Assessment of the possibility of using GPR to determine the working resistance force of tools for subsoil reclamation

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Abstract. The article presents a study on the determination of working resistance force of a tool that reclaims the topsoil based on GPR research. The experiment used a strain gauge force measurement system in a three-point linkage suspension system of the tool on a tractor with automatic registration of other operating parameters of the unit at a frequency of 10Hz. For the research with the use of GPR, a shielded antenna with a frequency of 800 MHz was used, allowing to obtain a wavelength of 0.12 m and a resolution of 0.03 m. The tests were carried out for several combinations of soil compaction, which was initially measured with the Eijkelkamp cone penetrometer. A large convergence of the results of the working resistance forces was found with the indications of the states of excessive compaction identified in the space of the echogram. It should be noted that the convergence of the measurement results increases with the degree of soil compaction. Therefore, it is possible to estimate the energy consumption of cultivation treatments on the basis of non-invasive GPR surveys and selective soil reclamation treatment with degraded subsoil.

1. Introduction

Accurate identification of soil compaction anomalies in the soil profile under production conditions is a necessary 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 methods from the group of geophysical measurements, which has been used in many areas, including in agriculture. During the measurement, a series of parallel profiling is performed, which enables the interpolation of results between successive profiles, and the result itself is presented in the form of transparent maps at any depth level [2,3].

Nevertheless, in the opinion of many authors, the development of GPR data is very complex and requires very good training of the staff performing the measurements and interpreting the obtained results. The speed of the electromagnetic wave (v) and the permittivity (k) are strongly dependent on the water content of the soil (θ), due to the high dielectric constant of water compared to other materials (K for water = 80, K for various geological materials = 5-15 and K for air = 1), e.g. the relative electric permeability of wet sand is eight times greater than the relative electric permeability of dry sand [4].
Due to non-invasiveness, speed, obtaining a large amount of information and relatively low costs, GPR is used in agricultural soil research as a method complementing conventional techniques. The development of precision farming technology is related to the need to determine the spatial variability of soil compaction. Mapping compacted areas in the field in comparison with yield maps may be helpful in explaining the reasons for its low values [5]. It can also be used as an application map for the deployment of spatially variable depth of cultivation, contributing to the reduction of energy consumption of cultivation treatments [6]. Among many authors who deal with mapping the variability of soil mechanical resistance in the form of a horizontal traction force with the use of a model tool [7-10].

The first two of the above-mentioned studies describe the design and field testing of a sensor in the form of a single chisel, dragged in the soil at a depth of 0.3 m with a constant speed of 5 km h\(^{-1}\). Budyn et al. [11] took advantage of the system used in precision agriculture LH-5000 to measure the skid of one of the driving wheels of the tractor. In this system, a radar was used to measure the real speed, while the theoretical speed was determined, among others from the number of revolutions of the wheel equipped with magnets cooperating with the inductive sensor. Kiełbasa et al. [12] measured the working resistance using a strain gauge frame equipped with strain gauges, which are measuring transducers working in a full bridge system, and the measurement signal was proportional to the value of longitudinal stresses of special connectors on which strain gauges were attached. The problem of soil resistance measurement is also presented in [13,14]. The integration of the sensors with the computer allowed for high sampling frequency and automatic saving of the obtained data on the computer disk. It seems that the use of the GPR method to estimate the working resistance of the tool gives new possibilities for determining the energy consumption of soil cultivation and, consequently, the possibility of new modeling of production as a function of its energy consumption.

2. Materials and methods

The aim of the research was to evaluate the possibility of using the GPR to determine the working resistance of a cultivation tool. The scope of the research included the measurements of the working resistance force in the three-point suspension system of the tool on the tractor, which was carried out in five combinations of subsoil compaction (identification for each combination of compaction of the subsoil structure based on the echogram, penetrometric and laboratory tests).

The tests were conducted out on the experimental field with artificially created parameters of soil profile density, which were adequate to the assumed combination of soil compaction by tractor wheels. Virtual paths were marked on the surface of the field, constituting measurement lines along which penetrometric, GPR and moisture measurements were carried out, as well as measurements of the working resistance force of the subsoil reclamation tool. The research time interval lasted 5 hours, which allowed to maintain homogeneous soil moisture conditions.

![Figure 1. View of the GPR measurements (a) and the track in which the measurement was performed (b)](image-url)
The measurement of soil compaction was conducted with the use of the invasive method using a cone penetrometer, Penetrologger Eijkelkamp model with the ThetaProbe probe designed to measure soil compactness and moisture on arable land according to ASAE standards (at present ASABE). The penetrometer housing was equipped with an internal GPS receiver, which was used to determine and save the coordinates of the measurements. The sounding depth was 0.8 m when registering the value of the measured compactness of the soil profile at intervals of 0.01 m. Measurements were taken by means of a cone with a nominal diameter of 11.28 mm and an opening angle of 30°. The depth was measured with an ultrasonic sensor cooperating with a reference plate. The compactness measurements were performed with the average penetration speed of the penetrometer cone of 5 cm · s⁻¹. As an alternative method, the ProEx System GPR by the Swedish company Mala GeoScience was used, which was guided along the same track as the cone penetrometer. This eliminated the limitations of penetrometric sampling techniques, creating a three-dimensional view of the soil cross profile characteristics. In GPR research, the method of reflection profiling was used, in which both antennas moved simultaneously along the measurement paths and perpendicular to the analyzed soil profile, which allowed to polarize the electric field parallel to the longer axis of the antennas. The tests were carried out with the use of a shielded frequency 800 MHz antenna allowing to obtain a wavelength of 0.12 m and a resolution of 0.03 m (Figure 1).

Measurement of the working resistance force of the reclamation tool was performed with a strain gauge frame equipped with six strain gauges operating in a full bridge system [7, 13]. The sensor system allows to measure the forces occurring in each of the rods of the three-point suspension system of the tool. The actual speed was measured with the CORREVIT L-400 optical sensor located in the axis of symmetry of the tractor drive wheel. The theoretical speed was measured with magnetic sensors mounted on the rims of the tractor driving wheels. The H-CE optical sensor mounted on the tool's support frame was used to measure soil penetration depth. The position (coordinates) of the tractor unit was also determined using a GPS receiver with a built-in microcomputer located on the tractor roof. All measuring systems were connected to a CF-29 notebook through the Daq Book / 200A measuring station. The applied system allowed to operate in the frequency range from 1 Hz to 10 Hz (Figure 2).

![Figure 2. View of a tractor equipped with a traction force measuring system (a) and an exemplary course of one of the component forces (b) (narrow)](image)

It was assumed that the run-up sections for the GPR measurement would constitute 10% of the measurement section length. Volumetric moisture and soil salinity were measured with a TDR probe. Measurements were made at three depths: 0 - 0.1 m, 0.1-0.2 m and 0.2 - 0.3 m. The humidity measurement is based on the use of the Time Domain Reflectometry method. The relationship between the values of the soil transverse profile and the value of the tool working resistance was determined, which enables automatic control of the tool working depth and the assessment of the energy consumption of the procedure.
3. Results

Figure 3a presents the mean values of the resultant force of the subsoil remediation tool working resistance for each level of soil compaction. "0" is the force measured by the strain gauge system in the three-point linkage of the tool on the tractor (three-point linkage), when the tool is not immersed in the soil and is not affected by any external forces. The zero measurement is the reference point for the remaining force measurements and identifies the occurrence of random mechanical stresses in the measuring system links. The combination "1" referred to the value of the tool resistance force measured within the designated testing ground, however, the soil was in its natural state. The average value of the force in this case was about 4.2 kN. In the next combination ("2"), the soil was compacted with one pass of the tractor and a significant increase in the average value of the working resistance force of the tool by almost 2 kN was noted. In the case of soil that was compacted with two tractor runs (combination no. 3), only a slight increase in the working resistance force was observed. Then the soil was compacted with four tractor passes, which was a combination of "4" experience and increased the tool working resistance force, which amounted for over 7 kN.

![Figure 3](image1.png)

**Figure 3.** Average value of the working resistance force of the subsoil reclamation tool (a) and its characteristics during the measurement (b).

![Figure 4](image2.png)

**Figure 4.** Compactness characteristics of the soil profile with various degrees of compaction: a) soil without being compacted, b) soil compacted by driving the tractor eight times through the soil.

It should be noted that the oscillation range of the measured force values resulting from the dynamic loads and local variability of the subsoil of the test site, despite compaction, did not exceed 2 kN, regardless of the combination of the experiment (Figure 3b). Figures 4a and 4b show the compactness characteristics of the soil profile with various degrees of compaction.
characteristics of the soil profile for two extreme levels of soil compaction, i.e., the combination "1" (Figure 4a) and the combination "6" (Figure 4b). Significant differences in soil compactness were noted, especially in the range of 0.05 m to 0.35 m depth. The increase in soil compactness translated into an increase in the resistance force of the reference tool, which, like the increase in soil compactness between extreme compaction levels, was similar to a linear course.

Figure 5a demonstrates the amplitude of the GPR signal from unpacked soil generated along the entire length of the measuring section. The range of the averaged signal amplitude from the entire measuring section, which is a measure of the differentiation of the measured medium, was about 15,000 units in the depth range from 0.01 m to 0.2 m, and then after exceeding the depth of 0.2 m, the signal amplitude range was stabilised at the level of 5,000 units. On the other hand, Figure 5b shows the course of the amplitude of the signal measured over the entire measuring section for the "1" combination of the experiment, i.e., non-compacted soil. It was noticed that the shape of the signal oscillation is close to the characteristics of the tool working resistance force for this experiment combination. This means that the value of the tool working resistance force can be estimated on the basis of the oscillation of the GPR signal and the resulting echogram measurement.

Figure 5. Averaged amplitude of the soil GPR signal without kneading with tractor wheels (a) and visualization of the signal amplitude for the entire measuring section.

Figure 6. Averaged amplitude of the GPR signal of the soil eight times kneaded with tractor wheels (a) and visualization of the signal amplitude for the entire measurement section.
On the other hand, Figure 6a presents the amplitude of the GPR signal of the maximally compacted soil (combination No. "6") averaged for the entire measuring section, the value of which did not exceed 10,000 units in the depth range of 0.01 m to 0.2 m. It was a value of about 30% lower than in the case of the signal amplitude recorded on non-compacted soil. Analysing the signal amplitude course for the entire measuring section of the sixth combination of the experiment, its shape was also found to be similar to the shape of the tool working resistance force characteristic. It was found that the high values of signal oscillation were incidental, however can also be identified at the value of the tool working resistance force.

4. Conclusion

The applied method of measuring the variability of soil compaction with the use of GPR allows for sufficient identification of anomalies in the soil profile, however at this stage of the research it can be used to estimate the working resistance of cultivation tools. The comparison of the obtained characteristics, i.e. the working resistance force and the echogram, gave satisfactory results, which justify detailed research on the parameterization of the GPR method in relation to the working resistance force of the tools. Each of the methods used enables the identification of areas in the soil profile with abnormal production properties.

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