviewed studies. Resistivity-moisture content relationships are Semi-Empirical, physically motivated through Archie's law, but require site-specific calibration due to the simultaneous sensitivity of resistivity to clay content, pore fluid salinity, saturation state and temperature. Correlations such as resistivity-SPT and composite indices such as the seepage potential index of Chen et al. [16] are purely empirical, valid only within their specific derivation contexts and not transferable without local recalibration. Practitioners should therefore prioritise physics-based and Semi-Empirical correlations and treat purely empirical relationships as site-specific tools requiring local validation before broader application.

4.3 | Calibration and the Laboratory-to-Field Transfer Problem

The reviewed studies reveal different calibration approaches and different levels of evidential support. Laboratory calibration, as exemplified by McCarter [25] and Alshameri and Madun [29], establishes relationships under controlled conditions but cannot be directly applied to field conditions because geological heterogeneity, scale effects and ambient factors alter the controlled conditions. Field calibration against borehole or CPT data, as practised by Karl et al. [19] and Vagnon et al. [23], represents a higher level of evidence. More rarely, independently validated correlations [31] transferable to new sites represent the highest level currently available in the reviewed literature. Practitioners should be cautious about applying published relationships beyond their derivation context without site-specific recalibration.

4.4 | Geophysical Inversion Uncertainty and Its Propagation to Geotechnical Estimates

Geophysical inversion uncertainty has direct consequences for the reliability of derived geotechnical parameters. ERT inversion is inherently nonunique, with multiple resistivity distributions potentially fitting the same surface measurements, particularly in clay-dominated or saline environments [26]. MASW inversion is subject to mode misidentification at shallow depths below 5 m, where low confining stress reduces Vs [18]. EM surveys are susceptible to metallic interference and conductive environments [20], and FWI is sensitive to the choice of starting model and can converge to local minima [35]. These sources of uncertainty directly influence the reliability of the inferred geotechnical information, and rigorous propagation of inversion uncertainty into the final geotechnical parameter estimate remains an important challenge and a priority for future research. Soil-type and site-condition factors further limit transferability: clay mineralogy, pore fluid salinity, stress history, cementation and seasonal fabric changes all alter geophysical responses independently of the target geotechnical parameter, as demonstrated by Hen-Jones et al. [32].

4.5 | Connecting Geophysical Outputs to Engineering Design Decisions

Geophysical methods directly estimate physical properties, such as seismic velocities or electrical conductivity and resistivity, whereas the engineering parameters required for design, such as shear modulus or hydraulic conductivity, can only be inferred from these properties through appropriate constitutive or petrophysical relationships and, where necessary, site-specific calibration. With this distinction in mind, the practical engineering value of the reviewed methods is most evident when geophysical outputs are explicitly connected to engineering design decisions. Vs-derived shear modulus profiles provide direct inputs to dynamic stability assessments for slopes and foundations. ERT-derived moisture distributions provide information on saturated and unsaturated conditions in slope stability analyses. The fines content imaging workflow of Di Buccio et al. [31] supports spatially continuous liquefaction susceptibility assessment. The seismically derived rock-quality indices of Khalil and Hanafy [24] support more informed foundation layout decisions across large areas, although these indices require independent validation against direct geotechnical testing before being applied to formal bearing capacity design.

4.6 | Decision Framework for Method Selection

Based on the synthesis of the reviewed literature, a concise decision framework can be proposed. For stiffness and shear modulus estimation, MASW is the recommended primary method, supplemented by cross-hole seismic, down-hole seismic or FWI where higher resolution is required. For moisture mapping and seepage detection, ERT is the primary method, with borehole calibration essential in clay-rich or saline environments. For soil layering and lithological discrimination, the combined MASW and ERT approach provides complementary mechanical

and hydrological information, with induced polarisation as a supplementary tool in clay-rich settings. For fines content and liquefaction assessment, the integrated ERT and in situ testing workflow of Di Buccio et al. [31] represents current best practise. For high-resolution anomaly detection, cross-hole seismic methods, including FWI, are most appropriate at high-consequence sites where boreholes are available.

4.7 | Advanced Data Integration and Emerging Approaches

Advanced data fusion techniques have also emerged as valuable geophysical-geotechnical integration tools. Belief function theory, as described by Dezert et al. [30], is a formal mathematical tool for managing uncertainties in combining different data sets, resulting in more dependable subsurface condition interpretations. Petrophysical clustering and inversion approaches, as demonstrated by Accaino et al. [36], offer a pathway from qualitative geophysical imaging to quantitative parameter estimation in complex geological settings. Emerging approaches, including machine learning, hold further potential for identifying geophysical-geotechnical relationships from large datasets, though systematic application remains limited by the absence of standardised training datasets and the site-specific nature of existing calibration data, and further field validation is required before routine application can be recommended.

A recurring challenge across the reviewed literature is the difficulty of transferring laboratory-based correlations to field conditions. Laboratory studies are invaluable for establishing fundamental physical principles, but their direct application to field settings is problematic because geological heterogeneity, scale effects and ambient environmental factors dominate the controlled laboratory conditions [11]. The computational cost of high-resolution techniques such as FWI and complications arising from soil heterogeneity, environmental noise and inversion nonuniqueness necessitate ongoing research into efficient algorithms and standardised procedures for data integration and interpretation.

5 | Conclusion

Characterisation of soils is fundamental to the resilience of civil engineering infrastructure. However, conventional geotechnical approaches to subsurface characterisation are limited by their invasive nature, point sampling data collection and inability to capture spatial variability adequately. The current review has shown that geophysical techniques provide spatially continuous information that complements conventional geotechnical investigations, improving subsurface characterisation when interpreted through physically based or appropriately calibrated geophysical-geotechnical relationships and validated against site-specific ground truth.

A critical synthesis of the reviewed studies reveals that the reliability of geophysical-geotechnical correlations is strongly parameter-dependent and can be classified according to their physical basis. Correlations grounded in established physical theory, such as the relationship between Vs and small-strain shear modulus

($G = \rho V_s^2$), are robust and transferable across soil types and geological settings. Semi-Empirical correlations, such as those between electrical resistivity and moisture content motivated by Archie's law, require site-specific calibration due to the simultaneous sensitivity of resistivity to clay mineralogy, pore fluid chemistry, saturation state and temperature. Purely empirical correlations, such as those between resistivity and SPT-N values or strength parameters, are valid only within their specific derivation contexts and not reliably transferable without local recalibration. The key finding is therefore that there are no universal geophysical-geotechnical correlations, and that predictions are most reliable when the geophysical measurement is directly governed by the same physical principle as the target geotechnical parameter and is validated against independent field measurements. Electrical Resistivity Tomography correlates well with moisture content but becomes ambiguous in clay-rich or saline environments without additional calibration data, and this limitation must be explicitly acknowledged in engineering applications.

Future research efforts should focus on three priorities. First, strengthening the quantitative basis of geophysical-geotechnical correlations through systematic field validation, standardised reporting of statistical metrics including R^2 and RMSE, and independent cross-site testing to establish the boundaries of transferability. Second, developing robust data fusion frameworks based on advanced methods such as belief function theory and, where training data permit, machine learning approaches, to manage the uncertainty inherent in combining datasets with different spatial sampling characteristics. Third, advancing the application of emerging technologies, including seismo-electric imaging and FWI, whose high-resolution capabilities have been demonstrated in targeted investigations but whose computational demands currently limit routine application. Addressing these challenges and committing to quantitative integration would allow the combined use of geophysical and geotechnical methods to evolve from a supporting tool into a fundamental element of infrastructure design, hazard minimisation and construction safety.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

No new data were collected or generated in this review. All data analysed are from previously published sources cited in the reference list.

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Appendix

Appendix A: Articles Initially Identified ($n = 100$)

TABLE A1 | Articles highlighted in green ($n = 25$) were ultimately selected for the review. The remaining 75 articles were identified during the initial database search, but did not meet the eligibility criteria for inclusion as core review studies.

No.	Full reference
1	Inazaki, T., & Sakamoto, T. [15]. Geotechnical Characterisation of Levee by Integrated Geophysical Surveying. <i>Proceedings of the International Symposium on Dam Safety and Detection of Hidden Troubles of Dams and Dikes</i> , 1–3.
2	Chen, C., Liu, J., Xia, J., & Li, Z. [16]. Integrated Geophysical Techniques in Detecting Hidden Dangers in River Embankments. <i>Journal of Environmental and Engineering Geophysics</i> , 11(2), 83–94.
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4	Rahimi, S., Wood, C. M., Bernhardt-Barry, M., & Himel, A. K. [18]. Updated Reference Shear Wave Velocity Curves for Near-Surface Site Characterisation. <i>Geo-Congress 2019: Engineering Geology, Site Characterisation, and Geophysics</i> , 324–333.
5	Karl, L., Fechner, T., Schevenels, M., François, S., & Grande, G. [19]. Geotechnical Characterisation of a River Dyke by Surface Waves. <i>Near Surface Geophysics</i> , 9(6), 515–527.
6	Niederleithinger, E., Weller, A., & Lewis, R. [20]. Evaluation of Geophysical Techniques for Dike Inspection. <i>Journal of Environmental and Engineering Geophysics</i> , 17(4), 185–195.
7	Arato, A., Vagnon, F., & Comina, C. [21]. First Application of a New Seismo-Electric Streamer for Combined Resistivity and Seismic Measurements Along Linearly Extended Earth Structures. <i>Near Surface Geophysics</i> , 20(2), 117–134.
8	Cosentini, R. M., & Foti, S. [22]. Evaluation of Porosity and Degree of Saturation From Seismic and Electrical Data. <i>Géotechnique</i> , 64(4), 278–286.
9	Vagnon, F., Comina, C., & Arato, A. [23]. Evaluation of Different Methods for Deriving Geotechnical Parameters From Electric and Seismic Streamer Data. <i>Engineering Geology</i> , 303, 106670.
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