Journal of Rock Mechanics and Tunnelling Technology (JRMTT)
32 (2) 2026 pp 129-144

Available online at www.isrmtt.com

Rational Use of Non-Invasive Geophysical Techniques for Foundation Characterization of Rock Structures

Sanjay Rana

PARSAN Overseas Pvt. Ltd., Nehru Place, New Delhi, India
Email: sanjay@parsan.biz

ABSTRACT

This paper explores the use of non-invasive geophysical methods such as Electrical Resistivity Tomography (ERT), Ground Penetrating Radar (GPR), and Seismic techniques in foundation characterization for rock-based infrastructure. These techniques provide continuous subsurface information on geophysical parameters (e.g., resistivity, shear-wave velocity, P-wave velocity), reducing risk and enhancing design reliability. Applications in dam sites, hydroelectric projects, and urban infrastructure are highlighted, along with advantages and limitations.

The current paper presents two case studies conducted to demonstrate the effectiveness of integrated geophysical methods for tunnel site characterization and geohazard assessment. An integrated ERT and SRT survey was conducted along a proposed tunnel alignment in basalt terrain to identify subsurface conditions. MASW and seismic tomography were used to characterize subsurface conditions in an urban tunnel affected by subsidence and seepage. The results revealed soft to stiff soils with low-velocity zones at tunnel depth, indicating weak ground conditions. Tomography identified additional weak and seepage-prone zones. The study demonstrates the effectiveness of integrated seismic methods for detecting instability zones and supporting tunnel risk assessment.

Keywords: Geophysics; Foundation characterization; Rock engineering; ERT; GPR; MASW

1. INTRODUCTION

The success of any civil or infrastructure project critically depends on a clear understanding of the subsurface conditions upon which the structure is to be founded. In rock engineering, the foundation serves not only as a physical support but also as a zone of potential risk due to unknown geological complexities. Traditional invasive exploration methods, such as boreholes and trial pits, offer valuable point-specific information but often fall short in providing continuous, lateral insights across the entire site. This is where non-invasive geophysical techniques have emerged as powerful tools. Capable of imaging subsurface features over large areas with minimal disturbance, these methods provide a continuous spatial understanding of the underground, enhancing the decision-making process for design, risk mitigation, and construction planning (Butler, 2005).

2. GEOPHYSICAL METHODS FOR FOUNDATION CHARACTERIZATION

Geophysical techniques help investigate the physical properties of subsurface materials using indirect measurements. These non-invasive methods are especially valuable in difficult terrains, heritage structures, and urban environments where drilling is limited or undesirable.

2.1 Electrical Resistivity Imaging (ERI)

Electrical Resistivity Imaging (ERI) is a widely used geophysical method in near-surface investigations, particularly effective for applications such as lithological mapping, identifying the depth to the groundwater table, detecting contaminant plumes, and delineating features like cavities or karst systems (Reynolds, 2011).

The method works by injecting electrical current into the ground and measuring the resulting voltage differences (Figure 1), which are used to infer the subsurface distribution of electrical resistivity. One of the key strengths of ERI lies in its ability to produce continuous two-dimensional or three-dimensional images of the subsurface, offering high spatial coverage with minimal surface disruption. It is particularly sensitive to variations in moisture content, porosity, clay fraction, and ionic concentration of pore fluids, making it useful for differentiating between coarse and fine-grained materials or identifying saturated versus unsaturated zones. However, the technique is not without limitations. ERI results are subject to the equivalence problem, where different subsurface models can produce similar electrical responses, leading to ambiguity in interpretation unless constrained by independent data such as borehole logs. Moreover, ERI is highly sensitive to environmental conditions such as recent rainfall, temperature, and anthropogenic noise from buried utilities or infrastructure, which can distort the signal~~.~~ (Loke 2015; Griffiths & Barker, 1993; McDowell, 2001).

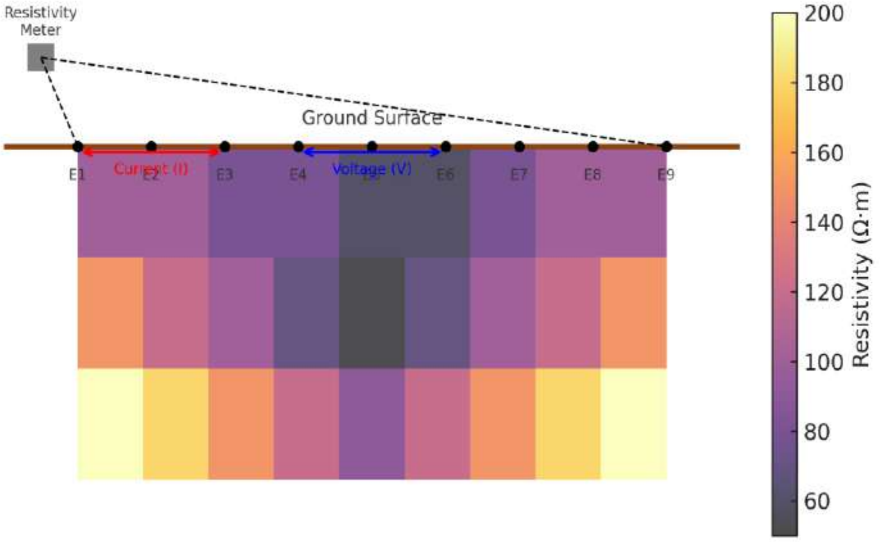

Figure 1 - ERT field setup and corresponding resistivity section, with electrode positions marked from E1 to E9

In terms of geotechnical integration, ERI is best used as a tool to define zones of interest based on resistivity contrasts that can be subsequently validated through direct methods. While there can be indirect correlations between resistivity values and geotechnical properties such as soil type, degree of saturation, and density, these relationships are not universal and require site-specific calibration. For example, fine-grained, saturated clays typically exhibit low resistivity, whereas dry sands and gravels show higher values. However, predicting parameters such as SPT-N values or CPT tip resistance directly from resistivity is not recommended without local empirical relationships and supporting data. Furthermore, while ERI has been explored in some studies to infer weathering profiles that might relate qualitatively to rippability (Loke 2015), the technique does not measure mechanical strength and should not be used independently for such assessments. Instead, its value lies in guiding the placement of boreholes, detecting subsurface anomalies, and improving interpolation between discrete investigation points within a broader geotechnical framework.

2.2 Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is a high-resolution geophysical technique used to image the shallow subsurface by transmitting short pulses of electromagnetic energy into the ground and recording the reflected signals from subsurface interfaces (Figure 2). It is particularly effective for detecting changes in dielectric properties, which typically occur at boundaries between materials with contrasting moisture content, composition, or density.

GPR is widely used in engineering and geotechnical contexts for applications such as mapping shallow stratigraphy, locating buried utilities and pipes, detecting voids and cavities, assessing pavement structures, and investigating archaeological features. The method offers excellent vertical and horizontal resolution- often in the range of a few centimeters- and can acquire data rapidly over large areas, making it ideal for urban and infrastructure settings where non-invasive investigation is essential (Annan, 2009)

The effectiveness of GPR, however, is highly dependent on subsurface conditions. It performs best in dry, resistive materials such as clean sands, gravels, or dry concrete, where signal attenuation is minimal. In contrast, its performance deteriorates significantly in conductive media such as clay-rich soils, saline groundwater, or areas with high moisture content, where electromagnetic waves are rapidly absorbed, leading to reduced penetration depth and poor data quality. Typical investigation depths range from 0.5 to 5 m, though under favorable conditions, depths of 40-50 m may be achieved using low-frequency antennas. GPR is also highly sensitive to surface roughness and metallic clutter, which can generate false reflections.

In terms of geotechnical integration, GPR serves primarily as a complementary mapping tool rather than a direct provider of engineering parameters. It is especially valuable in urban geotechnical studies, where locating subsurface infrastructure (service lines) or identifying shallow anomalies such as sinkholes, shallow bedrock, or changes in soil layering can help optimize the placement of boreholes or in-situ testing. While GPR does not provide direct correlations with strength or stiffness, its ability to delineate interfaces and anomalies can significantly reduce uncertainty in site characterization when used in conjunction with borehole logs, resistivity data, or seismic profiles. As part of an integrated workflow, GPR helps improve the spatial understanding of subsurface conditions and contributes to safer, more informed geotechnical designs.

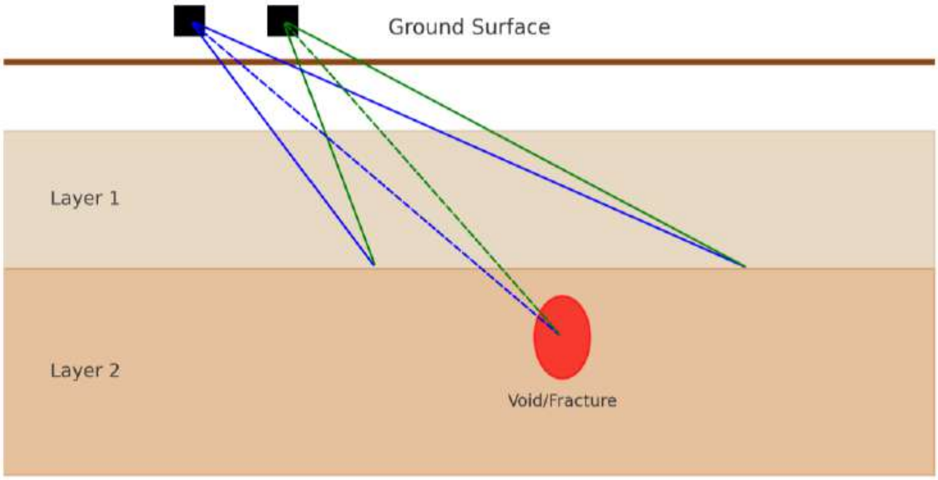

Figure 2 - GPR schematic with reflections from layers and void

2.3 Multichannel Analysis of Surface Wave (MASW)

Multichannel Analysis of Surface Waves (MASW) is a surface seismic method widely used in geotechnical and earthquake engineering for estimating shear-wave velocity (V_s) profiles in the near surface. It involves generating surface waves (typically Rayleigh waves) using a seismic source and recording their propagation using an array of geophones (Figure *3* 3). By analyzing the dispersion characteristics of these waves, MASW allows the construction of a one-dimensional or two-dimensional shear wave velocity (V_s) profile, which can be interpreted in terms of stiffness and stratigraphy. This method is particularly effective to depths of around 20 to 40 m and provides reliable information on subsurface layering, especially in relatively homogeneous soils. One of MASW's significant strengths is that it directly estimates shear-wave velocity, which is fundamental to evaluating small-strain shear modulus, a critical input in seismic site response analysis, liquefaction potential evaluation, and dynamic soil-structure interaction stuies (Park et al., 1999; Foti et al., 2015)

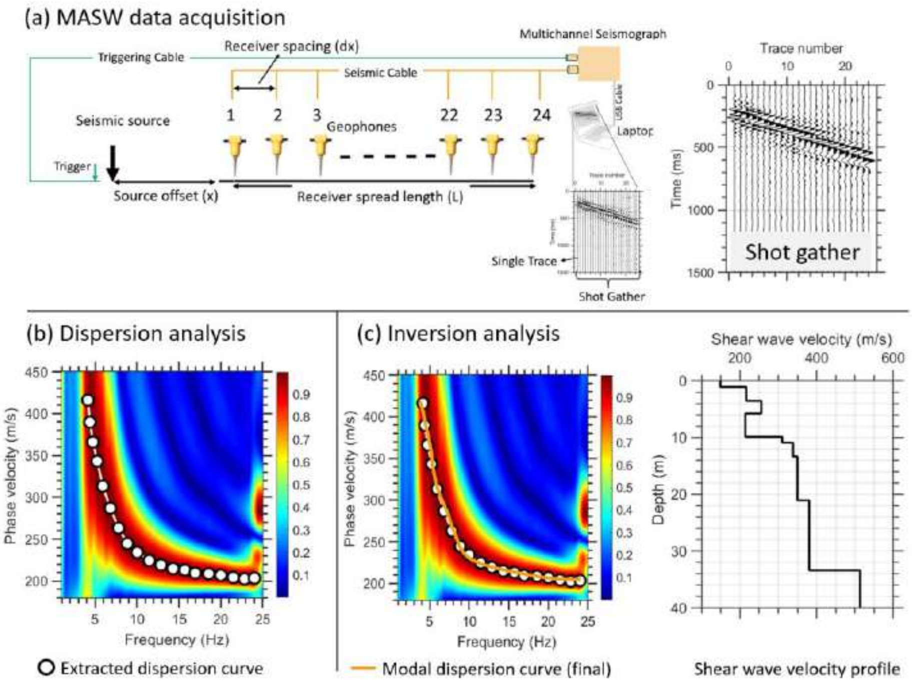

Figure 3 - MASW data acquisition and processing: (a) Acquisition of shot gather, (b) Recorded data is transformed into velocity-frequency space for dispersion analysis and then the dispersion curve is extracted, which is shown by a white filled circle, and (c) Shear wave velocity estimate from inversion of dispersion curves

In terms of integration into geotechnical workflows, MASW offers direct geotechnical relevance, since shear-wave velocity is empirically correlated with several engineering properties, including SPT-N values, soil stiffness, and liquefaction resistance (Andrus & Stokoe, 2000). Numerous well-established correlations exist in the literature that allow V_s profiles to be used in place of or to complement standard penetration testing in preliminary site assessments. Moreover, the method is non-invasive, relatively fast to deploy, and less affected by cultural noise compared to body-wave seismic methods. However, MASW does have limitations, especially in complex, laterally heterogeneous environments where wave propagation may be distorted, or where high noise levels obscure the surface wave signal. The method is also less effective at deeper depths, as the resolution of deeper layers diminishes due to the limited energy of long-wavelength surface waves. Despite these constraints, MASW is widely regarded as a robust and reliable tool for characterizing subsurface stiffness and stratigraphy, especially when used alongside borehole data for calibration and validation.

2.4 Seismic Refraction Tomography

Seismic Refraction Tomography (SRT) is a geophysical technique that utilizes the travel times of seismic compressional (P-) waves to image subsurface velocity structures. The method involves placing a line of geophones along the surface and generating seismic waves using an active source, such as a hammer or weight drop (Figure 4). As these waves travel through the subsurface, they refract along interfaces where there are significant contrasts in seismic velocity- typically associated with changes in material stiffness, density, or degree of weathering. SRT enhances traditional seismic refraction by applying tomographic inversion techniques to better resolve lateral and vertical variations in velocity. This results in more detailed imaging of subsurface features such as weathered zones, depth to bedrock, and competent strata boundaries. The method is particularly effective in identifying rippability, where P-wave velocity thresholds (e.g., <1500 m/s for soft soils, 1500-2500 m/s for weathered rock) are commonly used in empirical charts to estimate excavation difficulty (Hack & Huisman, 2002).

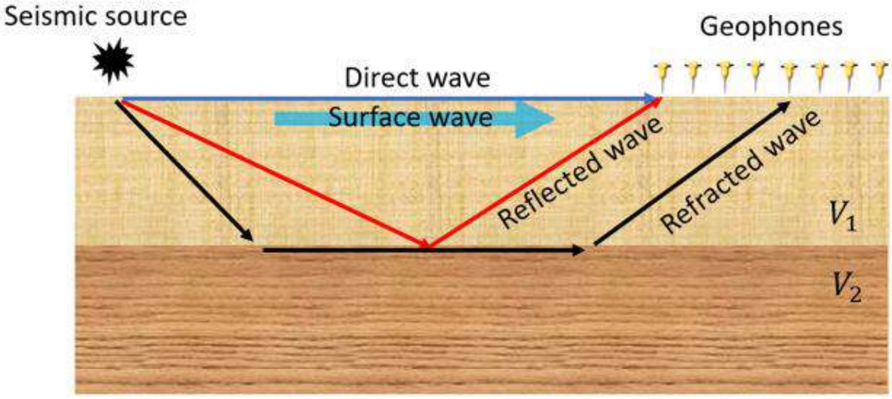

Figure 4 - Seismic data acquisition and wave propagation

In geotechnical investigations, SRT is often employed for bedrock profiling, locating weathered zones, assessing the depth to refusal for pile design, and estimating the competency of subsurface layers for foundation support. The technique is especially valuable in road, tunnel, and dam projects where understanding the depth and quality of underlying rock is essential for design and construction planning. However, like other seismic methods, SRT is susceptible to certain limitations. One significant challenge is the so-called "hidden layer problem," where a low-velocity layer beneath a higher-velocity layer may go undetected because refraction relies on increasing velocity with depth. In such cases, complementary methods like borehole logging or surface wave analysis e.g., MASW can be used to resolve ambiguities. Additionally, the resolution of deep layers diminishes with increasing depth unless long offsets and high-energy sources are employed. Cultural noise, access limitations, and topographic irregularities can also affect data quality. Despite these limitations, when applied correctly and interpreted alongside borehole data or other geophysical results, SRT provides a powerful means of evaluating subsurface conditions relevant to geotechnical design.

2.5 Seismic Tomography

Seismic tomography refers to a family of advanced inversion techniques that transform seismic wave travel-time data into spatially varying models of subsurface velocity, offering detailed two- or three-dimensional images of material stiffness and structure. In geotechnical contexts, travel-time tomography- whether based on first-arrival P-waves (compressional) or S-waves (shear)- is increasingly employed to characterize complex near-surface conditions where traditional layer-based models fall short. Unlike standard seismic refraction, which assumes laterally homogeneous layers with increasing velocity, tomographic methods solve for a velocity distribution across a finely discretized mesh, allowing for the imaging of gradual velocity transitions, lateral heterogeneities, and irregular interfaces. This makes seismic tomography particularly useful for identifying features such as weathered rock zones, shear zones, paleo-channels, weak layers beneath stronger strata, and variable bedrock topography- all of which are critical for foundation design, slope stability, and infrastructure planning (Cardarelli & Di Filippo, 2009).

The data acquisition for seismic tomography typically involves dense arrays of geophones and multiple shot points at varying offsets, which increase ray-path coverage and enhance resolution. Inversion algorithms- usually based on iterative least-squares or finite-difference approaches- are then used to reconstruct the subsurface velocity field. Depending on the inversion type, both P-wave and S-wave tomograms can be generated, providing insight into both compressional and shear properties of the ground. These velocity models can be used to infer mechanical properties such as stiffness, degree of weathering, and, in some cases, fracture density or porosity trends, although they must always be interpreted in conjunction with site-specific ground truth data such as borehole logs or in-situ testing results (Cardarelli & Di Filippo, 2009).

Seismic tomography is especially well-suited for projects involving critical infrastructure, such as tunnels, dams, or high-capacity foundations, where subsurface complexity poses significant design risk. Its primary limitations are related to cost, data acquisition logistics, and computational demands. High-resolution tomographic surveys require extensive source-receiver setups, good coupling, and high signal-to-noise ratios- conditions that may be difficult to achieve in urban, paved, or restricted-access sites. Moreover, accurate inversion depends on careful survey design, proper velocity model initialization, and quality control of arrival-time picks. Nevertheless, when implemented effectively, seismic tomography significantly enhances the spatial resolution and interpretability of geophysical investigations, providing geotechnical engineers with valuable insights into the subsurface that are difficult to obtain by drilling alone (Cardarelli & Di Filippo, 2009)

Geophysical investigation is a fast, cost-effective, and non-destructive testing (NDT) approach. For major infrastructure and prestigious projects, the cost of geophysical surveys is typically less than 1% of the total project cost, making it highly economical. In addition, geophysical methods provide rapid subsurface assessment; surveys that may take several weeks to a month using conventional borehole drilling can often be completed within a day in the field, followed by quick data processing and interpretation. This significantly reduces project time and helps in early decision-making.

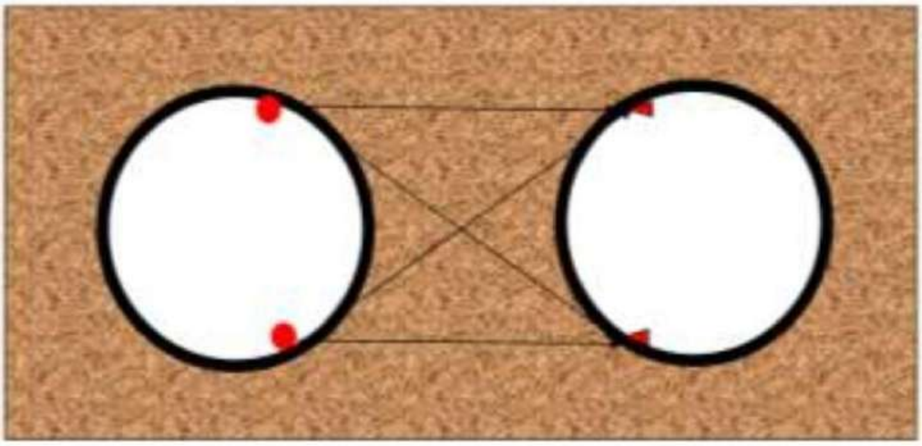

Figure 5 - Seismic Tomography Between Tunnels

2.6 Other Techniques

Emerging methods such as Transient Electromagnetics (TEM), Passive Seismic, and Seismic Interferometry are gaining popularity for deeper investigations and passive monitoring. TEM is sensitive to conductive features like groundwater or clay zones, while seismic interferometry leverages ambient noise to reconstruct seismic wavefields, offering non-intrusive insights in urban or environmentally sensitive areas. Passive seismic tomography is an excellent tool to create V_p and V_p/V_s models of the subsurface up to tens of kilometers. Heliborne geophysical surveys enable rapid and extensive subsurface mapping over large and inaccessible areas, offering valuable regional-scale insights; however, they are generally more expensive than ground-based geophysical techniques.

Tables 1 and 2 are given below summarizing the applicability, etc., of the techniques discussed in this paper.

Table 1 - Summary of key physical parameters derived from geophysical investigations, including their indicative ranges, and relevance for interpretation

Material type	Resistivity (Ohm-m)	V_p (m/s)	V_s (m/s)	Remarks
Soil (soft/clay)	1 to 100	300 to 1500	100 to 400	Lower resistivity if saturated; velocities increase with compaction
Soil (stiff/sand)	50 to 500	800 to 2000	200 to 600	Dry conditions increase resistivity; dense packing increases velocity
Weathered rock	10 to 1000	1000 to 3000	300 to 1200	Highly variable; decreases with fracturing and water content
Hard rock	1000 to 10000 +	3000 to 6000	1500 to 3500	High values; reduced if fractured or jointed
Saturated zone	1 to 50	1500 to 2500	200 to 800	Low resistivity due to water; velocities depend on material

Table 2 - Summary of the principles, applications, and limitations of the geophysical techniques

Principle	Applicable Depth	Application/ Suitable for	Limitations	Remarks
ERT				
Measures subsurface electrical resistivity	Near surface to ~100–150 m	Lithological mapping, groundwater detection, weak zones, cavities	Affected by contact resistance; poor in highly resistive ground	Sensitive to moisture and clay
GPR				
Electromagnetic wave reflection	0–10 m (site dpendent)	Utility detection, rebar mapping, void detection	Poor penetration in clay/wet soils	High resolution for shallow studies
MASW				
Surface wave dispersion analysis (V_s estimation)	~10–50 m	Soil stiffness, site classification, subsidence	Limited depth penetration	Reliable for shear strength
SRT				
P-wave travel time inversion	~20–100 m	Depth to bedrock, rock quality, fractures	Velocity inversion and masking issues	Good for competence evaluation
Seismic Tomography				

Seismic travel time inversion imaging	Variable (up to 100 m+)	Tunnel zones, weak zones, seepage	Needs dense data and geometry	High-resolution imaging

3. ADVANTAGES AND LIMITATIONS OF GEOPHYSICAL METHODS

3.1 Advantages

Geophysical investigations are non-invasive and rapid techniques that significantly reduce the need for extensive and time-consuming drilling. They provide continuous spatial coverage of the subsurface, allowing a better understanding of lateral and vertical variations in geological conditions. These methods are highly effective for pre-screening and optimizing the locations of boreholes and other invasive tests, thereby improving the efficiency of site investigations. In addition, geophysical surveys are environmentally friendly, causing minimal disturbance to the site compared to conventional methods. From an economic perspective, they are highly cost-effective, as the overall cost of geophysical investigations is typically less than 1% of the total project cost, while substantially reducing uncertainties and potential risks during construction.

3.2 Limitations

Geophysical methods have certain limitations that must be considered during interpretation. Signal quality can degrade in highly conductive or noisy environments, which may affect data reliability. The resolution of geophysical results is generally lower compared to direct methods such as drilling and sampling. Additionally, inversion results are inherently non-unique, meaning that multiple subsurface models can satisfy the same dataset. Therefore, accurate interpretation requires experienced professionals and should ideally be supported by borehole data or other ground-truth information.

Recent advancements in Artificial Intelligence (AI) and machine learning are increasingly being applied in geophysical data interpretation to automate pattern recognition, improve inversion results, and reduce subjectivity. AI-based approaches can enhance anomaly detection, integrate multi-geophysical datasets, and provide faster and more reliable subsurface models when combined with conventional interpretation methods.

4. CASE STUDIES

The two case studies were selected to represent contrasting geological and engineering conditions, one in basalt-covered terrain and the other in an urban, subsidence-prone environment, thereby demonstrating the applicability of integrated geophysical methods under different site scenarios.

In both cases, two complementary geophysical techniques were employed to overcome the limitations of individual methods and to improve the reliability of subsurface interpretation. For example, resistivity-based methods are highly sensitive to moisture and lithological variations, whereas seismic methods provide insight into mechanical properties such as stiffness and competence. The integration of these techniques enhances confidence in identifying weak zones, fractures, and groundwater conditions.

In certain simple and homogeneous geological settings, a single geophysical technique may be sufficient, particularly when the investigation objective is limited (e.g., depth to bedrock or shallow utility mapping). However, in complex conditions involving heterogeneous geology, variable saturation, or critical infrastructure such as tunnels and dams, the use of multiple techniques is recommended. The selection and number of geophysical methods to be used in a project should be based on factors such as site geology, depth of investigation, project objectives, required resolution, and the need to reduce uncertainty. Integrating multiple techniques ensures a more robust and reliable subsurface model, which is essential for safe and cost-effective engineering design.

4.1 Case Study 1: Near-Surface Geophysical Characterization for Proposed Tunnel Alignment using ERT and SRT in Nagpur Region, Maharashtra

4.1.1 Introduction

The present study is based on a tunnel site in the Nagpur region of Maharashtra, India. The proposed tunnel alignment lies below 330 m elevation and falls within the Deccan Trap basaltic terrain. The region is characterized by thick basalt flows that cover older sedimentary formations. In basalt-covered regions, tunnel investigations become more complex due to the presence of thick lava flows. These basaltic flows form a strong, hard, and compact cover over weaker sedimentary formations such as Lameta and intertrappean beds. Even though these sedimentary formations are not visible at the surface, they play a major role in controlling subsurface stability and groundwater movement. In such geological settings, geophysical methods become one of the most effective tools for identifying hidden weak formations and hazard zones along the tunnel alignment. Thus, the investigation aimed to provide a reliable near-surface model to support tunnel design and hazard mitigation planning.

The proposed tunnel depth was estimated to be in the range of approximately 20 to 40 m. The geophysical investigations, including ERT and SRT, were able to provide reliable subsurface information up to and beyond the proposed tunnel level, thereby adequately covering the depth of interest. This ensured proper delineation of lithological variations, weak zones, and potential geohazards along the tunnel alignment, which are critical for safe tunnel design and construction.

4.1.2 Selection of Geophysical Methods

In basalt-covered regions, conventional geotechnical investigation methods face limitations because the basalt layer is thick and resistant. Seismic surveys alone may not provide accurate imaging beneath basalt due to the high seismic velocity of basalt, which can cause velocity masking. Similarly, drilling alone may be expensive and insufficient to provide continuous subsurface information along a long tunnel alignment.

To overcome these challenges, this study applied two complementary geophysical techniques: Electrical Resistivity Tomography (ERT) and Seismic Refraction Tomography (SRT). These methods were selected because they provide different but supportive information. ERT is highly effective in detecting conductive layers such as weathered sediments and groundwater zones, while SRT provides information about subsurface mechanical competence through seismic velocity variations. Together, they allow better interpretation of tunnel-relevant lithological and structural features.

4.1.3 Electrical Resistivity Tomography in Tunnel Site Investigation

In this study, the ERT survey was conducted along a profile of approximately 2.2 km. The collected data were processed using inversion techniques to generate a two-dimensional resistivity model (Figure 3). The ERT results clearly revealed strong lateral and vertical resistivity variations beneath the basalt cover. A thin, low-resistivity layer of about 5 m thickness was identified at the surface. This layer represents weathered soil or unconsolidated material and is significant for tunnel portal construction, slope excavation, and shallow foundation design. Weathered zones often show reduced shear strength and may fail easily during excavation if not properly supported.

Below this shallow layer, the resistivity model showed a dominant high-resistivity zone corresponding to massive basalt. Basalt generally exhibits high resistivity due to its compact and less porous nature. For tunnel engineering, this basalt zone indicates competent rock suitable for excavation. However, even basalt may contain fractures and joints, which can reduce stability locally. Therefore, the resistivity distribution helps in identifying possible fractured basalt segments.

A key outcome of the ERT investigation was the detection of a prominent low-resistivity zone ranging from 5 to 30 ohm-m beneath the basalt layer (below 320 m). This conductive zone was interpreted as the Lameta Formation or the intertrappean sedimentary beds/weathered basalt layer. Such low resistivity suggests that the formation may be weathered, fractured, or saturated with groundwater. This is ~~highly~~ important for tunnel design because sedimentary beds below basalt are often weaker than basalt and may deform under excavation stress. If the tunnel intersects such a zone, additional ground support and reinforcement would be required to prevent tunnel collapse or excessive convergence.

ERT also identified a distinct anomaly around chainage 138,110 m, where resistivity drops sharply. This sudden resistivity change indicates the presence of a fractured zone or possible fault. In tunnel engineering, faults and fracture zones are considered critical hazards because they often contain crushed rock, increased permeability, and reduced rock strength. These zones can act as major groundwater pathways, leading to sudden inflow during excavation. Therefore, ERT proves to be a powerful tool for detecting tunnel hazard zones that may not be visible at the surface.

4.1.4 Seismic Refraction Tomography in Tunnel Site Investigation

In this study, the SRT survey was conducted along the same 2.2 km profile as the ERT survey. The acquired seismic data were processed to generate a two-dimensional velocity model (Figure 3). The SRT results showed clear P-wave velocity contrasts between basalt and the underlying formations. The basalt layer exhibited high seismic velocities, confirming its competent nature. This information is important for tunnel excavation planning because it indicates the zones where hard rock excavation methods may be required.

A thin overburden layer, approximately 5 meters in thickness, was also identified at the surface, representing weathered or unconsolidated soil. This layer is significant for construction planning. Additionally, a distinct zone around chainage 138,110 m exhibits a sudden drop in both resistivity and seismic velocity. This anomaly suggests the presence of a possible fault or fractured zone. Such structural weaknesses are critical indicators of potential geohazards, including ground subsidence, differential settlement, and increased groundwater flow pathways. The SRT velocity models provide complementary information on subsurface mechanical properties. The results show clear velocity contrasts between the basalt layer and the underlying formations. However, the study also highlights an important limitation of SRT in basalt terrain. Because basalt has a very high seismic velocity, it can cause velocity masking, meaning that seismic waves may not effectively resolve thin low-velocity layers beneath the basalt. As a result, SRT alone may fail to detect certain weak sedimentary horizons if they are thin or deeply buried. This is a common challenge in tunnel investigations within the Deccan Trap regions. Therefore, the integration with ERT becomes essential.

A major advantage of SRT in this study was its ability to confirm the presence of the weak zone detected by ERT around chainage 138,110 m. The velocity model showed a sudden reduction in seismic velocity at the same location where resistivity dropped. This correlation strongly supports the interpretation of a fault or fractured zone.

4.1.5 Integrated Interpretation for Tunnel Engineering

The combined interpretation of ERT and SRT provides a more reliable subsurface model compared to using a single method. ERT effectively detects conductive weak zones and groundwater-bearing formations, while SRT provides mechanical property estimation through velocity distribution. When both datasets indicate anomalies at the same location, the confidence in interpretation becomes significantly higher.

In this study, the integrated results suggest that the tunnel site consists of a shallow weathered overburden layer, followed by thick competent basalt, underlain by weaker sedimentary beds interpreted as Lameta or intertrappean formations. The identification of a major fractured or fault zone around chainage 138,110 m is the most important outcome from a geohazard perspective. Such a zone could represent a potential location for tunnel collapse, excessive deformation, and groundwater inflow if not properly treated.

The integrated approach also helps in identifying zones of varying rock competence along the tunnel alignment. This information is essential for deciding tunnel excavation strategy and for planning support systems. Without such integrated geophysical imaging, these hazardous zones may remain undetected until excavation, resulting in major construction risks and economic losses.

Around chainage 138110 m (Figure 6), the tunnel alignment rises to the ground surface, as observed in the geophysical sections. In this portion, the tunnel is effectively exposed at the surface, and a river is flowing across this zone. This indicates that the tunnel section in this stretch is likely to be constructed using a cut-and-cover method rather than conventional underground excavation. The geophysical results in this area are particularly important for assessing subsurface conditions, including potential weak zones and water-bearing formations, which are critical for designing appropriate excavation and support measures in the presence of surface water.

4.1.6 Recommendations

This case study demonstrates that geophysical methods play a vital role in tunnel site investigations, particularly in basalt-covered regions like the Deccan Trap terrain. The integrated use of Electrical Resistivity Tomography and Seismic Refraction Tomography provides a reliable and continuous subsurface model along the tunnel alignment. ERT successfully imaged conductive sub-basalt formations and identified weak sedimentary units, while SRT provided complementary information on subsurface mechanical competence through seismic velocity contrasts.

The results indicate the presence of a thin overburden layer, thick resistive basalt, and an underlying low-resistivity zone interpreted as Lameta or intertrappean beds. A major fractured or fault zone was identified around chainage 138,110 m, confirmed by both resistivity and velocity anomalies. This zone represents a significant geohazard concern for tunnel construction. However, as indicated in the longitudinal (L-) section, this stretch appears to be an open-to-sky segment rather than a fully underground tunnel section. Even so, the identified weak and potentially water-bearing zone is critical from an engineering perspective, as it may affect excavation stability and design considerations. The study highlights that proper selection of geophysical techniques and their integrated application are essential for safe planning, appropriate support design, and effective hazard mitigation in complex geological conditions.

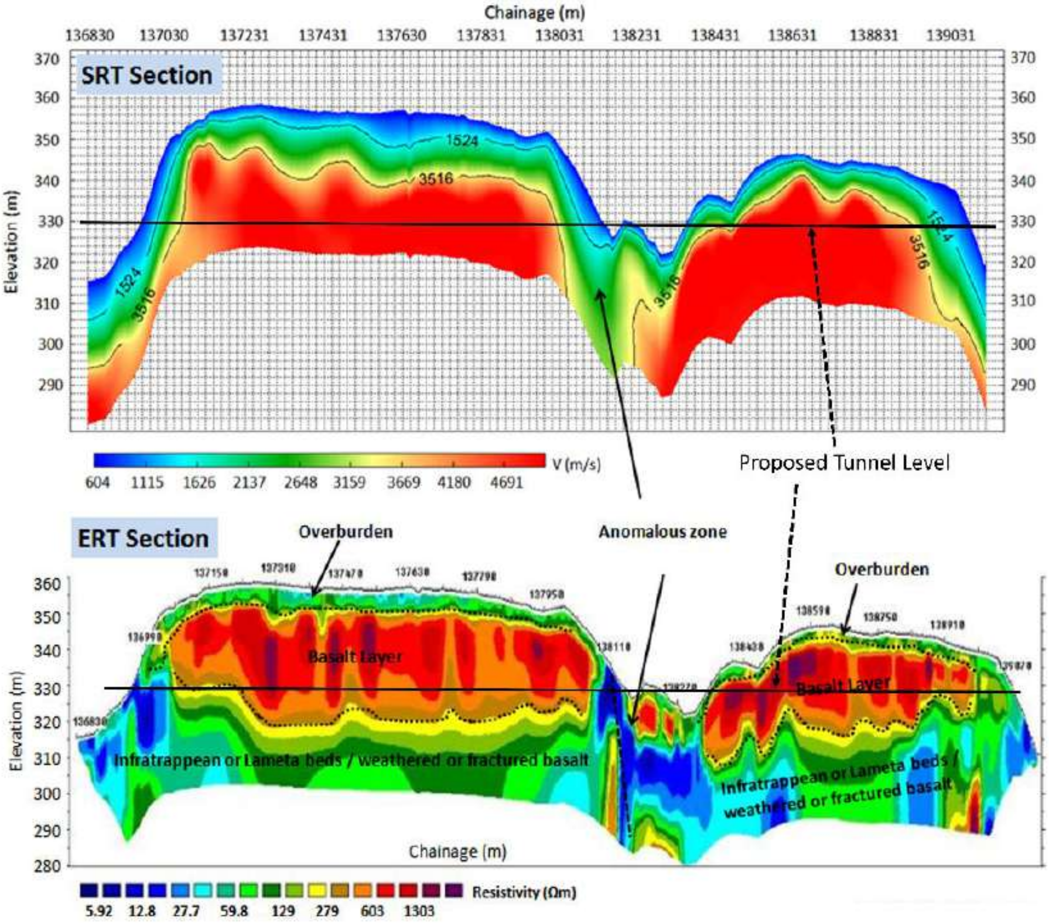

Figure 6 - SRT velocity and ERT sections along the ~2.2 km long tunnel profile in the Nagpur region, Maharashtra, showing subsurface lithological variations beneath Deccan Trap basalt. The proposed tunnel level (330 m elevation) is marked on both sections

4.2 Case Study 2: Tunnel Site Characterization Using MASW and Seismic Tomography in Urban Environment

4.2.1 Introduction

Urban tunnelling in densely populated regions often encounters significant geotechnical challenges due to variable soil conditions, shallow groundwater presence, and complex stratigraphy. Subsidence and seepage-related problems may arise when tunnels are constructed through weak or saturated deposits, potentially resulting in damage to surface infrastructure and tunnel lining. To address such risks, seismic-based geophysical investigations are widely adopted due to their ability to map stiffness contrasts and detect hidden subsurface anomalies. This case study describes the application of MASW and seismic tomography for tunnel site characterization and hazard identification in a subsidence-sensitive environment.

The geophysical investigation was carried out post-construction of the metro tunnel, following the observation of seepage and ground settlement issues, with the aim of identifying the underlying weak zones and subsurface anomalies responsible for these problems.

4.2.2 Multi-channel Analysis of Surface Waves (MASW)

MASW survey was conducted at the proposed location to assess subsurface conditions for settlement analysis. MASW surveys typically involve recording high-amplitude surface waves using a linear array of geophones and an active source such as a sledgehammer. The recorded wavefield is processed to generate dispersion curves, which are then inverted to obtain 1D shear wave velocity (V_s) profiles (Fig. 4). Multiple profiles along a survey line are combined to produce 2D sections. Shear wave velocity (V_s) values are widely used for site classification and stiffness assessment, making MASW highly suitable for tunnel site investigation and subsidence risk evaluation.

4.2.3 Seismic Tomography

Seismic tomography was performed between the two tunnels (Fig. 5). In tunnel investigations, seismic tomography is particularly effective for imaging the zone around tunnel walls, crown, and between adjacent tunnels. Low-velocity anomalies often indicate weak ground, seepage zones, fractured material, or loosened strata, whereas high-velocity zones represent compact and competent formations. Tomographic inversion is commonly performed using iterative reconstruction techniques such as SIRT (Simultaneous Iterative Reconstruction Technique), which improves the accuracy of the velocity model by minimizing the difference between observed and calculated travel times.

4.2.4 Results and Interpretation

MASW-derived shear wave velocity (V_s) sections from surface-level profiles indicated low to moderate velocities, suggesting that near-surface deposits are dominated by soft to stiff soils. The profile showed V_s values below typical stiffness thresholds, reflecting weak soil zones and reduced shear strength. Localized low V_s pockets were detected in multiple sections, which may correspond to loosened ground or weak alluvial deposits. In some cases, velocity inversions were observed, indicating alternating layers with varying degrees of compaction.

Inside-tunnel MASW profiles showed comparatively higher Vs values, suggesting the presence of denser strata at tunnel depth. However, small low-velocity anomalies were still identified, indicating heterogeneity and possible disturbed zones near tunnel boundaries.

The 2D MASW V_s section (Figure 7 & Figure *8*) was acquired at the road top above the tunnel alignment. The 2D Vs MASW section reveals significant insights into subsurface layering and material properties, with velocities ranging from 147 m/s to 250 m/s. The site characterization follows the guidelines set by the International Building Code (IBC) and the National Earthquake Hazard Reduction Program (NEHRP). Velocities below 180 m/s indicate the presence of soft soil, typically comprising loose, unconsolidated materials like recent alluvial deposits or clays with low shear strength. Velocities >180 to 250 m/s correspond to stiff soils, characterized by moderate strength and consolidation, such as silty or sandy soils. Notably, the section reveals patches of low-velocity zones or velocity inversions, which may reflect areas of less compacted materials or alternating layers of strata with varying compaction. The tunnel passes at an approximate level of 14 m, where the MASW results indicate a low-velocity zone. This low V_s zone represents soft to stiff soil conditions, suggesting reduced stiffness and weaker ground at the tunnel level. Such conditions may increase the risk of settlement and instability during tunnelling.

The section presented below (Fig. 8) was acquired inside the tunnel along the tunnel alignment. The 2D Vs section provides crucial insights into subsurface layering and material properties, with velocities ranging from 471 m/s to 1310 m/s. The site characterization follows the guidelines set by the International Building Code (IBC) and the National Earthquake Hazard Reduction Program (NEHRP). Velocities between 360 m/s and 760 m/s suggest the presence of dense soil.

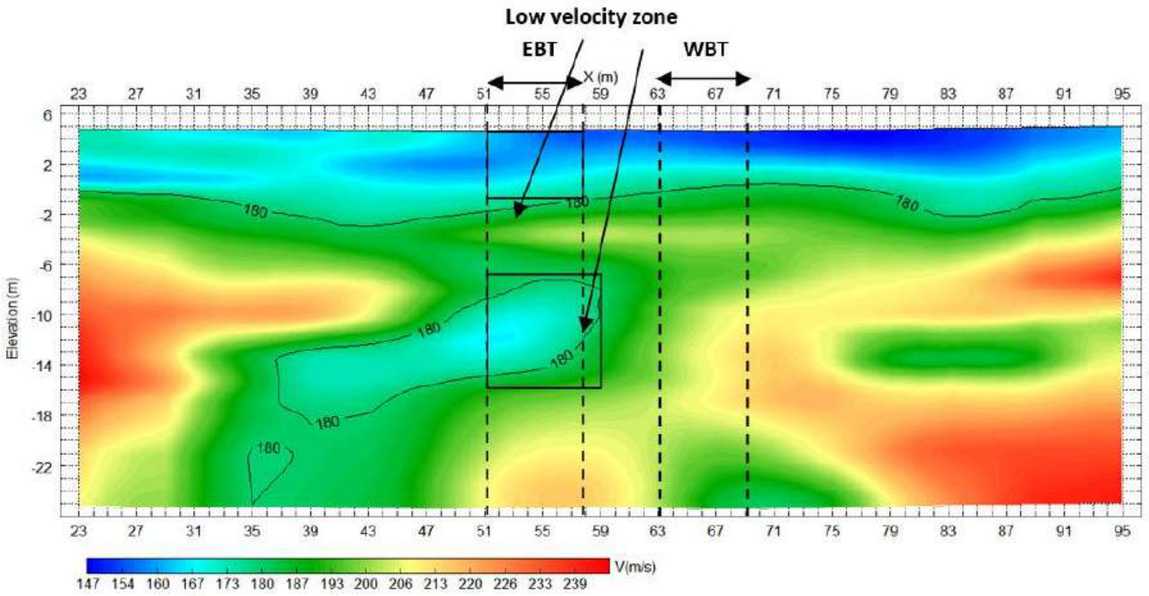

Figure 7 - 2D MASW shear wave velocity section acquired at road top above the tunnel alignment, illustrating subsurface stiffness variation and highlighting low-velocity zones corresponding to soft to stiff soil conditions. Two parallel tunnels are marked by vertical dashed lines

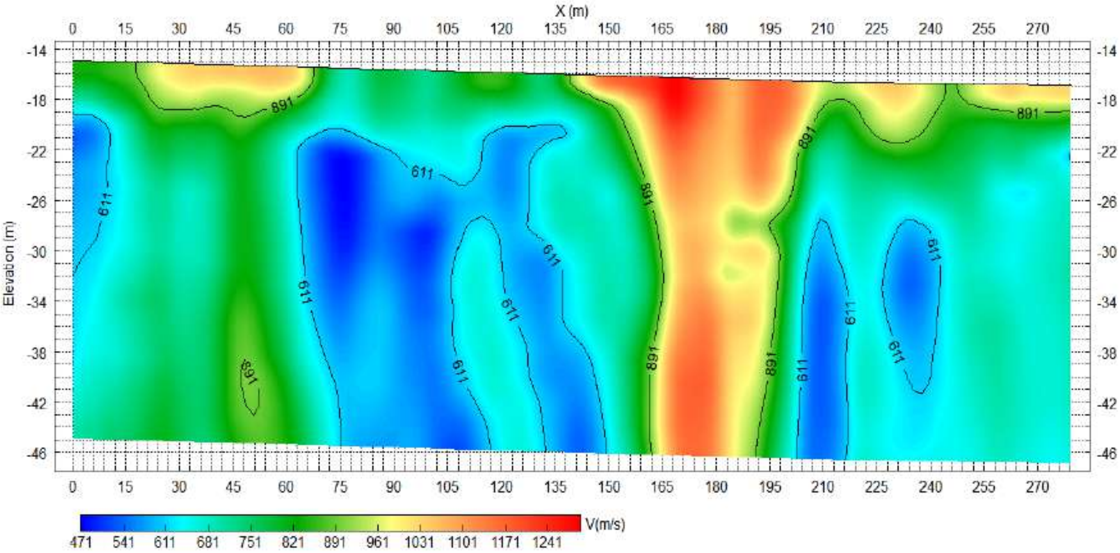

Figure 8 - 2D MASW shear wave velocity section acquired inside the tunnel, showing subsurface stiffness variation around the tunnel zone and indicating relatively higher velocity strata with localized low-velocity anomalies

Velocities exceeding 760 m/s, reaching up to 1310 m/s, indicate hard or firm strata, which may correspond to highly compacted sediments or partially lithified formations. Such layers are typically associated with greater strength, higher stiffness, and improved geotechnical stability, making them more suitable for structural foundations or load-bearing applications. Additionally, the section highlights localized low-velocity zones or velocity inversions, which may represent pockets of loosely compacted materials, variations in moisture content, or the presence of softer interbedded layers. These features suggest heterogeneity in subsurface conditions, possibly due to depositional processes, weathering, or past geological activity.

Seismic tomography provided high-resolution imaging of the zone between tunnel sections. The tomograms (Figure 9) revealed distinct velocity contrasts, highlighting both competent zones and anomalous low-velocity regions. Low-velocity anomalies were observed in specific segments, interpreted as loose or disturbed ground, seepage-prone zones, or weakened strata. These zones are considered critical for tunnel safety, as they may indicate potential void development or reduced load-bearing capacity. High-velocity zones were interpreted as compact and stable formations, likely representing consolidated soil or stiff geological units.

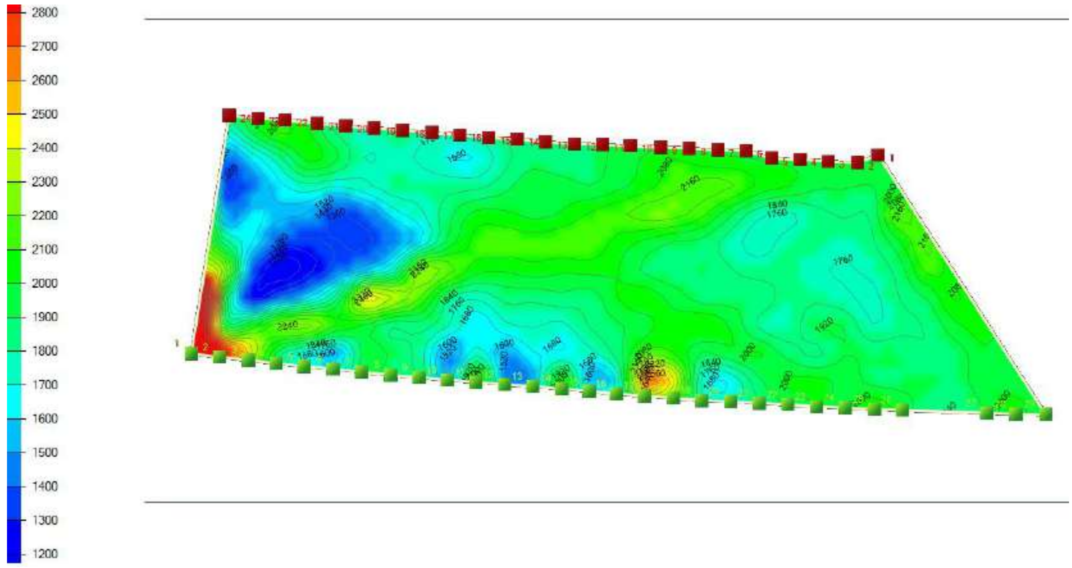

Figure 9 - Seismic tomography velocity section acquired between the two tunnels, illustrating subsurface velocity distribution and highlighting low-velocity anomaly zones indicative of weak/loose ground formations

4.2.5 Recommendations

This case study highlights the application of MASW and seismic tomography for tunnel corridor characterization in a subsidence-sensitive urban environment. The investigation delineated soft soil zones near the ground surface, identified through low shear wave velocity values, along with significant stiffness variations and velocity inversions reflecting subsurface stratigraphic complexity. The seismic tomography results further revealed low-velocity anomaly zones, interpreted as weak and seepage-prone formations, as well as high-velocity competent zones representing relatively stable strata. In addition, localized heterogeneity at tunnel depth was observed, indicating areas that may require mitigation and reinforcement. The integrated seismic investigation provided critical inputs for tunnel risk assessment, stability evaluation, and planning of suitable remedial measures.

5. FUTURE DIRECTIONS

As computational and sensing technologies continue to advance, geophysical investigations are evolving towards higher resolution, increased automation, and integrated platforms. Emerging approaches such as joint inversion techniques, which combine multiple datasets (e.g., ERT and MASW) within a unified framework, help reduce uncertainty and improve the robustness of subsurface models. The growing application of machine learning and artificial intelligence is enabling real-time data classification and faster inversion, thereby supporting quicker and more informed decision-making in the field. Additionally, passive seismic monitoring using ambient noise is gaining importance for continuous subsurface assessment and early warning in critical infrastructure projects. Furthermore, the integration of geophysical sensors with geotechnical and environmental monitoring systems is leading to the development of hybrid platforms, allowing more comprehensive and holistic subsurface characterization.

6. CONCLUSIONS

Non-invasive geophysical techniques are transforming the approach to foundation investigations in rock engineering by providing spatially continuous and multi-parameter insights into subsurface conditions. These methods serve as valuable complements to traditional invasive techniques, enhancing the overall understanding of geological variability. When properly planned and interpreted, geophysical investigations help reduce uncertainty, optimize design, and support sustainable infrastructure development. As engineering projects become increasingly complex and large in scale, the integration of geophysical methods at the early stages of site characterization is becoming not only beneficial but essential. It is further recommended to adopt at least two complementary geophysical techniques, especially in complex geological settings or critical infrastructure projects. The combined use of electrical methods (such as ERT) and seismic methods (such as SRT or MASW) provides a more comprehensive and reliable assessment of subsurface conditions, as they offer sensitivity to different physical properties. This integrated approach reduces ambiguity, improves interpretation confidence, and enables more effective identification of weak zones, fractures, and seepage pathways, thereby supporting informed decision-making for design, excavation planning, and hazard mitigation while minimizing project risk.

References

Andrus RD, Stokoe KH (2000). Liquefaction resistance of soils from shear-wave velocity. Journal of Geotechnical and Geoenvironmental Engineering, 126(11), 1015–1025.

Annan AP (2009). Electromagnetic Principles of Ground Penetrating Radar. In: Jol, H.M., Ed., Ground Penetrating Radar: Theory and Applications, Elsevier, Amsterdam,1,3-40. https://doi.org/10.1016/B978-0-444-53348-7.00001-6.

Butler DK (2005). Near-surface geophysics. Society of Exploration Geophysicists.

Cardarelli E, Di Filippo, G (2009). Integrated geophysical methods for site characterization. Journal of Applied Geophysics, 68(3), 359–368.

Foti, Sebastiano, Lai, Carlo, Rix, Glenn and Strobbia, Claudio. (2014). Surface Wave Methods for Near-Surface Site Characterization. 10.1201/b17268.

Griffiths DH, Barker RD (1993). Two-dimensional resistivity imaging and modelling in areas of complex geology. Journal of Applied Geophysics, 29(3–4), 211–226.

Hack R, Huisman M (2002). Geophysical methods for engineering purposes. Geotechnical and Geological Engineering, 20(2), 151–168.

Loke MH (2015). Tutorial: 2-D and 3-D electrical imaging surveys. Geotomo Software (https://www.researchgate.net/publication/264739285_Tutorial_2-D_and_3-D_Electrical_Imaging_Surveys)

McDowell PW (2001). Engineering applications of resistivity surveys. Quarterly Journal of Engineering Geology and Hydrogeology, 34(3), 199–208.

Park CB, Miller RD, Xia J (1999). Multichannel analysis of surface waves. Geophysics, 64(3), 800-808.

Reynolds JM (2011). An introduction to applied and environmental geophysics. Wiley-Blackwell, USA.