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Enhancing Infrastructure Development: The Role of Geophysical Methods in Civil Engineering Projects

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Abstract

Geophysical engineering and civil engineering are related fields that are essential to the planning, building, and sustainability of infrastructure projects. Geophysical methods provide essential insights into subsurface conditions, enabling civil engineers to optimize infrastructure design, ensure long-term safety, and mitigate risks. The integration of geophysical techniques into civil engineering has transformed project workflows by offering non-invasive solutions for subsurface investigations, reducing the reliance on intrusive methods such as drilling and others that are disruptive to the environment. These methods are particularly valuable in high-cost infrastructure projects, such as bridges, tunnels, and dams, where understanding the subsurface is crucial for structural integrity. This study, based on a comprehensive literature review, analyzes the capabilities and applications of geophysical methods, including ground penetration radar, seismic method, and electrical resistivity in civil infrastructure projects. This study outlines the current state of knowledge and identifies potential to improve the use of geophysical techniques in civil infrastructure projects by combining findings from prior research.

Keywords: *Geophysical Engineering, Non-Invasive Method, Subsurface Investigation, Construction Monitoring.*

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INTRODUCTION

Civil engineering and geophysical engineering are interconnected fields that play a crucial role in the development and sustainability of infrastructure projects. Geophysical engineering methods can provide valuable insights into subsurface conditions, allowing civil engineers to make more informed decisions and optimize the design and construction of these infrastructure projects. The integration of these two disciplines enables a comprehensive approach to infrastructure development, ensuring the long-term viability and safety of critical public works.

Geophysical engineering is a field within Earth Science that utilizes principles and methodologies derived from physical parameters to investigate the properties of the Earth. There are two fundamental categories of Geophysics such as Global Geophysics and Applied Geophysics (Romagnolu et al., 2010). Global geophysics focuses on studying large-scale issues concerning the Earth's overall structure and dynamic processes. In contrast, applied geophysics, is more specialized and applies geophysical techniques to address challenges related to the exploration of resources such as oil, gas, water, and engineering projects. This study will focus on the application of geophysics in civil engineering projects.

In construction, costly infrastructure projects such as bridges, buildings, and tunnels frequently rely on invasive methods without fully utilizing modern non-invasive scanning techniques. Geophysical methods offer a valuable solution by enabling detailed imaging of subsurface conditions, providing critical information for engineering assessments and minimizing the need for intrusive investigations.

Geophysical engineering methods have been extensively utilized and accepted in civil engineering projects for decades, despite the allocation of significantly larger budgets to hydrocarbon exploration and mineral resource searches. The primary focus of this integration has been on geotechnical projects, where geophysical techniques are employed to investigate the often complex and variable subsurface, which serves as the foundation for large engineered structures such as dams, bridges, and buildings (CSMRS Booklet, 1992).

Geophysical engineering methods can be applied throughout the lifecycle of civil engineering projects, encompassing feasibility assessments, design optimization, construction monitoring, and post-construction evaluation. The selection of specific geophysical techniques is determined by the project stage, the study objectives, and the respective advantages and limitations of each method (Niederleithinger et al., 2015).

Throughout the past decade, the application of geophysical studies extends to the assessment of stability, infrastructure planning and monitoring, hydrological investigations, and environmental monitoring. However, the full potential of geophysics in engineering investigation is yet to be realized. Diverse methodologies have the capacity to provide vital insights into the sub-surface, encompassing details regarding the ground, its mass properties, and structural anomalies. The investigative capabilities span a spectrum, ranging from the intricacies of well-logging to the extensive traverses involved in the examination of geological structures. The benefit of a geophysical survey is that it allows gathering data over expansive areas of ground that cannot be explored directly due to the limitations of equipment and cost.

Modern geophysical methods have been widely adopted for geotechnical investigations across various fields. These techniques enhance the quality of subsurface imaging, allowing for the detection of even small variations in geological layers and subsurface features (Anderson, 2006).

METHOD

This study is based on systematic literature review that examines the application of geophysical techniques in civil engineering projects. The study synthesizes findings from peer-reviewed journal articles, technical reports, and industry publications to analyze the potential and effectiveness of various geophysical methods. To select the most pertinent reference articles for the topic, the authors used an approach that balances relevance, scope, and diversity in the reference list. This study aims to explore how non-invasive geophysical methods have been used to address the challenges and complexities associated with subsurface investigations in infrastructure projects in the design, construction, and maintenance phases of civil engineering projects.

This study examines on the used of three geophysical methods, such as ground-penetrating radar, seismic techniques, and electrical resistivity, evaluating their roles in specific civil engineering contexts, including infrastructure planning, construction monitoring, and post-construction evaluation. This study provides a comprehensive understanding of the integration of geophysics into civil engineering workflows. In addition, this study also identifies gaps in the current understanding, which could serve as valuable insight for future research efforts aimed at advancing the integration of geophysical methods into civil engineering projects and addressing persistent challenges in subsurface investigations..

RESULT AND DISCUSSION

Geophysical methods have been widely used in civil engineering projects to investigate subsurface conditions and support decision-making throughout the project lifecycle (Azahar et al., 2019). Geophysical studies offer a fundamental, non-invasive, and cost-effective approach to exploring and characterizing the Earth's subsurface, providing high-resolution data essential for a range of applications. Geophysical engineering is particularly valuable, as it allows us to investigate the unseen realms beneath the surface. By analysing surface-collected data, geophysical methods enable us to infer the underlying structures and conditions, bridging the gap left by geological maps, which depict surface features but cannot accurately reveal subsurface continuity (Kan, 2019).

Geophysical data interpretation often involves sophisticated modelling and inversion techniques, which transform raw measurements into subsurface models that delineate material properties and boundary conditions. Integrating geophysical data with conventional geotechnical testing significantly enhances the accuracy of these models, leading to more comprehensive subsurface characterization. However, limitations exist, as geophysical methods are sensitive to environmental noise and require specialized expertise for accurate interpretation (Joseph et al., 2018).

The objectives of subsurface geophysics investigations is to find a discontinuity in which one area of the sub ground differs significantly from another in terms of physical properties. Geophysical investigation serves as an indirect method for assessing both the ground and built structures. Geophysical techniques measure variations in the physical characteristics of subsurface materials, such as compressional and shear wave velocities, electrical resistivity, and Electromagnetism. A successful interpretation of geophysical survey data usually requires a solid understanding of the geological structure beneath the surface. To enhance the accuracy of this interpretation, it is essential to have sufficient direct control, often facilitated by means such as boreholes, trial pits, or other direct measurement techniques. The integration of geophysical data with these direct observations and measurements can provide a more comprehensive understanding of the subsurface conditions, leading to more reliable and informed decision-making for civil engineering projects.

The sufficient option of a specific geophysical method depends very much on the relative contrasts of the physical contrast between the target structure and the surroundings, depth extent of a target, and the nature properties as feasible by geophysical method. Petrologists and field geologists have revealed that distinctions between rocks go beyond their microscopic and macroscopic properties. They are distinguished by their molecular and physical properties as well. Thus, the rocks vary in terms of their density, magnetization, resistivity, and other characteristics in addition to their origin, structure, and texture.

The challenge is that the physical characteristics do not always translate accurately into geological condition in the subsurface. For example one sort of rock can have the same physical properties as another. Therefore, geological terminology must be used to interpret the physical properties obtained from the geophysical approach.

Geophysical engineers must understand that more caution must be taken in the interpretation and reporting of geophysical results. Geophysical studies have a significant role to play in geotechnical investigations for civil engineering projects. Geophysicists in particular must learn to be more sensitive to different interpretations that are consistent with a measurable data set and their implications for engineering (Ehlers et al., 2008).

Geophysical methods are used to investigate the near-surface features of the Earth's crust, which vary according to the physical properties, such as density, porosity, and electrical conductivity, of the underlying rocks and soils. These physical properties can provide valuable insights into the subsurface conditions, allowing for more informed decision-making in civil engineering projects. These methods can be categorized into static and dynamic approaches. Static methods involve the detection and precise measurement of distortions in a static physical field to identify the features that cause them. In contrast, dynamic methods involve sending signals into the ground and detecting the returning signals, measuring their strengths and arrival times at specific locations.

Ground Penetrating Radar Method

Ground penetrating radar (GPR) is a cutting-edge geophysical measurement technique used to investigate near-surface underground structures. This method operates on the principle of transmitting high-frequency electromagnetic pulses into the ground. Ground-penetrating radar uses a transmitting antenna to generate an electromagnetic pulse that travels into the subsurface. The pulse reflects off interfaces or scatters off point sources within the ground (Figure 1). The receiving antenna then detects the reflected and scattered energy that returns to the surface. The time it takes for the wave to travel down to an interface and return to the surface is the travel time, which is used to determine the propagation velocity of the subsurface material. (Srinaiah et al., 2022).

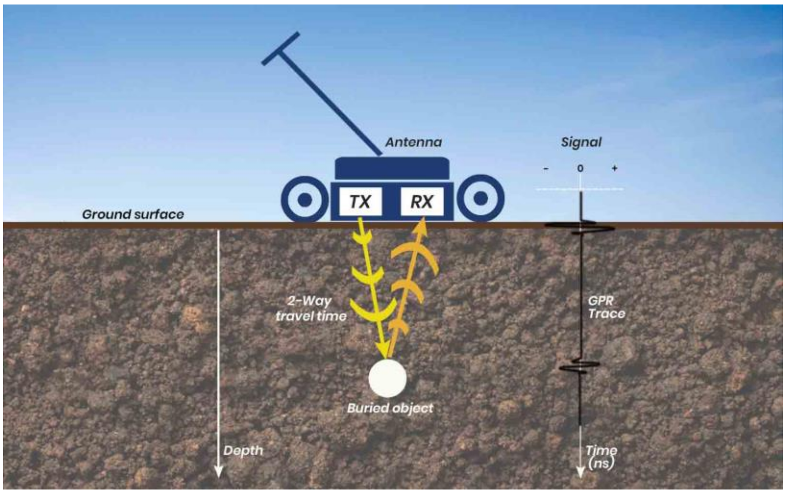

Figure 1. Ground Penetrating Radar Method Deplyoment Illustration (Troiano et al., 2024)

Seismic Method

Seismic method in civil engineering involve measuring the propagation of elastic disturbances, commonly referred to as seismic, shock, or acoustic waves, through the subsurface. These methods allow for the investigation of the Earth's interior structure and properties by analyzing the behavior of these waves as they travel through various materials and reflect or refract at boundaries (Figure 2). Seismic surveys can provide valuable information about the density, porosity, and other physical characteristics of the subsurface, which is crucial for assessing site conditions, designing infrastructure, and monitoring ground movements during construction and operation. (Srinaiah et al., 2022). Seismic methods are a key non-destructive prospecting technique that play a crucial role in geophysical investigations. Seismic methods analyze the propagation of mechanical waves through the inspected material. This allows examination of materials like concrete, determining their homogeneity and detecting any defects or anomalies. The seismic refraction method, in particular, has been widely used in civil engineering applications to map the depth to bedrock, identify soil/rock interfaces, and characterize the properties of subsurface materials (Allalan et al., 2022)

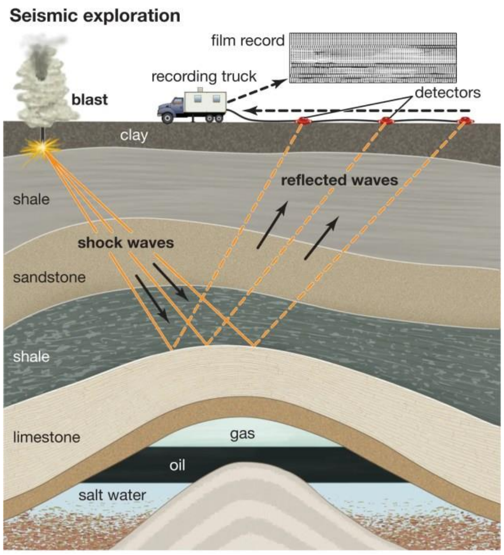

Figure 2. Seismic Method Deployment Illustration. **(USGS,** https://www.epa.gov/environmental-geophysics/seismic-refraction)

Seismic methods can be categorized into two main types based on the mode of wave propagation: surface reflection and direct transmission. These waves are reflected or refracted at boundaries defined by variations in density and/or deformation properties.

Seismic methods can effectively evaluate the internal structure of materials within a slope. However, practical challenges with positioning geophones and sources may sometimes make the method impractical. Refraction seismic studies have been commonly used in geotechnical investigations.

Electrical Resistivity Method

Geophysical resistivity method harness the Earth's response to the flow of electrical current. By transmitting an electrical current through the ground and measuring the resulting potential difference between two electrodes, we can directly evaluate the electrical impedance of the subsurface materials illustrated in figure 3. This approach provides valuable insights into the subsurface characteristics and properties. The electrical resistivity of subsurface materials is a fundamental property that depends on the magnitude of the applied current, the measured potential difference, and the arrangement of the electrodes used to make the measurements.

This resistivity data can provide valuable information about the subsurface geological conditions, such as the presence of different soil or rock types, groundwater levels, depth to bedrock, detecting anomalies and potential subsurface structures (Tsai et al., 2021) (Azahar et al., 2019). Electrical resistivity is a fundamental property that quantifies the material's ability to impede or oppose the flow of electrical current through it. Highly resistive materials, such as insulators and ceramics, impede the flow of electrical current, as they have a high resistance to the passage of electric charge. In contrast, low-resistivity materials, like metals and conductive materials, facilitate the easy passage of electric charge due to their high electrical conductivity. (Rhett, 2001). The inverted resistivity model produced from field measurements can be used to identify potentially anomalous zones within the subsurface, which may indicate the presence of buried obstacles, voids, or zones of weathering (Rabinah et al., 2020).

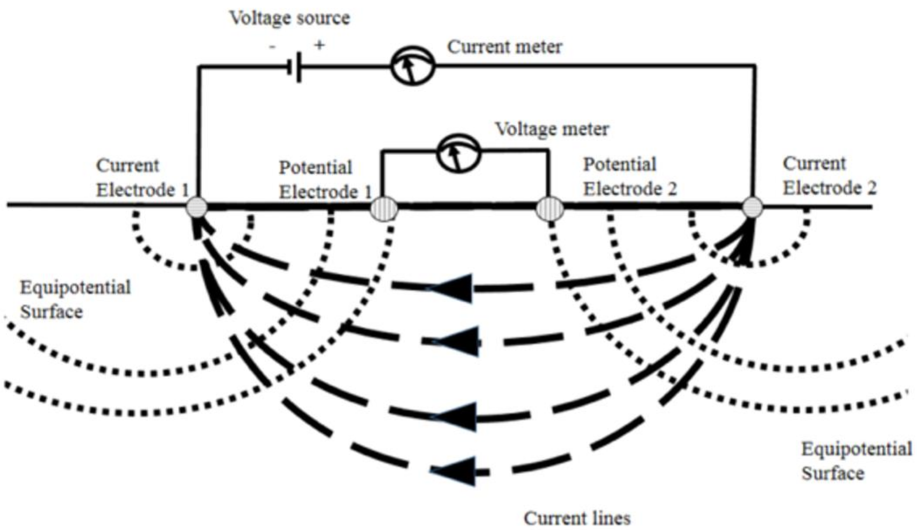

Figure 3. Resistivity Method (https://subsurfaceinsights.com/electrical-resistivity-method/)

Current Aplication In Civil Engineering

In civil engineering, a structure is a network of interconnected elements that supports external loads. Additionally, there is a relationship between the structure and its interaction with the soil. This interaction demonstrates the genuine interconnectedness of civil engineering and geophysics, particularly concerning the physical and chemical evolution of soils.

Several physical properties and analytical techniques are employed to evaluate soil structure and related subsurface components. Two distinct approaches exist for retrieving subsurface information: direct and indirect methods. The following consist of direct methods:

1. Geologic field observation, which includes examining in situ materials, man-made structures, groundwater levels, etc;
2. Geophysical methods to investigate subsurface structures;

3. Using borings, test pits, and trenches, to obtain representative samples of the in situ materials; and
4. Other geotechnical field tests, such as standard penetration test (SPT), that can be correlated with other engineering parameters.

Modern structures must maintain equilibrium against both static and dynamic pressures in the soil. The interaction of these soil and structural forces can lead to instability. Static forces cause issues like slope instability, settlement, and bearing capacity problems. Dynamic pressures result in liquefaction and soil amplification, further disrupting the balance.

In civil engineering, estimating the maximum potential earthquake motions at a site is crucial. Geophysical approaches, such as seismic microzonation studies, can provide valuable insights for urban planning, while the soil/rock model relies on geotechnical, geological, and geophysical data (Manzunzu et al., 2024). Modelling the soil/rock media beneath the civil structure and the geotechnical characteristics of the various materials present at the site are the main objectives of the site/soil investigation procedure in civil engineering. Locating and assessing the impact of both man-made and geological risks, such as abandoned mining shafts, on every facet of a planned construction project, is crucial as well as estimating the faults, zones of cracked rock, natural cavities, etc (Ozcep, 2011)

In the context of building construction, geophysical methods can be employed for exploratory purposes to yield valuable insights into the early identification of potentially hazardous subsurface conditions. The primary sources of risks in civil engineering originate from undetected shallow structures, such as voids and/or variations in the foundation materials. Here are a few examples of civil engineering issues that can be investigated utilizing geophysical approaches.

Pavements

An evaluation of the state of the supporting ground and the roads is necessary for any transportation network to operate effectively over the long run. Although intrusive investigations yield important information, they are expensive, time-consuming, and have the drawback that data is discrete in an extremely variable setting.

The extent of maintenance and reconstruction that is required for existing road structures varies. Their interior construction can be extremely intricate, with multiple layers and parts made of variously aged and condition-varying materials. It is crucial to properly and efficiently monitor the structural characteristics of roadways in order to maximize their structural reliability and increase the amount of time that they can be used. When planning maintenance and rehabilitation activities, early and precise identification, localization, and assessment of problems or defects in pavements are very valuable as they can greatly slow the spread of deterioration and lower maintenance costs.

Because in-situ density is an excellent predictor of future performance, it is considered one of the most critical controls to ensure that a pavement being put is of high quality in roadway asphalt pavement (Xia and Huston, 2016). Nevertheless, in-situ techniques only yield density estimates at specific sampling points and are disruptive. Additionally, they are slow and could impede traffic flow. Their applicability for pavement profile assessment during route construction and lifetime maintenance are limited by these disadvantages.

GPR is one of the most significant instruments for enabling subsurface structural characterizations among all Non-Destructive Test (NDT) techniques. The most advanced method for inspecting pavements is to employ 3D GPR arrays, which enable analysis to be expanded to include the road's traversal direction. Road engineers and maintenance personnel will find a lot of important information in these perpendicular cross-sections.

Concrete

Concrete is the most widely utilized man-made substance on Earth. Concrete is a structural material used in building that is made up of aggregate and bonded together by water and cement. Concrete is a common construction material used in buildings, bridges, highways, and dams. Structural applications, driveways, basements, pavement, curbs, pipelines, and drains are just a few of its uses.

Even though concrete is a material that is naturally resilient, after time, it deteriorates. This is because different concrete mixture proportions, the presence and placement of reinforcement, and the detailing, putting, finishing, curing, and protection the concrete receives all affect how long the concrete lasts under a given set of exposure conditions.

The most popular non invasice method for evaluating the quality of concrete is ground penetrating radar (GPR). It does not require coring or breaking out, and it can show a multitude of interior detail. The survey data are displayed as sections, elevations, and engineering CAD layouts that are simple to comprehend. The use of high frequencies from GPR can be used for several purposes, such as:

a. Determine the location of cable ducts, rebars.
b. Assess the reinforced concrete and brickwork, delamination the small voids and other defects.
c. Determining the concrete cover thickness, dimensions of slab bands, and the location of PVC conduits.

Embankments

Geotechnical infrastructure, such as embankments, canals, earth dams, sea walls, and flood control structures, necessitate ongoing surveillance and upkeep to detect potential zones of failure and accommodate the effects of ground settlement. Furthermore, extreme weather occurrences that precipitate prolonged periods of drying or saturation pose a threat to the stability of these earthen constructions. Geophysical methods could be utilized to study about the embankment condition.

a. Electrical resistivity is sensitive to lithological and mineralogical variability, as well as changes in soil moisture content. In areas with constant lithology and minerals, changes in sequential electrical resistivity studies will be caused by underground water movement and consequent moisture content variations. Electrical resistivity has emerged as a crucial engineering property, as it can be leveraged to derive the volumetric moisture content, a critical parameter in the calculation of soil moisture deficit. Electrical resistivity is a fundamental physical property that quantifies a material's ability to impede the flow of electrical current. This knowledge is particularly valuable for assessing the stability and performance of geotechnical infrastructure, such as earthen embankments and dams, which can be significantly impacted by changes in soil moisture content over time. Additionally, resistivity imaging can be utilised to track the temporal and spatial changes in moisture content, allowing for the real-time evaluation of plasticity changes, such as those brought on by prolonged rainfall or drought. (Gunn et al., 2015).
b. Seismic methods provide very important information about the elastic properties within embankments and levees. Non-invasive surface wave surveys yield depth profiles that can be used to create ground models for evaluating the state of foundations. Characterising heterogeneity is important in connection to the stability of designed backfill and the lifespan deterioration in ageing utility and other infrastructure, as stiffness throughout earthworks governs behaviour under static and dynamic stresses. Surface wave methods are commonly employed to detect the boundaries between fine-grained and coarse-grained fill materials within an end-tipped embankment. Additionally, Multi-Channel Analysis of Surface Waves is utilized to evaluate the low stiffness (Gmax) values of the embankment fill (Gunn et al., 2016).
c. Ground Penetrating Radar (GPR) can help find animal burrows on monitoring river levee, which could cause levee failures due to plumbing. Because GPR is an extensive investigation method that allows one to quickly cover a large area and locate voids that are difficult and expensive to locate using other intrusive methods, as well as because it returns detailed information about the possible presence of voids and discontinuities within embankments, its manageability and non-invasiveness make it particularly well-suited for this application.

Tunnels

When it comes to tunnel applications, geophysical methods can be used in the design phase to determine the mechanical properties of the ground (using seismic profiles or borehole methods); in the construction phase as a means of ensuring quality and mitigating hazards (such as void detection or grout thickness control); or even in the tunnel's service phase.

Tunnel engineers require a diverse set of inspection techniques for regular monitoring of tunnel linings. The main approach involves visually identifying any anomalies. Once a specific area needing attention is pinpointed, more advanced methods are typically necessary. Ground Penetrating Radar (GPR) is frequently chosen as a tool to locate subsurface defects and identify moisture in concrete, which can contribute to reinforcement corrosion. The swift operation of GPR and its responsiveness to alterations in surface dielectric properties make it well-suited for integration with laser scanning. Ground Penetrating Radar (GPR) is employed to assess the quantity of reinforcing layers, spacing between reinforcements, and the depth of cover. It is also utilized to identify regions where moisture or water is trapped, as well as to measure liner thicknesses, detect voids behind the liner, and determine moisture concentration.

Buildings

The primary applications of Ground Penetrating Radar in building inspection include locating concealed objects and structures to support heritage conservation and construction compliance, mapping deterioration as an input for preventive/ad-hoc maintenance decisions, and assessing structural damage after natural disasters such as flooding, earthquakes, and landslides. GPR is one of the tools that can be utilized to evaluate the post-disaster safety of buildings (Lai et al., 2017).

The assessment of building deterioration is a critical application area that provides substantial benefits for occupied structures. While some evaluation methods may disrupt the daily activities of residents and tenants, making them less desirable, Ground Penetrating Radar (GPR) stands out as a minimally intrusive alternative. It allows for effective condition assessment without significantly affecting the occupants' routines. (Gracia et al., 2008). Building maintenance and repair are also costly, and in many cases, owners tend to respond only when visible damage or failure occurs. An early identification of problems using non-destructive testing methods and a focus on areas of minor but long-term concern is a more prudent approach

Kannan (1993) recommends the use of Ground Penetrating Radar (GPR) during the site investigation and formation phases of building projects. This approach aids in identifying zones near active sinkholes and provides critical data for structural calculations related to foundation design. However, the number of such applications remains limited due to the difficulty in accessing the subsurface with the GPR antenna. Borehole GPR holds potential for assessing foundations, but limited use of this method for foundations has been reported. Most applications have focused on tunnels and geologic assessments.

Regarding mechanical damage, natural disasters such as earthquakes and landslides can cause significant damage to buildings. In the aftermath of these events, GPR has proven to be a valuable tool in supporting the diagnosis and rehabilitation process, as well as in identifying the possible causes of visible damage.

CONCLUSION

We believe there is immense potential for strengthening interdisciplinary collaboration between the fields of geophysics and non-destructive testing in civil engineering. Incorporating innovative geophysical methods could help address existing constraints, such as the challenge of imaging small structures or subtle changes. Conversely, conducting measurements on concrete structures could serve as valuable scale experiments to validate geophysical algorithms or simulation models.

Future research should focus on further developing strong, collaborative partnerships between civil engineers and geophysicists. This interdisciplinary approach would enable the identification and addressing of critical problems that lie at the intersection of these fields. By leveraging the expertise and insights from both disciplines, researchers could tackle challenging issues more comprehensively and develop innovative solutions that advance the civil engineering and geophysics domains.

RECOMMENDATIONS

There remains significant potential for advancing the integration of geophysical methods in assessing civil infrastructure projects. Future research should focus on demonstrating the full capabilities of these techniques in various project contexts. Expanding the scope of studies to include geotechnical and geophysical methods, cost-benefit analyses, and real-time monitoring applications can provide valuable insights. In addition, addressing adoption gaps through training programs and collaboration between geophysics and civil engineering can promote broader and more effective use of these methods.

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