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Identification of anomalies under the road surface using GPR

***Abstract**. The study aimed to identify surface structure anomalies of selected concrete transport routes for special vehicles based on the analysis of GPR echograms, enabling the identification of areas with potential subsurface structural degradation. The scope of the work included conducting research in five stages using a 2000 MHz Horn shielded antenna. The analysis of echograms and GPR images suggests that the overall condition of the road is good. Distinct construction layers and areas showing variability in the road structure were identified, indicating material heterogeneity and the presence of objects with high dielectric contrast.*

***Streszczenie.** Celem badań była identyfikacja anomalii struktury powierzchniowej gruntu wybranych betonowych ciągów transportowych pojazdów specjalnych na podstawie analizy echogramów georadarowych pozwalająca na identyfikację miejsc o potencjalnej degradacji struktury podpowierzchniowej podłoża. Zakres pracy obejmował przeprowadzenie badań w pięciu etapach z wykorzystaniem anteny ekranowej Horn 2000 MHz. Analiza echogramów i obrazów georadarowych sugeruje, że stan drogi jest ogólnie dobry. Zidentyfikowano wyraźne warstwy konstrukcyjne, a także obszary zmienność w strukturze drogi, ze wskazaniem na niejednorodność materiału oraz obecność obiektów o wysokim kontraście dielektrycznym. (**Identyfikacja anomalii pod nawierzchnią drogi przy użyciu georadaru**)*

Keywords: Ground-Penetrating Radar (GPR), subsurface structure, ground profile anomalies, electromagnetic wave
Słowa kluczowe: georadar, struktura podłoża, anomalie profilu gruntu, fala elektromagnetyczna

Introduction

The identification of subsurface anomalies in road infrastructure is critical for the durability and safety of roadways. Undetected irregularities such as voids, moisture pockets, and material discontinuities can lead to costly disruptions and pose significant safety risks. Timely and precise detection of these irregularities is essential for proactive maintenance and management of road infrastructure, allowing transportation agencies to extend the lifespan of road assets and optimize maintenance costs [1].

Traditional invasive techniques, such as core drilling and excavation, though accurate, are disruptive and provide only localized information. Core drilling involves the extraction of material to examine underlying layers, leading to traffic disruptions and damage to the road surface. Excavation, which involves digging up large sections of pavement, is even more disruptive and requires extensive and costly repairs post-assessment [2].

Advancements in technology have led to the adoption of non-invasive methods like Ground Penetrating Radar (GPR), which have revolutionized road surveys by providing comprehensive subsurface data without damaging the pavement. These modern methods are not only less invasive but also allow for faster evaluations over extensive areas, making them ideal for routine maintenance and early anomaly detection. GPR technology is highly valued for its ability to offer detailed insights below the road surface by emitting electromagnetic waves into the ground and analyzing the changes in signal reflections caused by different subsurface materials. This technique accurately maps the subsurface layout, identifying problematic areas that are not visible to the naked eye. The quality and clarity of the data collected through GPR heavily depend on the frequency of the radar waves, with higher frequencies providing better resolution, ideal for detecting small abnormalities in the upper layers of the pavement [3].

The use of GPR in evaluating roads has been well-documented in many research studies and real-world applications. Mapping pavement layer thickness, subsurface void detection, material property characterization, and moisture content identification are essential for road maintenance to ensure structural integrity and safety [4,5,6]. For instance, a research demonstrated the use of GPR in evaluating the state of pavement layers along multiple kilometers of road, offering important information used in the strategic planning of pavement maintenance and rehabilitation [7].

In regions where the road infrastructure is subjected to extreme weather conditions, such as those found in Finland and Sweden, GPR plays a crucial role in monitoring the effects of freeze-thaw cycles, water penetration, and other environmental stresses that can accelerate the deterioration of roads [6]. The technology is also essential in assessing roads that must withstand high levels of traffic from heavy industrial vehicles, such as logging trucks or mining equipment, ensuring that the road surface remains intact and safe for use [8].

Despite the proven benefits of GPR technology, its adoption in road construction and maintenance is still relatively limited. In particular, roads designed for the transport of specialized equipment and vehicles, such as those used in agriculture, forestry, and industrial settings, often do not receive the same level of scrutiny as public highways. This is an area where GPR could offer significant advantages, helping to extend the lifespan of these roads and improve safety for both equipment operators and the general public.

As GPR technology continues to advance, with improvements in resolution, data processing, and interpretation, its potential applications in road infrastructure will likely expand. Future developments may allow for even more detailed mapping of subsurface conditions, providing road engineers with the tools needed to design and maintain roads capable of withstanding the demands of modern transportation and industrial activities.

Purpose of the studies

The aim of the research was to identify surface structure anomalies of selected concrete transport routes used by special vehicles, based on the analysis of ground-penetrating radar (GPR) echograms. This analysis allows for the detection of areas with potential subsurface structural degradation. The study focused on identifying changes in the subsurface layers that could indicate damage, voids, or other forms of deterioration, which are critical for maintaining the structural integrity of these high-demand transport routes. The scope of the research also included the analysis of the variability characteristics of the GPR signal and its attributes, such as the signal envelope in selected depth intervals related to the top surface, the interface and the bottom surface of the concrete layer of the road and its substructure.

Material and methods

This study focuses on the analysis of concrete roads subjected to known traffic loads from specialized vehicles. The specific transport routes analyzed were intensively used by heavy machinery, including industrial and agricultural vehicles, which exert considerable stress on both the road surface and subsurface layers. The scope of the work included conducting tests on five selected roads using the shielded Horn 2000 MHz antenna (Figure 1). This high-resolution equipment is particularly well-suited for capturing detailed subsurface images, allowing for a precise evaluation of the ground beneath concrete transport routes, especially in areas subjected to heavy loads from specialized vehicles.

Fig.1. View of the GPR measuring system and the measuring software interface

Raw GPR (Fig. 2) data were collected across various sections of each road under study. To ensure the accuracy and relevance of our findings, the raw data were processed (Fig. 3) using K2 FastWave software, which allowed for the application of several signal and image processing techniques composed in processing flow dedicated to applications in the analysis of road infrastructure defects:

- **DC Component Removal** was the initial step to clarify the data by eliminating constant background noise that does not provide useful structural information.
- **Dewow Filtering** followed, targeting the removal of low-frequency variations to enhance the detection of finer subsurface features.
- **Butterworth Filtering**, a band-pass technique, was used to isolate the frequency components most relevant to the depth and resolution required.
- **Signal Enhancement** (gain) techniques were then applied to strengthen the detectability of weaker reflections from deeper structures.
- **Time Slicing** allowed for focusing the analysis on specific time windows where reflections of interest are most likely to occur, improving the precision in identifying structural anomalies.
- **Static Correction** adjusted for any temporal shifts or variations caused by uneven terrain or other external factors.
- **Zero-offset Trace Interpolation** was employed to create a continuous and uniform data set, filling in any gaps in the recorded paths.
- **Background Filtering** was applied to further clean the data, removing any persistent noise that could obscure key details.
- **FK Stolt Migration** utilized Fourier and wave-vector domain transformations to enhance the image resolution and accuracy.
- **2D Median Filtering** was the final step, used to reduce random noise and improve the overall quality of the visual output.

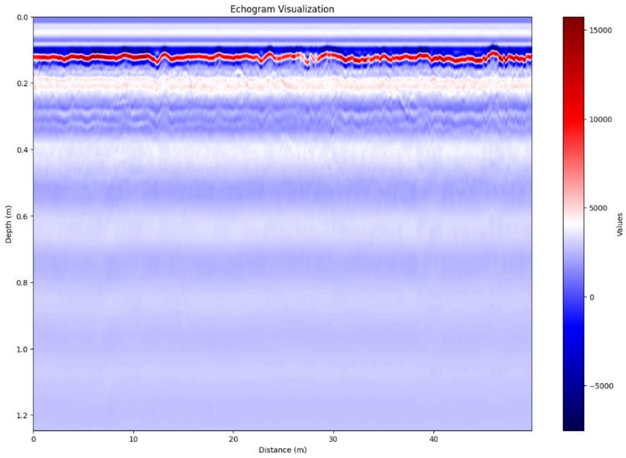

Fig.2. Example of raw GPR data

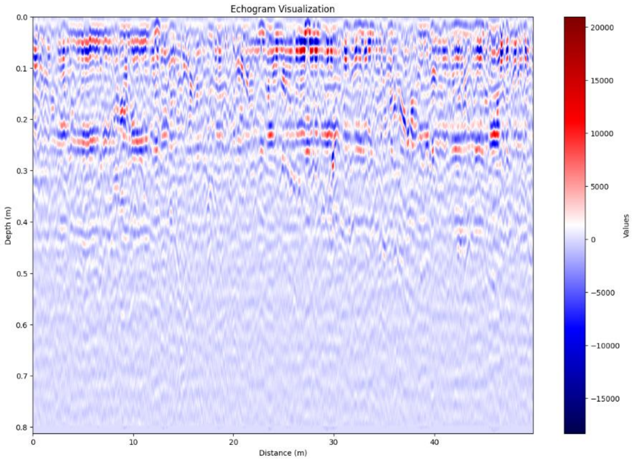

Fig.3. Example of processed GPR data

The resulting echograms were analyzed in a way that enabled the identification of areas where the subsurface structure deviated from the average for that particular section of the road. It is important to note that concrete roads possess a specific structure and properties that can influence the propagation and reflection of electromagnetic waves, thereby affecting the results of the study.

Figure 4 presents the echogram (after application of aforementioned processing steps) of the investigated concrete road, with the bottom surface (ranging from elevation -0.1 m to -0.3 m) highlighted in a red square. These surface layers are critical in understanding how the road's sub-subsurface and surface structure behaves under stress and wear, and deviations from the norm may suggest areas of concern and its contact with the sub-surface that could require further investigation or maintenance.

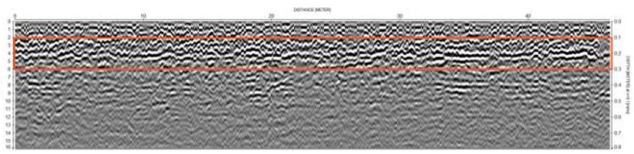

Fig.4. GPR image of a concrete road with the analyzed range from 0.1 m to 0.3 m marked

GPR data processed according to abovementioned processing flow facilitate direct structural analysis. To further enhance the quantitative visualization of anomalies, the signal envelope was calculated from the processed data. Additionally, based on the signal envelope, amplitude sum analyses were conducted at selected depth intervals corresponding to the successive layers of the concrete road.

Results

The results presented in this chapter highlight the analysis of one concrete road from among several tested in the experiment. This example demonstrates the methodology's applicability to other similar roads, underscoring its potential for broader implementation in structural assessments.

Figure 5 shows an echogram of the concrete road signal envelope obtained during GPR surveys. The low and high amplitude signal anomalies visible on it indicate the occurrence of non-uniform zones within the concrete surface, the surface-subgrade contact boundary and within the subgrade.

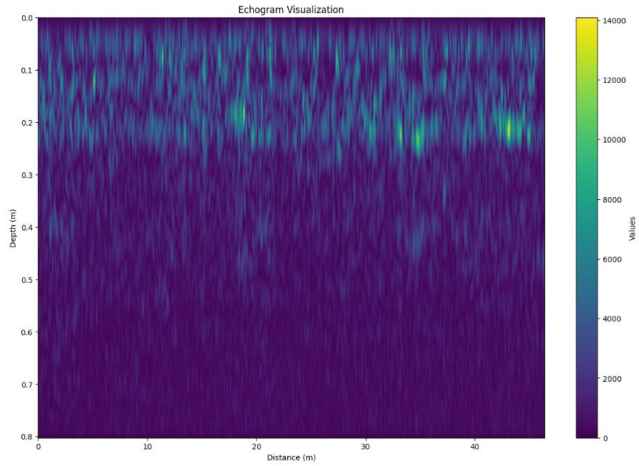

Fig.6. Signal envelope section for selected road

The presented graphs (Figs. 6-9) illustrate the cumulative envelope amplitude of the ground-penetrating radar (GPR) signal at varying depths along a road paved with concrete slabs.

Figure 6 depicts the cumulative amplitude of the GPR signal from a depth range of 0.0 to 0.1 meters. The blue line represents the aggregated data, while the red line illustrates a polynomial fitting (22nd degree) of these data. The horizontal axis (X) measures the distance in meters over which the measurements were conducted, from 0 to 50 meters, and the vertical axis (Y) represents the cumulative amplitude of the signal envelope, indicating the intensity of the reflected signal from the subsurface layer within the analyzed depth range. From 0 to 10 meters, there is a noticeable increase in amplitude, peaking around 5 meters, suggesting the presence of more reflective structures or joints between the concrete slabs. The increased amplitude could result from surface irregularities, gaps between slabs, or the presence of highly reflective materials just beneath the surface of the slabs. From 10 to 20 meters, the amplitude shows a tendency to decrease, albeit with numerous fluctuations. Relatively stable values in this range may suggest a more uniform surface of the concrete slabs without significant obstacles or joints, while fluctuations could indicate minor irregularities or changes in substrate density just under the slabs.

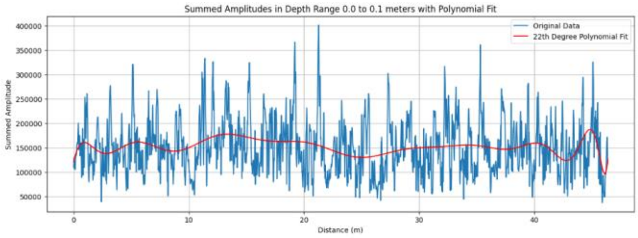

Fig.6. Summed GPR signal amplitudes in the depth range from 0 m to 0.1m

Figure 7 covers a depth range from 0.1 to 0.3 meters, showing clear fluctuations with a slight increase at the beginning. These variations may be related to reflections from joints between the slabs or more reflective materials beneath them, indicating a variety of materials or minor obstacles just beneath the slab surface.

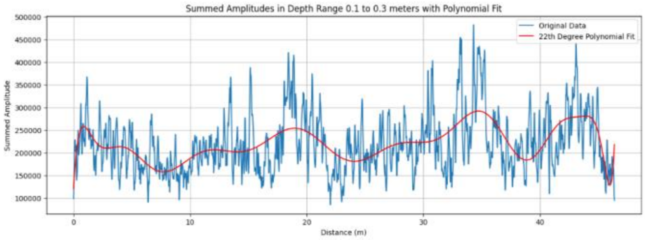

Fig.7. Summed GPR signal amplitudes in the depth range from 0.1m to 0.3m

Figure 8 extends the depth analysis to 0.3 to 0.5 meters, where the amplitude exhibits noticeable fluctuations with a significant rise at the beginning of the graph. This increase could result from the presence of reflective materials or structures, such as large stones, tree roots, or other objects, influencing the reflection of electromagnetic waves. Such objects at this depth may indicate geological diversity of the terrain.

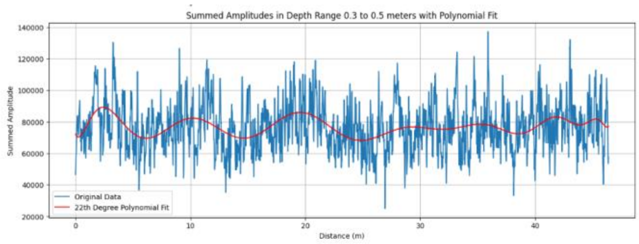

Fig.8. Summed GPR signal amplitudes in the depth range from 0.3m to 0.5m

Figure 9 explores deeper, from 0.5 to 0.8 meters, where the amplitude shows marked fluctuations, with peaks reaching about 200 units, indicating the presence of reflective materials or structures under the surface, such as stones, tree roots, or other obstacles. The stability of the amplitude at lower values suggests that, apart from these objects, the subsurface structure is relatively uniform.

These findings collectively provide valuable insights into the subsurface conditions along the surveyed road, indicating a mixture of uniform areas punctuated by zones of significant reflective anomalies. Such detailed GPR analysis is crucial for understanding the structural integrity and variability of the road foundation, which is essential for maintenance planning and structural assessments.

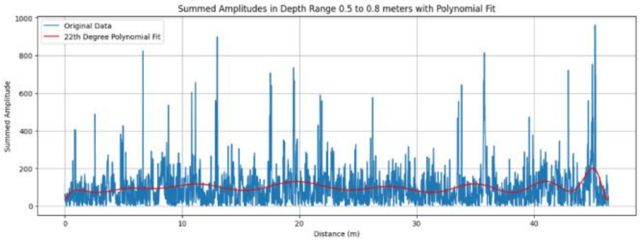

Fig.9. Summed GPR signal amplitudes in the depth range from 0.5m to 0.8m

Conclusion

This study successfully demonstrated the effectiveness of Ground-Penetrating Radar (GPR) technology in identifying subsurface anomalies in concrete roads used by special vehicles. Utilizing a 2000 MHz Horn shielded antenna allowed for high-resolution imaging, crucial for assessing structural integrity and detecting potential degradation areas beneath the road surface. Key findings confirm the presence of structural anomalies, including distinct construction layers and material heterogeneity, which are essential for pinpointing potential failure zones. GPR's non-invasive nature proved superior to traditional methods such as core drilling, offering extensive subsurface data with minimal disruption, thus supporting proactive maintenance strategies and potentially extending the infrastructure's lifespan. The efficiency of GPR in scanning large areas quickly enables timely anomaly detection, crucial for maintaining road safety and durability. Although focused on specialized roads, the results suggest GPR's broader applicability across various infrastructure settings, advocating for its integration into regular road evaluation protocols. Future research should explore combining GPR data with other diagnostic technologies to develop comprehensive road health monitoring systems, enhancing predictive maintenance and roadway design to meet the demands of modern transportation and industry.

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