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The Use of Ground Penetrating Radar in Road and Bridge Deck Evaluation: A Review

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Abstract

Ground Penetrating Radar (GPR) is a non-invasive geophysical method widely used for imaging near-surface subsurface features, providing detailed insights into dielectric properties. Bridges, critical for infrastructure, face threats from natural elements and traffic, compromising their structural integrity. Non-destructive testing (NDT), including GPR, is essential for monitoring and preserving bridge health, ensuring safety and minimizing repair costs. This review comprehensively explores GPR's application in assessing road and bridge decks. It surveys advancements in GPR technology for bridge engineering, emphasizing its ability to characterize key components like slabs, beams, and pillars. Drawing from scholarly journals and conferences, the review assesses GPR's effectiveness in evaluating masonry and reinforced concrete structures. It examines methodologies used in practical settings, highlighting innovations in data processing and visualization that enhance GPR's diagnostic capabilities. Case studies demonstrate GPR's precision in locating reinforcement bars and assessing concrete cover, particularly in detecting moisture ingress. The review advocates systematic approaches to data collection, processing, and interpretation to enhance bridge health assessments and ensure long-term structural reliability. The review concludes by discussing the limitations of GPR in road and bridge deck evaluation and proposes potential solutions to ensure its continued effective use.

Keywords: Ground Penetrating Radar, GPR, Bridge Inspection, Non-destructive Testing, Structural Health Monitoring, Infrastructure Upkeep

1. Introduction

The Ground Penetrating Radar (GPR) is a non-invasive, non-destructive evaluation method that allows for the analysis of subsurface materials and structures without actually altering or damaging it. It uses radar to image the subsurface by transmitting electromagnetic waves into the ground or material which then reflects back to the surface, providing information about the subsurface structure.

Roads and bridges are vital assets that should be looked after but not in a ruinous manner. Any method for assessing and monitoring these structures should also be cost effective, efficient and fit for purpose, and the GPR system is qualified by all these requirements.

The use of Ground Penetrating Radar (GPR) in road and bridge deck evaluation involves the application of GPR technology in the assessment of the conditions and integrity of roads and bridges. The journey of GPR in civil engineering began in the 1970s. Initially developed for geological and archaeological purposes, its potential in non-destructive testing (NDT) caught the attention of civil engineers. Early GPR systems, as described by Daniels (2004) [10], were basic but demonstrated the potential of radar waves in detecting subsurface features, setting the stage for future infrastructure applications.

The 1980s marked the beginning of GPR's application in road evaluation. Researchers identified its potential for measuring pavement thickness and identifying subsurface anomalies like voids and moisture. Morey (1998) [16] was instrumental in validating GPR's effectiveness in these applications, demonstrating that it could provide continuous subsurface data non-invasively across extensive roadway sections. This era saw enhancements in hardware and signal processing, significantly improving the resolution and reliability of GPR surveys.

In recent times, GPR is applied in road and bridge deck evaluation with the objectives to detect defects in the deck such as structural cracks, delamination and voids, identify moisture ingression and water content, evaluate pavement and bridge deck thickness, map reinforcing bars and estimate concrete cover conditions among others.

Maser and Scullion (1991) [15] conducted systematic studies showcasing GPR's effectiveness in identifying areas of deterioration needing maintenance. Their research highlighted GPR's advantages over traditional methods, which often involved destructive testing or labor-intensive inspections.

The foundational work by Maser and Scullion (1991) [15] and others established GPR as a reliable tool for bridge deck evaluation. This led to its adoption by various transportation departments and agencies, with standardized procedures and best practices being developed for GPR-based bridge inspections.

GPR provides accurate, high resolution images of the subsurface structure, enabling engineers and infrastructure managers to make informed decisions about deck maintenance, repairs and upgrades in order to ensure the safety, durability and sustainability of the infrastructure.

GPR has been used in various road and bridge monitoring activities. An example is the assessment of the Forth Road Bridge which is a suspension bridge located at East Central Scotland. The test was carried out by Amir M. Alani, Morteza Aboutalebi and Golchan Kilic in 2011.

An observation made is the fact that the GPR on its own cannot be used to ascertain the complete health conditions of a road or bridge deck but it has been proven successful in certain applications. This is because each NDT technique provides different information about the road or bridge structure. It therefore has to be used in conjunction with other non-destructive techniques (NDT) to give a more accurate and widespread assessment. (Annan *et al*., 2002; Parrillo and Roberts, 2006 [18]).

The application of GPR is also relevant in other fields such as mineral exploration, detection of oil and gas leaks, agricultural research, forensic investigation, archaeology, geotechnical engineering, waste detection and many others.

This review aims to provide a comprehensive overview of GPR applications in road and bridge deck evaluation. It will examine recent advancements in GPR technology, focusing on its ability to characterize key structural components and detect common defects. The review will synthesize findings from scholarly journals, conference proceedings, and technical reports to assess GPR's effectiveness in evaluating both masonry and reinforced concrete structures. Methodologies used in practical settings will be examined, highlighting innovations in data processing and visualization techniques that enhance GPR's diagnostic capabilities. The limitations of GPR in road and bridge deck evaluation and possible solutions to ensure the continuous use of the GPR system will also be discussed.

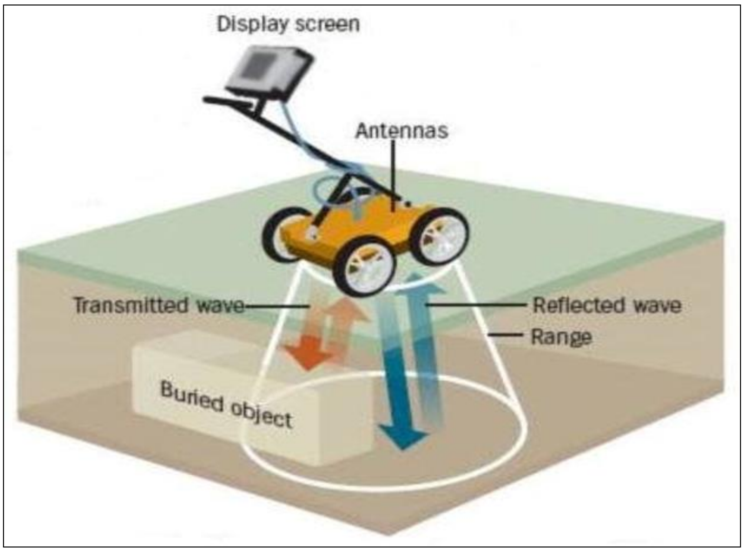

Fig 1: The diagram illustrate how the GPR system transmits electromagnetic waves into the ground and receives reflections from subsurface interfaces (GPR) (Abdulrazzaq, 2019) [2]

2. Literature Review

Ground Penetrating Radar (GPR) has been extensively studied and applied as a non-destructive evaluation (NDE) technique for assessing the condition of road and bridge decks. This section synthesizes findings from a wide range of published studies, highlighting the evolution, capabilities, and limitations of GPR in infrastructure assessment.

2.1 Applications of GPR in Bridge Deck Evaluation

2.1.1 Detection of Delamination and Corrosion

Early foundational studies by Maser and Scullion (1991) [15] demonstrated GPR’s ability to detect delamination in bridge decks by identifying hyperbolic reflections caused by separation between concrete layers. Subsequent research by Daniels (2004) [10] and Alani *et al*. (2011) confirmed that GPR can effectively map corrosion-induced deterioration by detecting changes in electromagnetic wave velocity and signal attenuation caused by rust formation on reinforcing bars.

More recent work by Al-Hameedawi *et al*. (2022) [4] applied advanced signal processing techniques to improve the accuracy of corrosion detection in reinforced concrete bridge decks, showing that combining amplitude and phase information from GPR signals enhances defect characterization. Similarly, Liu *et al*. (2018) employed machine learning algorithms to classify corrosion severity levels based on GPR data, improving the objectivity of assessments.

2.1.2 Moisture Content and Structural Geometry Assessment

GPR has been used to assess moisture ingress in bridge decks, which is critical for predicting freeze-thaw damage and corrosion risk. Alani, Aboutalebi, and Kilic (2011) applied GPR to the Forth Road Bridge, successfully identifying areas of high moisture content that correlated with known deterioration zones. This was supported by work from Tosti *et al*. (2017), who demonstrated that GPR dielectric property measurements can quantify moisture content in concrete with reasonable accuracy.

In addition to moisture detection, GPR has been employed to map bridge geometry and identify structural anomalies. Studies by Sangoju *et al*. (2018) [20] used GPR to measure concrete cover thickness and locate reinforcing bars, aiding in structural evaluation and retrofit planning.

2.1.3 Defect Detection and Material Characterization

Sareenketo and Scullion (2000) provided a comprehensive review of GPR's ability to detect subsurface defects such as cracks, voids, and delamination in pavement and bridge decks. Their work highlighted GPR's sensitivity to dielectric contrasts caused by such defects.

Further investigations by Goodman *et al*. (2013) showed that combining GPR with ultrasonic pulse velocity testing improves the detection and characterization of microcracks and voids in concrete. This multimodal approach addresses limitations of GPR resolution and increases reliability.

Material characterization studies, such as those by Annan *et al*. (2002), demonstrated that GPR can estimate dielectric permittivity and electrical conductivity of pavement layers, which are indicators of material condition and degradation.

2.1.4 Subgrade Evaluation and Pavement Layer Thickness

Timo Sareenketo and Tom Scullion (2000) applied GPR for nondestructive evaluation of subgrade soil properties, pavement layer thickness, and base course quality. Their research showed that GPR can accurately measure layer thicknesses, detect subsurface defects, and assess frost susceptibility of soils beneath pavements.

Complementing this, research by Wang *et al*. (2019) [22] utilized GPR to monitor the compaction quality of asphalt layers during construction, demonstrating its potential for quality control and assurance.

2.1.5 Quality Control and Post-Repair Monitoring

Post-repair evaluation using GPR has been documented by Parrillo and Roberts (2006) [18], who used GPR to verify the integrity of repaired bridge decks and monitor defect progression over time. Their findings suggest that GPR is effective for longitudinal monitoring, enabling proactive maintenance planning.

2.2 Synthesis of Findings

Across these studies, GPR consistently emerges as a valuable, rapid, and non-destructive tool for infrastructure evaluation. Its ability to provide continuous subsurface imaging without damaging structures is a major advantage over traditional methods such as core sampling or visual inspection.

However, the literature also reveals that GPR's effectiveness depends heavily on factors such as antenna frequency selection, material properties, moisture content, and operator expertise. For example, lower frequency antennas penetrate deeper but provide lower resolution, while higher frequencies offer better resolution but shallower penetration (Daniels, 2004) [10].

Integration with other NDT methods (e.g., ultrasonic testing, infrared thermography, electrical resistivity) is frequently recommended to overcome individual limitations and improve diagnostic accuracy (Annan *et al*., 2002).

Recent advances in data processing, including machine learning and advanced signal analysis, are enhancing GPR's capability to interpret complex data sets, reduce operator dependency, and quantify defect severity (Liu *et al*., 2018; Di Maio *et al*., 2015).

2.3 Gaps and Challenges in Current Research

Despite extensive research, several critical gaps remain:

Data Interpretation and Standardization: There is a lack of universally accepted standards and protocols for GPR data acquisition, processing, and interpretation in bridge and road deck evaluation. Variability in methodologies leads to inconsistent results across studies and projects.

Quantitative Defect Assessment: Most studies focus on qualitative or semi-quantitative defect detection. More research is needed to develop reliable quantitative metrics for defect size, depth, and severity from GPR data, enabling better structural health assessments (Parrillo & Roberts, 2006) [18].

Long-Term Monitoring: Few studies have systematically evaluated GPR's effectiveness for long-term monitoring of infrastructure degradation. Research into how GPR data can predict future performance and deterioration trends is limited (Alani *et al*., 2011).

Environmental and Material Variability: The influence of environmental factors (temperature, moisture variability) and heterogeneous material properties on GPR signal behavior requires further investigation to improve data interpretation accuracy (Tosti *et al*., 2017).

Integration with Emerging Technologies: While some studies have explored combining GPR with other NDT techniques, comprehensive frameworks for multi-sensor data fusion and automated defect classification remain underdeveloped (Faris *et al*., 2024).

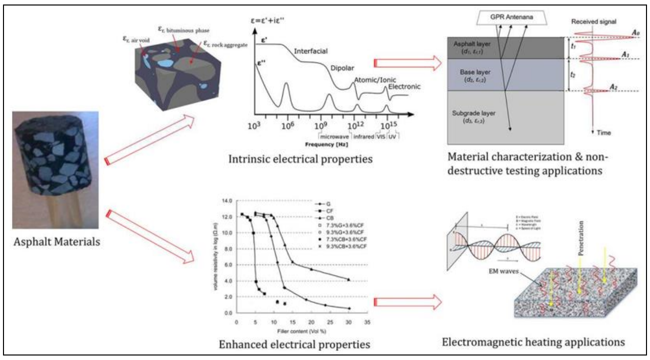

Fig 2: Shows the relationship between the electrical properties of asphalt materials and their applications in non-destructive testing using Ground Penetrating Radar (GPR), as well as in electromagnetic heating. The diagram illustrates how intrinsic and enhanced electrical properties influence material characterization and signal response in layered pavement systems (Feng, C., & Balieu, R., 2020) [12]

2.4 Types of Ground Penetrating Radar (GPR)

There are several types of Ground Penetrating Radar (GPR) systems. These types of GPR systems vary in their operating principles, frequencies, and applications, allowing users to choose the most suitable system for their specific needs.

They include; Pulse Radar which transmits high-power electromagnetic pulses intoxicated the ground used in utility mapping and subsurface imaging, Frequency Modulated Continuous Wave (FMCW) Radar which transmits a continuous wave with a swept frequency used for high-resolution imaging and bridge deck evaluation, Stepped Frequency Continuous Wave (SFCW) Radar that transmits a continuous wave with a stepped frequency used in road inspection and concrete assessments, Synthetic Aperture Radar (SAR) GPR which uses advanced processing to create high-resolution images used for HRI and landmine detection, Ultra-Wideband (UWB) GPR, Ground-Coupled GPR, Air-Coupled GPR, Horn Antenna GPR, Array GPR, Bistatic GPR, Multistatic GPR, and GPR with GPS system which integrates GPS for precise location and mapping.
Each system is applied for different needs for road and bridge deck evaluation or other scientific research.

2.5 Theoretical Backgrounds and Causes of GPR Reflections

The material properties that control the behaviour of electromagnetic energy in a medium are dielectric permittivity(e), electrical conductivity(r) and mag-netic permeability(l). When an alternating electric field is applied to a material, those electric charges that are bound, and, therefore, unable to move freely, still respond to the applied field by undergoing a small amount of displacement. When the resulting internal electric field balances the external electric field, the charges stop moving (Olhoeft, 1998). This charge separation in distance is called polarisation and can be of various types (Powers, 1997): Circular orbits of electrons become elliptical (electronic polarisation), charged molecules undergo slight distortion (molecu-lar polarisation), neutrally charged dipole molecules rotate into alignment with the applied field (orienta-tional polarisation), and ions accumulate at interfaces (interfacial polarisation). Polarisation processes store electric field energy. The amount stored during each cycle of the alternating electric field determines the real dielectric permittivity at that frequency (Powers,1997). In addition, a small amount of energy is lost as heat due to resistance to the transportation of charge resulting from polarisation processes.The amount of energy dissipated determines the imaginary compo-nent of the dielectric permittivity at that frequency (Powers,1997). These properties influence how GPR signals propagate and reflect, providing valuable information about subsurface features and material composition. The real and imaginary dielectric permittivities are often quoted relative to the dielectric permittivity of free space (i.e.a region where there is no matter and no electromagnetic or gravitational fields) Dielectric permittivity is measured in units of electrical capacitance (farads) per metre, and rep-resents a measure of the material's ability to store electrical charge.
Dielectric permittivity is in part dependent upon frequency of the applied, alternating electric field (Powers,1997; Olhoeft, 1998). At low frequencies, charges move the full distance required to balance the applied field, but only spend a fraction of the time moving and the rest waiting for the field to reverse (Olhoeft,1998). This results in maximum energy storage and minimum energy loss. At high frequencies, polarity reversals occur much more quickly and charge movement may not be complete before the field reverses. This results in charge storage proportional to the distance moved and a proportionally small energy loss through dissipation (Olhoeft,1998). At a certain intermediate frequency, a charge will move the full distance required to balance the external field in the same time as one cycle of that field. This will produce maximum energy loss and energy storage that is an average of the high and low frequency limits (Powers,1997; Olhoeft,1998). Clearly, each polarization process will vary in its ability to respond to the applied electric field and the net effect will be very much dependent upon the medium involved.

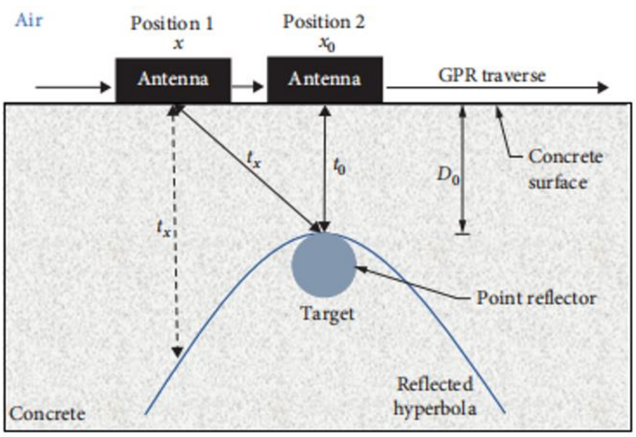

Fig 3: The reflection model for GPR wave propagation and reflection with consideration of antenna separation (Cham and Lai, 2023) [8]

2.6 GPR Materials and Methods Employed in Road and Bridge Deck Evaluation

In the employment of GPR in road and bridge deck evaluation to detect potential problems, such as delamination and corrosion, some of the GPR method and materials used includes Radar pulses which are sent to the structure via an antenna, and the reflections are recorded by a receiver, data processing software such as RADAN (GSSI) and REFLEX (Sandmeier company) are used to process the data and create maps and 3D models, Global Navigation Satellite System (GNSS) which is connected to GPR to control the distance trace range and measure the distance traveled, Antennas with different central frequencies (e.g., 1500 MHz, 2.6 GHz), Post-processing algorithm used to improve the quality of the data and create detailed images of subsurface structures, Microwave tomographic approach applied in the creation of detailed images of subsurface structures based on variations in dielectric properties, Step Frequency GPR (SF-GPR) emit radar signals at discrete frequencies across a range, and by analyzing the reflected signals, it is possible to create subsurface images, Fuzzy sets modeling for developing a bridge slab condition rating methodology.

2.7 Successful Applications of GPR in Road and Bridge Deck Evaluation

2.7.1 GPR for Bridge Deck Evaluation

Ground Penetrating Radar (GPR) has been applied successfully in conjunction with other NDT in the assessment and monitoring of the health of roads and bridges.
One of the successful applications was in the assessment of the Forth Road Bridge located at East Central Scotland. The bridge provides access from the capital city of Edinburgh to North Queensfery.

The GPR survey was performed using the RIS HI-BrigHT Bridge High resolution Tomography, see Fig. 2. Designed specifically for the inspection of bridge decks, this high frequency array antenna system is lightweight and maneuverable yet provides high quality, densely sampled data. Denser sampling produces higher quality tomography, and three dimensional (3D) images assist considerably in the interpretation of data.

The system is composed of an array of eight horizontally polarized 2 GHz channels spaced at 10 cm intervals, mounted on a lightweight and highly maneuverable trolley and powered by a large, 24 Ah 12 V battery (RIS Fast Wave control box — DAD which allows driving larger arrays at greater speed). The additional speed also allows for greater stacking (averaging) which gives a better resolution and at the same time a slightly deeper penetration.

The DAD FastWave is controlled by IDS K2 FastWave acquisition software running on a Panasonic Tough Book CF19. The K2 FastWave SW makes the collection of radar data simple. It features a signal calibration and diagnostic check for the radar, and offers the facility to insertvscan coordinates and interface with GPS. The RIS Hi-BrigHT was specifically designed to work in conjunction with advanced software processing allowing the detection of shallow features and the structure's condition. It was particularly intended for the concrete assessment of bridges, to detect the thickness of layers, shallow utilities and drainage, location and spacing of rebar, and moisture penetration and delamination.

The survey was performed by pushing the system in an 80 cm grid, producing 10 cm spacing between scans. These scans can be interpreted to produce images and recover information about the condition of the structure's constituent materials.

The main objectives of this survey were as follows:

- Estimation of thicknesses of different structural layers of the bridge deck
- Location of shallow utilities and drainage
- Location and spacing of rebar
- Possible moisture penetration and delamination.

Data processing was performed using the IDS GRED data analysis software. The software provides a two-dimensional (2D) tomography of the underground layers and a 3D view of the surveyed area. The capability of merging on the same tomographic map datasets collected along both longitudinal and transversal scans considerably increases the reliability of the results of the analysis. The software allows the development of optimised processing macro which can be applied to either all or subsets of the data. It also features automatic hyperbola detection, layering capabilities, and transfer to CAD. By performing this interpretation on several B-scans side by side it is possible to build up a picture of the conditions inside the bridge.

The exact data processing procedure included; background removal, set start time/zero position, leading to some filtering and sometimes adjusting the gain. The B-scan presented is in fact a longitudinal section down the centre of the perceived damaged area, identified by the red line in the horizontal section (C-scan). In the section represented by the red line (at approximately 25 cm depth) the concrete in "good" condition is represented by lighter contrast and the rebar can be clearly seen. The area of possible moisture is also identified by a patch of reduced contrast.

The images in Fig. 3 show the expansion of a possible moisture affected area at reducing depths: In the first instance, one may interpret this deteriorated area as an area of subsidence in the bridge deck as there is a change in the level of rebar within this area. However, when this area was excavated later it was revealed that there is no structural subsidence whatsoever. This change of signal attenuation is basically due to the presence of moisture which has penetrated well below the upper rebar layer of the bridge deck. The presence of moisture was confirmed during the excavation. A similar phenomenon presented itself during the processing and interpretation of the data collected from the Pentagon Road Bridge, the second case study presented in this paper. Due to the density channels of the RIS Hi-BrigHT, it is possible to recover large quantities of information during a radar acquisition. This gives a high level of confidence in the data acquired as well as enabling images of exceptional quality to be produced, which aids data interpretation. It also allows more advanced processing techniques to be performed such as the mathematical calculation of the areas with higher than average attenuation (absorption of the radar signal), producing a 2D map of the moisture levels within the bridge. (Amir M. Alani, Morteza Aboutalebi, Golchan Kilic, 2013) [3].

2.7.2 GPR for Road Deck Evaluation

Rural roads are exposed to an increased risk for geotechnical instability. Ground-Penetrating Radar (GPR) for geotechnical inspection of pavement and sub-pavement layers was proposed for the assessment of E18 highway located at Norway, USA. The test was carried out in 2011. A three-step protocol has been calibrated and validated to allocate efficiently and effectively the maintenance funds. In the first step, the instability is localised through an inspection at traffic speed using a 1-GHz GPR horn launched antenna. The productivity is generally about or over 300 Km/day. Data are processed offline by automatic procedures. In the second step, a GPR inspection restricted to the critical road sections is carried out using two coupled antennas. One antenna is used for top pavement inspection (1.6 GHz central frequency) and a second antenna (600 MHz central frequency) is used for sub-pavement structure diagnosis. Finally, GPR data are post-processed in the time and frequency domains to identify accurately the geometry of the instability. The case study shows the potentiality of this protocol applied to the rural roads exposed to a landslide. (F. Benedetto and F. Tosti, 2011).

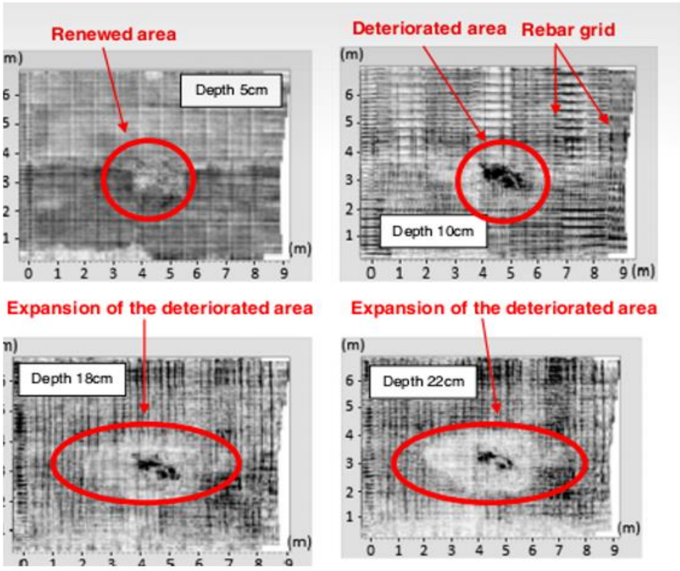

Fig 4: Depiction of affected and good areas of the bridge deck (Alani *et al*., 2013) [3]

2.8 Challenges Encountered with Using GPR

2.8.1 Challenges in GPR Data Acquisition

GPR signals are susceptible to noise and interference from various sources, including electromagnetic interference, thermal noise, and instrumental noise (Daniels, 2004) [10]. GPR data quality can be affected by factors such as antenna frequency, survey speed, and soil moisture content (Annan, 2009) [6]. GPR signals attenuate rapidly with depth, making it challenging to penetrate deep into the material (Daniels, 2004) [10].

2.8.2 Challenges in GPR Data Analysis and Interpretation

GPR data requires sophisticated processing techniques to remove noise and correct for instrumental effects (Liu *et al*., 2015). Interpreting GPR data requires expertise in radar theory, signal processing, and materials science (Yelf, 2004) [25]. Identifying targets and distinguishing them from clutter and noise can be challenging (Saarenketo *et al*., 2010) [19].

2.8.3 Challenges in GPR Equipment and Antenna Design

Antenna frequency and size affect the resolution and depth of penetration, requiring a tradeoff between the two (Daniels, 2004) [10]. Antenna design can affect the directivity and sensitivity of the radar signal (Annan, 2009) [6]. GPR equipment can be expensive and bulky, limiting its portability and accessibility (Liu *et al*., 2015).

2.8.4 Challenges in GPR Applications

GPR signals can be affected by soil and material variability, including electromagnetic properties and moisture content (Saarenketo *et al*., 2010) [19]. Complex targets, such as those with multiple layers or irregular shapes, can be challenging to detect and interpret (Yelf, 2004) [25]. Environmental factors, such as temperature and humidity, can affect GPR signals and data interpretation (Annan, 2009) [6].

3. Discussion

This review aimed to investigate the effectiveness of Ground Penetrating Radar (GPR) in evaluating road and bridge deck conditions, with a focus on detecting defects, deterioration, and thickness. The literature search yielded a comprehensive overview of the current state of knowledge in this field. The findings suggest that GPR is a promising non-destructive testing technique for road and bridge deck evaluation, with high accuracy in detecting various types of defects and deterioration. The studies demonstrated the versatility of GPR in assessing different types of infrastructure, including concrete and asphalt roads, bridges, and tunnels.

However, the review also revealed some notable gaps and limitations in the existing literature. While GPR has shown excellent potential in detecting defects and deterioration, there is a need for further research on its application in complex infrastructure systems, such as those with multiple layers or varying material properties.

This discussion will synthesize the findings and examine the strengths and limitations of GPR in road and bridge deck evaluation, discuss the potential applications and limitations of the technique, and highlight the research gaps that need to be addressed to advance the field.

3.1 Addressing the Challenges

From the literature review, it is seen that the GPR has successfully been applied to conduct NDE in past and recent times. The success of the GPR NDE technique can be attributed to various factors including the frequency applied, antenna configuration, road or bridge deck condition and the targeted size.

The existing literature on the use of Ground Penetrating Radar (GPR) in road and bridge deck evaluation has consistently demonstrated its potential as a non-destructive testing technique for assessing the condition of infrastructure. numerous studies have reported high accuracy in detecting defects, deterioration, and thickness of road and bridge decks using GPR (Hasan and Yazdani *et al*, 2014) [13]. However, despite its promise, the use of GPR for this purpose is not without limitations.

One major limitation is the depth of penetration, which is influenced by the frequency of the antenna and the electromagnetic properties of the material being surveyed (Yazdani *et al*, 2016) [24]. Lower frequencies can penetrate deeper, but at the cost of reduced resolution, while higher frequencies provide higher resolution but shallower penetration. This tradeoff limits the effectiveness of GPR for evaluating thicker decks or detecting deeper defects (Daniels, 2004) [10]. For road and bridge deck evaluation, this limitation means that GPR may not be able to detect defects or deterioration at greater depths, potentially missing critical information.

The electromagnetic properties of the material being surveyed significantly affect GPR signals. The dielectric permittivity and conductivity of the material determine the velocity and attenuation of the signals (Annan, 2009) [6]. In road and bridge deck evaluation, the electromagnetic properties of the concrete or asphalt can vary significantly, affecting the accuracy and reliability of GPR measurements.

Reinforcing steel and metallic objects can cause significant interference and clutter in GPR signals, making it challenging to distinguish between targets and clutter (Yelf, 2004) [25]. This limitation is particularly significant in bridge deck evaluation, where reinforcing steel is often present. Environmental factors such as temperature, moisture, and salt content can significantly affect GPR measurements (Saarenketo *et al*., 2010) [19]. In road and bridge deck evaluation, these factors can cause errors in data interpretation, leading to inaccurate conclusions. The signal-to-noise ratio (SNR) of GPR signals is critical in determining the accuracy and reliability of measurements (Liu *et al*., 2015). In road and bridge deck evaluation, a low SNR can result in inaccurate data interpretation, highlighting the need for robust signal processing techniques.

Data analysis and interpretation are critical steps in GPR surveys, requiring expertise in radar theory, signal processing, and materials science (Yelf, 2004) [25]. In road and bridge deck evaluation, inaccurate data interpretation can lead to incorrect conclusions, highlighting the need for trained professionals.

The limited availability of large-scale field studies and the lack of benchmarking datasets also hinder the development of more advanced GPR systems and data processing algorithms.

In summary, while GPR has shown significant potential for road and bridge deck evaluation, its limitations must be acknowledged and addressed through continued research and development. Future studies should focus on overcoming these limitations and exploring new approaches to improve the accuracy, reliability, and practicality of GPR for infrastructure assessment.

3.2 Future Directions and Solutions

In addition to addressing the existing limitations of GPR technology, several future directions and solutions are proposed to further improve the accuracy, reliability, and practicality of GPR in infrastructure inspection. These include:

- Developing advanced data analysis software and providing training for users to improve data interpretation skills
- Developing cost-effective and portable GPR systems that are accessible to a wider range of users
- Collaborating with regulatory bodies to establish guidelines and standards for GPR use in infrastructure inspection
- Educating the public about the benefits and limitations of GPR technology to increase acceptance and adoption
- Encouraging continuous research and development to stay ahead of technological advancements and ensure GPR systems remain relevant.

4. Conclusion

In recent years, GPR technology has continued to evolve, with advancements in hardware and software further expanding its applications in road and bridge deck evaluation. Alani *et al*. (2018) [5] highlight the integration of GPR with other NDE technologies, such as LiDAR and infrared thermography, to provide a comprehensive assessment of infrastructure conditions. These multi-modal approaches leverage the strengths of each technology, offering more accurate and holistic evaluations.

Today, GPR is routinely used to monitor the health of roads and bridges, providing critical data for maintenance planning and asset management. The technology's non-invasive nature, combined with its ability to deliver real-time results, makes it an invaluable tool for ensuring the safety and longevity of transportation infrastructure.

In conclusion, GPR technology has the potential to revolutionize infrastructure inspection, but its limitations must be addressed to ensure its widespread adoption. By developing solutions to overcome these limitations and pursuing future directions, GPR technology can become a powerful tool for ensuring the safety, durability, and sustainability of our infrastructure.

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