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THEORETICAL FUNDAMENTALS AND PRACTICAL ASPECTS OF THE APPLICATION OF ULTRASOUND FOR DETECTION OF COMPACTED SOIL LAYER

Abstract. The issue of over-compaction of fertile soil is actually very important for agricultural enterprises, as a violation of the technological process of tillage depth significantly affects the yield of crops and also causes wasted fuel. So, it's not just a matter of adhering to a certain technology, it's rather an economic issue. There are many devices for detecting the depth of the over-compacted soil layer, but they all have one significant drawback: they allow you to examine a small area of the field, i.e. a kind of local research. In order to detect the depth of the compacted soil layer on a larger scale, advanced methods are needed, for example, why not explore the use of ultrasound to solve this problem, so this article will compare the theoretical (acoustic) and practical (based on laboratory and field experiments) possibilities of using ultrasound to quickly detect the depth of the compacted soil layer. To do this, we will introduce the system of operational control of the depth of travel of the soil ripper of a machine-tractor unit and its main element – an experimental radio physical device for determining the depth of the most compacted soil layer, and describe the results of laboratory and field studies.

Keywords: ultrasound, radio physical device, compacted soil, sensor, tractor.

Problem Statement. Today, the agriculture of Ukraine and many other countries faces such challenges as a decrease in natural soil fertility, an increase in the cost of material and energy resources, as well as an increase in the consumption of agricultural products. Intensive use of natural resources has led to negative changes faced by modern agricultural enterprises. These changes are manifested in the form of economic and environmental problems associated with the cultivation of agricultural land. In such conditions, traditional methods of soil cultivation and crop cultivation are gradually being replaced by technologies with minimal cultivation, which are aimed at protecting the soil, preserving its fertility, and also at reducing the costs of cultivation. However, these technologies, although they partially solve the mentioned problems, have their drawbacks, in particular, the risk of formation of an over-compacted soil layer.

And an over-compacted soil layer is another problem for its productivity, because poorly compacted soil has a rather negative effect on the root system of cultivated plants and moisture exchange between soil layers, which leads to a decrease in the yield of agricultural crops, because the depth of soil cultivation is a very important indicator for agricultural production, and violations often occur in this areas.

Taking into account all these urgent issues for agriculture, it was decided to investigate the possibilities of using ultrasound to detect the depth of the compacted soil layer during the movement of the machine-tractor unit. An experimental one was developed for this purpose ultrasonic device, which became the main element of the system of operational control of the depth of travel of the soil cultivator of the machine-tractor unit.

Analysis of latest research and publications. Given that the problem of soil compaction at depth is quite serious and requires urgent solutions today, scientists are, of course, trying to solve it all the time by developing new devices for determining soil density, as evidenced by many publications in both domestic and foreign periodicals. There are already many soil hardness testers that allow for continuous measurement in the mode of continuous registration simultaneously with soil cultivation, such hardness testers are made in the USA, the Netherlands and Slovakia [10, 16].

More advanced are hardness gauges using strain gauges that are attached to the cultivator tines and measure hardness during tillage, but their use requires a very low tillage speed. A similar hardness tester was developed and tested in Sweden [6].

There are developments where hardness gauges are mounted on the wheels of trucks or trailers – these are mobile penetrometers [5, 11, 14]. They are delivered to the test site along with motors, electric batteries, or other energy sources. The addition of extra weight for the mobile truck device increases the potential maximum immersion force of the punch, and the length of the penetrating stroke can be increased without limiting the required weight compared to other types of penetrometers. These devices are equipped with multipenetrometers to simultaneously examine several areas to obtain data on the three-dimensional spatial characteristic of soil hardness for the construction of a corresponding map [11, 14].

In recent years, digital technologies [16] have been used in Ukraine to detect compacted areas of the field, in particular: GPS-penetrometers [12], which, with the help of certain applications installed on a smartphone, display the place of measurement and the location of the person making the measurements.

The problem of using ultrasound to determine the over-compacted area of the field, or rather, to determine the depth of its occurrence, has also been actively reflected in publications in recent years [1, 2, 3, 4], which describe the results of both laboratory and field studies, and review the acoustic behavior of the over-compacted soil layer.

Aim of the article. Soil is not an easy environment for the transmission of ultrasound. According to the basic laws of acoustics, this is not possible, however, in the case of a compacted soil layer, depending on the purpose of the ultrasound application, i.e., depending on what we want to get, what results we need, it is possible according to the same acoustics.

The aim of this paper is, firstly, to compare the theoretical possibilities and practical achievements, and secondly, to show what made it possible to achieve certain results and to find out what factors hinder the use of ultrasound in the natural environment, especially if we take into account the fact that the over-compacted soil layer is an absolutely rigid environment (body).

The main part of the research. After all, as is known from the laws of acoustics, in order for a sound wave to pass, an elastic environment is needed in which deformation processes would take place. However, as regards the detection of the depth of the over-compacted soil layer, it is precisely the non-passage of ultrasound through the compacted soil layer without air phases and liquid that is taken as the basis for such research, that is, not the scattering and attenuation of the sound wave, as, for example, in sandy soils and clay , and the quick reflection of the wave, that is, the time interval from the moment of reference and reception of the reflected sound pulse by the sensor is taken into account, of course, taking into account energy losses when passing through the upper layers of the soil, since the over-compacted soil layer usually lies at a depth of 25-50 centimeters.

The main constants of the acoustic behavior of an over-compacted soil layer are such informative parameters as: acoustic stiffness, which shows the dependence of sound pressure on the amplitude of the displacement of medium particles, and acoustic resistance of soil layers, which more clearly and generally shows the resistance to sound wave propagation [7, with. 166-169].

The first constant is the acoustic stiffness of the medium, which is calculated according to the formula:

$$Q_{\text{А.ж.}} = pcw = \frac{D}{A}, \tag{1}$$

where $\boldsymbol{p}$ is the density of the medium (kg/m^3), $\boldsymbol{c}$ is the speed of sound in the medium (m/c), $\boldsymbol{w}$ is the frequency of the sound wave. This formula shows the dependence of the sound pressure $\boldsymbol{D}$ on the displacement amplitude of the particles of the environment $\boldsymbol{A}$.

The second constant is the wave (or acoustic) resistance of the environment. This constant more clearly and generally shows the resistance to the sound wave propagation, which is determined by the absorption, refraction and reflection of the sound wave. Acoustic resistance is calculated according to the formula:

$$R_{\text{А}} = pc = \frac{D}{U}, \tag{2}$$

where $\boldsymbol{p}$ is the density of the medium (kg/m^3), $\boldsymbol{c}$ is the speed of sound in the environment (m/c), $\boldsymbol{D}$ is the sound pressure amplitude, and $\boldsymbol{U}$ is the maximum amplitude of the oscillating speed.

For different soils, the absolute value of the acoustic resistance differs sharply from each other. In the technique of acoustic measurements, acoustic resistance is an important informational parameter, because it determines the property of the environment to conduct acoustic energy, including ultrasound. Thus, reflected waves necessarily occur at the boundary of the distribution of environments with different acoustic resistance.

Table 1.

Variable research factors

Depth of compacted soil layer A(X_1)	
-1	50 см
0	25 см
+1	0 см
Installation height of the sensor above the ground surface H(X_2)	
-1	40 см
0	25 см
+1	10 см
Soil moisture δ (X_0)	
-1	54%
0	42%
+1	31%

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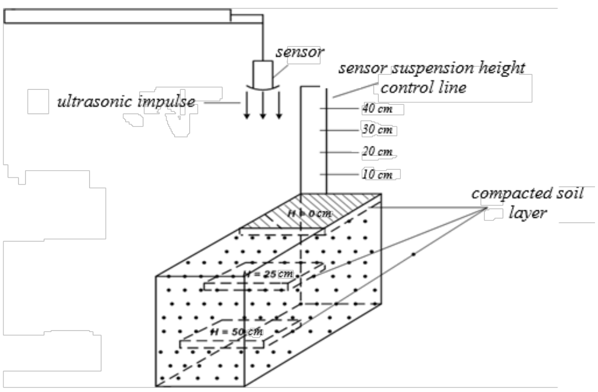
That is, if we take the over-compacted soil layer as a completely rigid body, then a reflected wave will appear at the boundary of the upper and compacted soil layers, which was confirmed by the laboratory experiments.

The aim of this study, both in the laboratory and in the field, was to confirm the theoretical arguments that the acoustic behavior of a plough sole is identical to the acoustic behavior of an absolutely solid (rigid) body (environment), which makes it possible to use ultrasound to determine the depth of the over-compacted soil layer.

The research in the laboratory was carried out using two receiving and transmitting devices (sensors) of radiation: one and two channels.

The research was carried out according to three main variables: the depth of the compacted soil layer ($A(X_1)$), the height of the sensor above the soil surface ($H(X_2)$), and soil moisture ($\delta(X_0)$), the degree of moisture being determined as a percentage (Table 1).

A special laboratory stand was developed for the laboratory experiments (Figure 1). The methodology for determining the dependence of the readings of the experimental radio physical device on the depth of the control compacted surface in the conditions of one type of soil involved installing the device sensor at a given height (0.4 m, 0.3 m, 0.2 m) above a special mobile platform, in which identical boards covered with homogeneous soil were laid at a depth of 0.05 m, 0.25 m, 0.5 m. By moving the platform in such a way that the board was under the sensor at the appropriate depth, the readings of the experimental radio physical device were recorded.



a) Layout of the laboratory setup

б) Installation of the sensor of the experimental radio physical device on the T-150K tractor

Fig. 1. Laboratory test bench

A well-known methodology is used to determine the analytical dependence of the sensor signal on the depth of the compacted soil layer:

$$U = kH, \tag{3}$$

where U is the pressure on the receiver (Pa), k is the ultrasonic wave reflection coefficient ($\%$), H is the depth of the compacted soil layer (cm).

The methodology for determining the dependence of soil moisture on the readings of the radio physical device involved installing its sensor at a height of 0.5 m above a special mobile platform, in which soil of different moisture content is placed in three separate compartments. By moving the platform in such a way that the compartment with soil of this or that moisture content was under the sensor, the readings of the experimental radio physical device were recorded. The analysis of the research results showed that the measurement error increases with the depth of the compacted soil layer (for a depth of 0.25 m - from 4 to 14%, for a depth of 0.5 m - from 6 to 16%).

The volume content of water in the soil, i.e. the soil moisture content, is an important factor that affects the absorption of ultrasonic waves.

As the soil becomes wet, the state of water changes radically. Initially, with a small amount of water, it is only in a chemical or mechanical bound state. When water molecules interact with soil molecules (chemical state) or when they cover the surfaces of solid soil components in a thin layer and are under the significant influence of surface tension forces (mechanical state), this is the so-called bound water. Then, as its amount in the soil increases, the water is already in a free state, and as a result, the physical and mechanical properties of the soil change significantly.

The results of determining the readings of the radio physical device of the depth of the control compacted surface (0.5 m) in the conditions of one type of soil of different humidity (31%, 42%, 54%) when the sensor was installed at a given height (0.4 m, 0.3 m, 0.2 m) are as follows: the measurement error was up to 18%, i.e. the presence of water in the soil causes partial attenuation of the sound wave (its speed decreases): the wetter the soil, the weaker the signal received by the receiver, and if the overly compacted soil layer is at its maximum depth (50 cm) and the topsoil is too wet, the signal may be too weak, leading to false measurements.

One of the tasks of the laboratory study was to determine the dependence of the sensor signal on the soil type. The sensor of the experimental radio physical device was installed at a height of 0.2 m above a special mobile platform. Three types of soil were placed in the mobile platform in turn: sand, black soil and clay, and identical boards were placed at a depth of 0.4 m. By moving the platform so that there was a compartment with a particular soil under the sensor, the sensor signal was recorded. As a result of the test, it was found that these three types of soil have completely different ultrasonic transmittance.

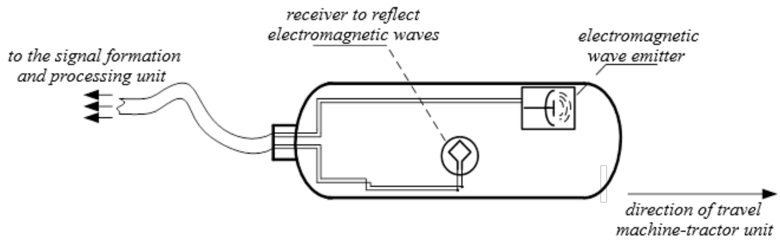
When a wooden board was placed at a depth of 20 cm, imitating the compacted layer, the fastest signal returned to the sensor was from sand, the signal from black soil was weaker, and when scanning clay, the signal was even worse. Without simulating compaction, the signal did not return to the receivers from any type of soil, i.e. the wave was attenuated in sand, black soil, and clay.

However, for our study, this behavior of ultrasound with different soil types is not particularly important, because the main goal is to detect the plough sole, and its acoustic behavior is the same for any type of soil, except for sand, where the wave always dampens.

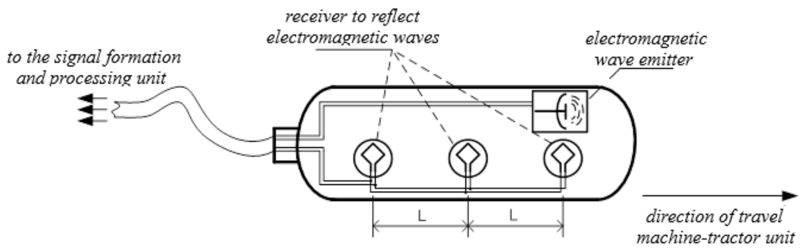
The fact that the measurement error increased with increasing depth of the over-compacted soil layer indicates that due to the acoustic resistance of the upper soil layers, the coefficient of sound energy transmission from one layer to another decreased due to energy losses of the sound wave. Thus, the deeper the over-compacted soil layer is, the greater the measurement error.

The most accurate measurements were achieved when the sensor was installed at a height of 20 cm (error was 4-6%), and the error increased with increasing installation height.

After conducting the first laboratory studies, which were carried out with a single-channel experimental radio physical device, and obtaining quite good results, but taking into account all objective factors related to the mechanical and physical properties of soils, as well as taking into account the natural state of soils, considering that soil, especially in the field, is an extremely difficult environment for ultrasound transmission, with a heterogeneous surface, it was decided to improve the sensor (Figure 2) by adding two additional elements that will be designed only to receive reflected signals. That is, one element of the sensor emits and receives the signal, and the other two elements only receive it, which would allow recording the strongest signal reflected from the soil surface.



a) before improve the design of the sensor



b) after improve the design of the sensor

Fig. 2. Improving the design of the sensor for determining the depth of the compacted soil layer

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After installing two additional elements for all four parameters of the laboratory study: depth of the plough sole, height of the sensor above the soil surface, soil moisture, soil type, the signal received by the sensor became better. The measurement error was decreased by 1-3% in general, and 14-16% in wet soil. The installation height of the sensor of up to 25 cm has also become acceptable (Figure 3).

Another main objective of the research that was carried out was to find out the economy effect, i.e.: whether the application of the experimental radio physical device affects the reduction of fuel consumption during the technological operation of soil loosening. It was possible to verify these theoretical calculations only in the field.

The purpose of the field tests was to: conduct a production test of the operational control system; to establish the effect of automatic control over the execution of the technological process of loosening the soil by a machine-tractor unit on fuel consumption in real operation conditions.

Test objects: Case IH Magnum 290 tractor; Case IH Tiger Mate II soil cultivator; a device for operational control of the depth of movement of a soil cultivator with a two-channel sensor (experimental radio physical device); fuel flow meter IP-151; linear dimensions were fixed with a certified measuring ruler and tape measure P10UZK; a certified electronic stopwatch JS-307 was used to measure time; Revyakin hardness tester.

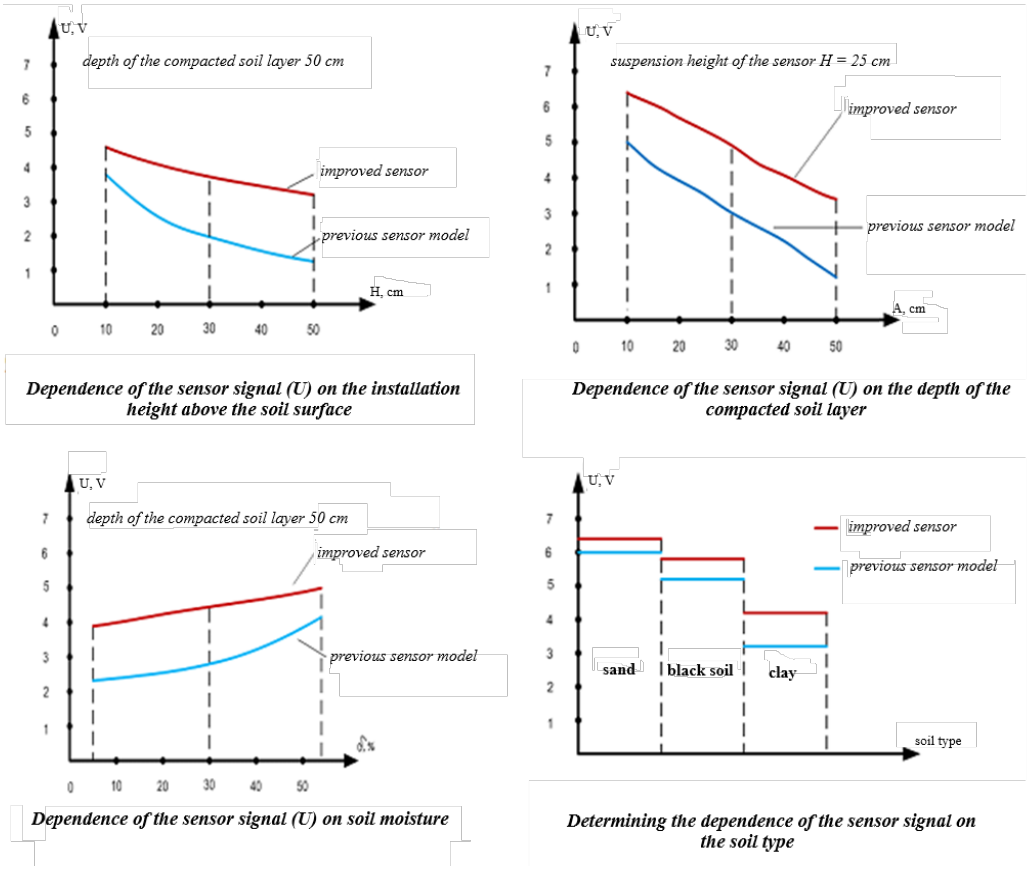

Fig. 3. Results of laboratory tests of signal quality after improving the sensor for determining the depth of the compacted soil layer

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The operability of the device for operational control of the depth of travel of the tiller in the field was checked on a specially prepared area of the field (measurements were taken and stubble was removed). At the same time, the depth of the most compacted soil layer at the points marked by the machine-tractor unit passage points determined by the ultrasonic device was compared with the Revyakin hardness tester readings obtained at these points.

The effectiveness of the operational control of the depth of travel of the tiller was determined by determining the completeness of loosening of compacted soil layers at certain points of the test section of the field. In this case, the height of the cultivator stroke was set by the operator according to the relevant indicators of the information panel of the operational control device.

In general, the production test for detecting over-compacted areas of the field in the field confirmed the theoretical feasibility of using ultrasound and the technical feasibility of using a device for operational control of the depth of travel of the tiller.

However, not everything is so clear. As you can see, even in laboratory conditions, the result of the readings is influenced by the height of the sensor, the degree of moisture in the upper layers of the soil, and the type of soil. The impact of all these factors is amplified in natural conditions. Ultrasound is especially affected by wind, which carries the emitted signal to the side. And even with a reinforced sensor, nothing can be done against the laws of acoustics: the wind has always affected the ultrasound in the field being processed and will continue to do so; water absorbs ultrasound waves and will continue to do so under any conditions.

And if the issue of sensor placement can be solved, for example, by designing a device that will protect the sensor from the wind and this will allow the sensor to be as close to the soil as possible, then stubble or grass must be removed every time, because the wave will scatter in it. Let's summarize this research.

Conclusion. The analysis of the obtained results of laboratory studies showed that the measurement error increases with an increase in the depth of the compacted soil layer. This is due to the negative influence on the emitted ultrasonic pulse of the air and its temperature (and in field conditions, also of the wind).

It was found that the wetter the soil, the weaker the signal that reaches the receiver.

After installing two additional signal receivers on the ultrasonic transmitter and receiver of radiation (sensor of the depth of the compacted soil layer), the research results improved significantly and the height of the sensor installation increased by 5 cm.

The values of the determined depths of the compacted soil layer by the ultrasonic device and the Revyakin hardness meter varied from –9.4 to +16.4%.

The system ensures complete loosening of the compacted soil layer in the zone of seed germination of grain crops.

The developed device for operational control of the depth of travel of the soil cultivator of the agricultural machine-tractor unit provided a reduction in fuel consumption during the technological operation of deep loosening of the soil by 18.7%.

And the main thing – possible operating conditions: ambient temperature from -5^{0} to +55^{0} C; external magnetic fields of direct and alternating current with a frequency of 50 Hz with an intensity of 400 A⋆v/m; atmospheric pressure from 84 to 106.7 kPa; relative air humidity up to 98% at a temperature of 25^{0} C.

In general, both the theoretical and practical possibilities of using ultrasound have been proven by this study, but the practical benefit from this did not completely satisfy us, because to conduct the study in the field we had to wait for dry, windless weather, and the fact that each time you need to remove the stubble - so-so economic benefit.

However, this problem is of interest to us, it raised a lot of questions that need to be answered.

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