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Effect of geo-radar signal processing method on the degree of reflection of soil cohesion

***Abstract**. The purpose of the study was to determine the extent to which the processed GPR signal matched the compactness characteristics of the soil profile determined by penetrometer using different signal processing methods. The scope of the study included an area of about 300 hectares where 100 soundings were made with a cone penetrometer and geo-radar measurements were made in 10-meter sections at the sites where the aforementioned soundings were made. Penetrometric surveys were performed with an Eijkelkamp penetrologger, while geo-radar surveys were performed with a Horn 2000 MHz shielded antenna with a sampling frequency of 400 KHz and a scanning rate of more than 850 scans/sec. The existing processing capabilities of the GPR signal make it possible to interpret its results with an error of 20% in relation to penetrometric methods recognized as benchmarks.*

Streszczenie.** Celem badań było określenie stopnia dopasowania przetworzonego sygnału georadarowego do charakterystyki zwięzłości profilu glebowego określonego penetrometrem przy wykorzystaniu różnych metod przetwarzania sygnału. Zakresem badań objęto powierzchnię ok. 300 ha gdzie wykonano 100 sondowań penetrometrem stozkowym oraz wykonano pomiary georadarowe na odcinkach 10 m w miejscach, gdzie dokonano w/w sondowań. Badania penertometryczne wykonano penetrologger Eijkelkamp, natomiast georadarowe antena ekranowaną Horn 2000 MHz o częstotliwości próbkowania 400 KHz i tempie skanowania powyżej 850 skanów/sek. Istniejące możliwości przetworzenia sygnału georadarowego pozwalają interpretować jego wyniki z błędem wynoszącym 20% w stosunku do metod penetrometrycznych uznanych jako wzorcowe (Wpływ metod przetwarzania sygnału geordarowego na stopień odzwierciedlenia zwięzłości gleby***).*

Słowa kluczowe: geo-radar, gleba, fala elektromagnetyczna
Keywords: GPR, soil, electromagnetic wave

Introduction

Accurate identification of soil cohesion anomalies in the soil profile under production conditions is an essential element that can play a key role in modern production systems [1]. Currently, the isolation of areas that require special attention on the field surface is very complex and requires advanced technical means that can perform their functions in real time. The GPR method is one of the most advanced of the geophysical survey group. During the measurement, a series of parallel profiling is performed, which makes it possible to interpolate the results between successive profiles, and the result itself is presented in the form of clear maps at a given depth level [2,3]. The method used to measure soil compaction variation using GPR allows sufficient identification of anomalies in the soil profile, but at the current stage of the research it can only be used to estimate various soil parameters [4,5]. The chemical, physical and mineralogical properties of the ground medium determine the suitability of GPR [6]. The most important physical properties of the test medium for radio waves are dielectric and magnetic permeability and electrical conductivity. Other factors affecting the effectiveness of GPR measurements include the salt content and type of salt in the soil solution, clay content and type, and moisture content, as they affect electrical conductivity (Sudduth et al., 2005). Clay soils have high conductivity and quickly attenuate radar energy. Clay minerals increase the scattering of electromagnetic energy due to their adsorptive capacity, radio waves decrease exponentially, which limits the depth at which measurements can be taken and thus significantly reduces the effectiveness of GPR. Doollittle [6] reports a penetration range with a 120 MHz antenna for sandy soil of 1 - 25 m, coarse dust of 1 - 5 m, clay or fine-grained dust of 1 - 2 m, and fine and very fine clay soil of 0.5 - 1 m. In most materials, energy is also lost due to scattering due to material variation and due to the presence of water. The effect of water is twofold: water contains ions that contribute to total electrical conductivity and water molecules absorb electromagnetic energy at high frequencies, usually above 1000 MHz. When classifying soils for suitability for GPR measurements, the content and type of clay, electromagnetic conductivity, sodium absorption coefficient, calcium carbonate and calcium sulfate content are taken into account [7,8]. With regard to the use of GPR in agricultural soil surveys, the basic questions concern the required depth and horizontal and vertical resolution, assuming that the electrical properties of this environment are known and the soil is suitable for such measurements. Based on this information, the frequency of antenna operation and the optimal spacing between measurements on the field surface are determined. The rule of thumb for correctly determining the spacing of measurements is that it should be twice the Nyquist frequency. King et al. [9] used radar in their study of noninvasive sensors for measuring the physical properties of soil. They found that the applicability of GPR was limited by the mineralogical composition of the soil. In contrast to sandy soils, they did not get any positive results on soils with high clay content. The signal was reflected before it could penetrate the soil layer. The GPR measurements were most affected by the soil's electrical conductivity and dielectric constant. GPR proved useful for determining the depth of the soil profile, the depth of clay-rich layers on sandy material and the depth of the water level during drought, among other things. Petersen et al. [10] in their study were concerned with mapping soil compaction and soil variability on a farm. To do this, they used GPR operating at the main frequency of 500 and 900 MHz and an EM38 probe to measure electromagnetic conductivity. They successfully distinguished between areas with a higher risk of compaction (clay soils) and areas with a lower risk (sandy soils); however, due to the low contrast, they could not fully confirm whether the deeper layers were more compacted. Freeland et al. [11] developed a method to map soil compaction caused on a golf course by players. They used GPR and a very high frequency antenna to locate compacted areas for reclamation. This allowed them to scan the profile to a depth of 50 cm below the turf. They obtained a spatial distribution of soil compaction and the thickness of the organic layer, sand and gravel. Jaklinski [12] used GPR to detect plow sole. Widespread use of GPR is limited by the complexity of data compilation [13].

Purpose and scope

The purpose of the study is to determine the degree of matching of the processed GPR signal to the soil profile cohesion characteristics using different signal processing methods. The scope of the study included an area of about 300 hectares where 100 penetrometer soundings were made and GPR measurements were made on 10m sections in places where the above mentioned soundings were made.

Methodology and results

Penetrometer surveys were performed with an Eijkelkamp penetrologger, while GPR surveys were performed with a Horn 2000 MHz shielded antenna with a sampling frequency of 400 KHz and a scan rate of more than 850 scans/sec (Fig. 1)

Fig. 1. Testing ground with measuring equipment

The echogram was processed using procedures: Raw GPR Data (Input) to acquire raw ground penetrating radar (GPR) data, which are essentially electromagnetic wave reflections from subsurface structures (Fig. 2).

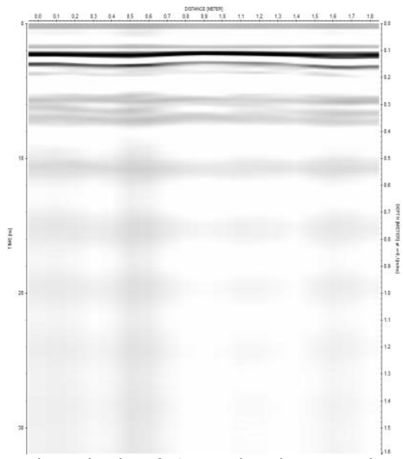

Fig. 2. Selected methods of GPR signal processing - Raw GPR Data (Input)

Start time correction to correct the start time in GPR data processing corrects the initial time record of the radar signal, Dewow Filter to eliminate low frequency trends or “wow” effects from GPR data. This filtering process is necessary to clarify the high-frequency signal components that are critical for detailed subsurface imaging; Manual Gain involving amplification, is a critical step in GPR data processing in which the amplitude of the radar signal is manually altered to compensate for signal attenuation with depth. This process improves the visibility of deeper targets by increasing their relative amplitude; Band-pass Butterworth Filter to remove unwanted frequency components from GPR data (Fig. 3). The Butterworth band-pass filter is known for its smooth frequency response, effectively isolating the frequency band that carries the most important subsurface information. This step is crucial for reducing noise and improving clarity of subsurface images; Background Removal Filter is used to subtract coherent, unwanted signal patterns, often caused by system-specific or environmental noise. This process increases the relative visibility of anomalies in GPR data.

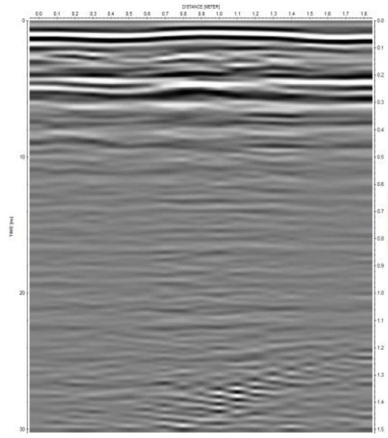

Fig. 3. Selected methods of GPR signal processing - Band-pass

It is particularly effective in highlighting subtle subsurface structures in a noisy background; FK Filter used to suppress coherent noise in GPR data based on its velocity characteristics. By transforming data into the frequency-wave domain, it allows selective suppression of noise that differs in speed from the signal of interest; Kirchhoff Migration involves a computational process used to reposition reflected GPR signals at their correct spatial locations. This step is crucial for constructing accurate and interpretable subsurface images. It compensates for the effects of wave propagation, providing a more realistic representation of the subsurface; Envelope to determine the amplitude of the wave field, which helps identify and more clearly define subsurface features. This process involves transforming GPR data to highlight boundaries and interfaces in the subsurface (Fig. 4).

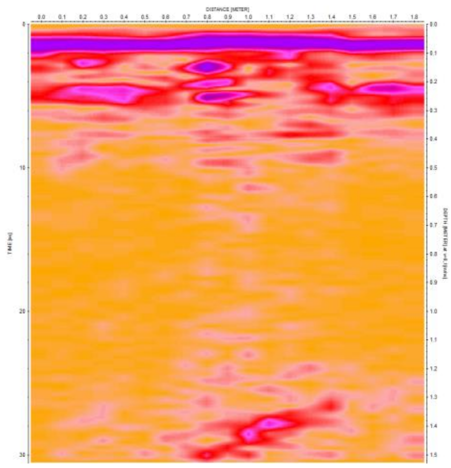

Fig. 4. Selected methods of GPR signal processing - Band-pass

Karhunen-Loeve Filter also known as Principal Component Analysis (PCA), used for advanced signal processing in GPR data. This technique reduces the dimensionality of the data, highlighting the most important features while suppressing noise. It is particularly effective in extracting meaningful patterns and trends from complex GPR data sets. To achieve the goal, a sequence of mathematical transformations was used to match the signal obtained from the GPR scan of the subsurface soil structure with the penetrometric characteristics of the analyzed soil profile. In the first phase of processing the GPR signal was used: move starttime, substract DC-shift, substract-mean dewow, bandpass Buttwerwoth filter, background removal, divergence compensation, time to depth conversion, resampling (1 cm), depth cut (81 cm), stacking, envelope. Subsequently, the following were determined: the scaling function of the GPR data to the penetrometric data, which was realized by performing difference minimization using the bounded Brent method; the approximation of the scaling function by a polynomial; the product of the scaling function and the GPR data; the compactness curves from the GPR data, and the absolute error with respect to the penetrometric data was calculated. Figure 5 shows the fitting characteristics of the GPR signal to the average compactness characteristics of the soil profile. The degree of fit was determined by the mean-square percent error (RMSPE).

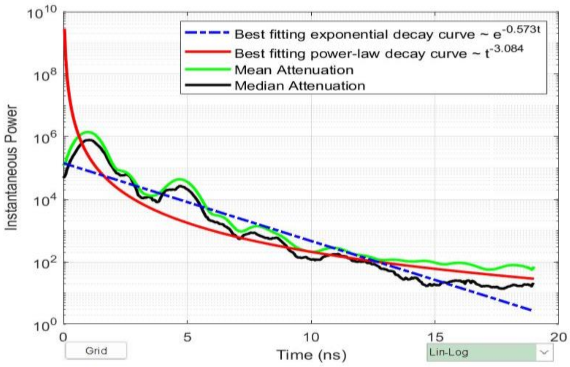

Fig. 5. Matching characteristics of the processed GPR signal

Figure 6 shows the spatial structure of the soil cohesion distribution generated from the amplitude of the GPR signal.

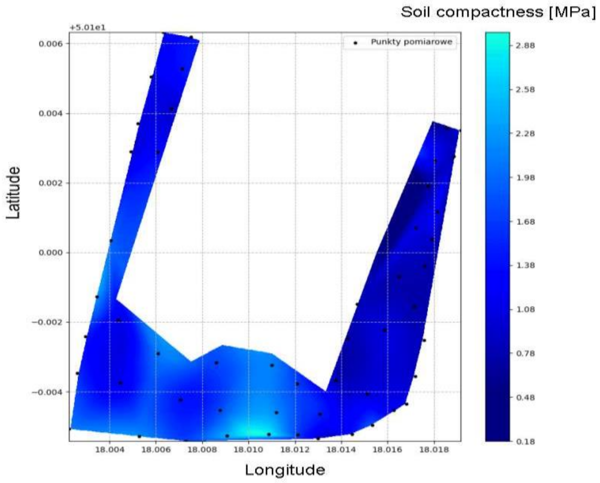

Fig. 6. Matching characteristics of the processed GPR signal at the depth of 0,1m

It was observed that at a depth of 0.1 m in the soil profile, the spatial distribution of variability of the GPR signal converted to soil compactness units (Fig. 6) was very similar to the spatial distribution of soil compactness determined by the cone penetrometer (Fig. 7). The only variation was in the southwestern part, where the penetrometer result indicated less soil variability. However, it should be noted that the spatial variation between methods was incidental.

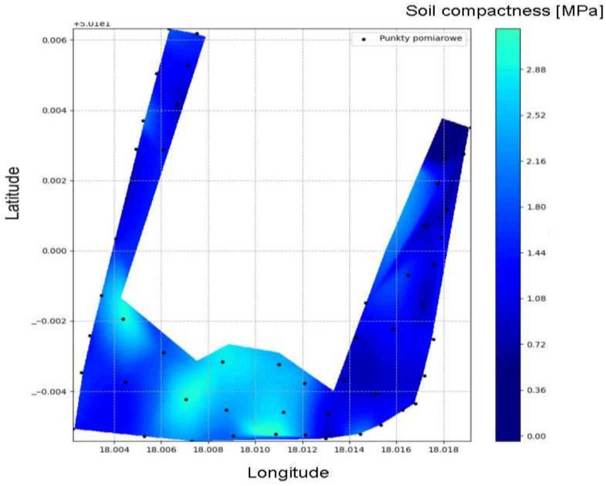

Fig. 7. Spatial distribution of soil profile compactness at a depth of 0.1 m determined by penetrometric method

Slightly greater variation in the results of soil compactness determined by GPR and penetrometric methods was recorded for the depth of the soil profile of 0.3 m. In the analyzed space of the field, the lowest values of compactness were recorded in the western part of the field, while observing a high correspondence between the indications of the geo-radar method (Fig. 8) and penetrometric method (Fig.9).

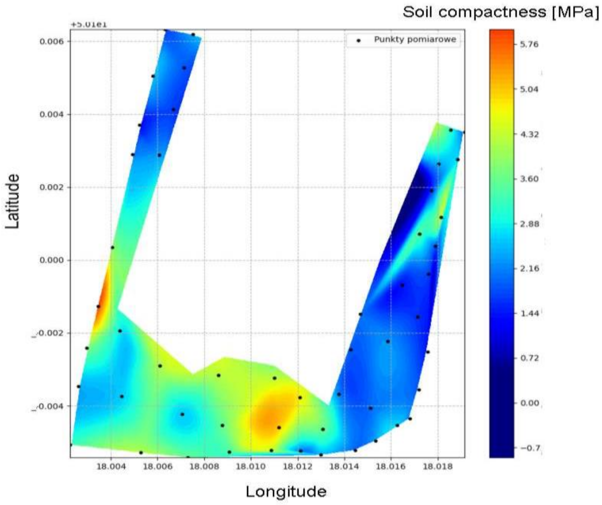

Fig. 8. Matching characteristics of the processed GPR signal at the depth of 0,3m

Analyzing the variation between measurement methods approximated to spatial variation maps, it was found that inconsistent indications apply to the southwestern part of the field, where the penetrometric method showed significantly higher values of soil compactness compared to the compactness determined by the GPR method.

A similar observation applies to the comparison of soil compactness maps at a depth of 0.8 m. Lower values of soil compactness in the middle part of the field were noted when the GPR method was used (Fig. 10) compared to the compactness determined by the penetrometric method (Fig. 11).

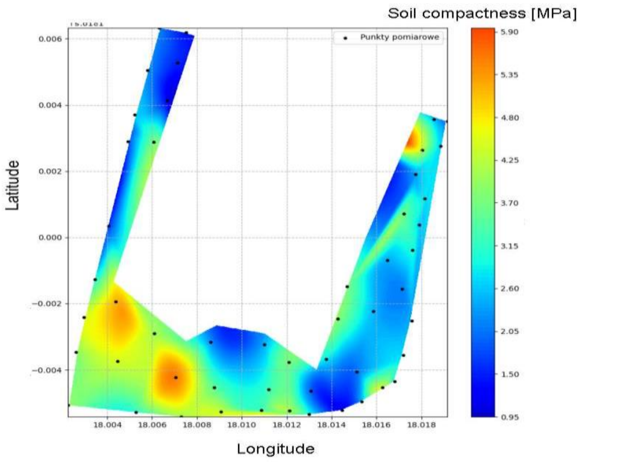

Fig. 9. Spatial distribution of soil profile compactness at a depth of 0.3 m determined by penetrometric method

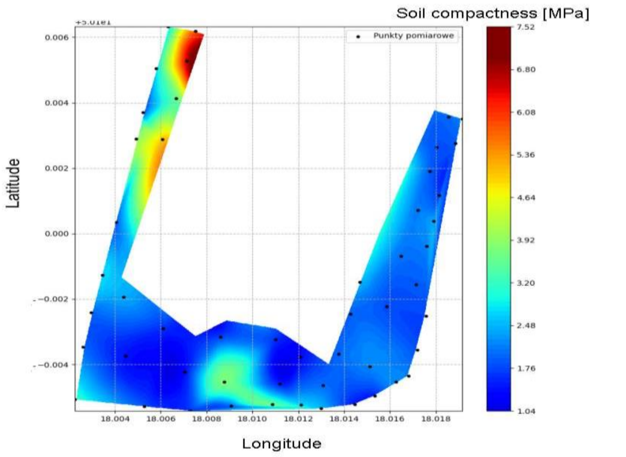

Fig. 10. Matching characteristics of the processed GPR signal at the depth of 0,8 m

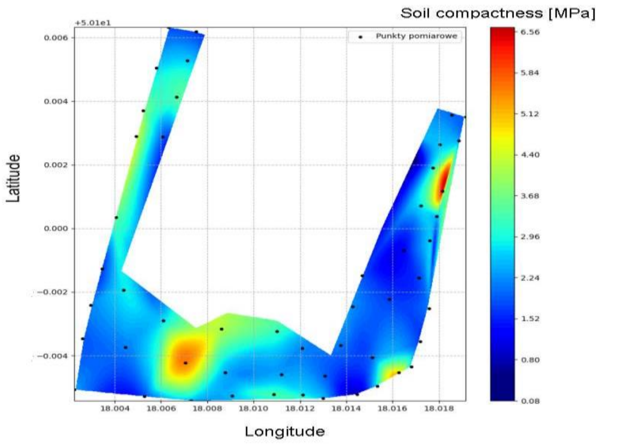

Fig. 11. Spatial distribution of soil profile compactness at 0.8 m depth determined by penetrometric method

However, it should be noted that in all analyzed cases, the variation of soil compactness determined by GPR and by penetrometric method in spatial terms was incidental representing an area-wide small part of the field area.

Conclusion

The existing capabilities of GPR signal processing allow interpreting its results with an error of 30% in relation to penetrometric methods recognized as benchmarks. Thus, it is possible to control the technology of tillage machinery based on the GPR signal. The presented solution applies to a specific soil type and the built algorithm for other soil types must be modified.

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