Propagation of Waves in the Soil Under the Vibration Effect of Working Bodies on It

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Abstract. The article shows the main problems in using the bit for the main tillage. A method for reducing traction resistance by introducing internally oriented vibrations into the design of a tillage tool is proposed. The design of a debalance vibrator, as well as the principle of its operation, which helps to reduce the traction resistance of deep rippers, is considered. Theoretical hypotheses and directions for further research of this method of solving the identified problem are formulated.

1. Introduction
The main task of reducing the specific fuel consumption, and therefore reducing the cost of production, was solved. It is necessary to look for new progressive approaches to soil treatment with the help of existing well-proven machines.

This kind of soil treatment can include the process of longitudinal cutting. It is well established in North and South America, as well as in some European countries. This has played a crucial role in reducing soil erosion and increasing yields. Although the slits reduce the cost of tillage due to productivity, the traction resistance of the tools is still high, since the slits are cut to a depth of up to 40 cm. In addition, the slits are not made by individual tools, but by combined ones. As a result, we have to use energy-saturated tractors. This problem can be solved using vibration tools [1, 2, 3].

The use of vibrations in soil cultivation is quite promising, but insufficiently studied process [4, 5]. The main difficulty of theoretical research is that soils are very diverse in their properties and are a complex viscoplastic environment. It is believed that vibration reduces the coefficient of friction of the soil on the working body, since it is recognized as obvious: during vibration, the contact surfaces are momentarily separated, and the material passes through the working body some part of the way without friction.

V. V. Vasilenko et al. [6], the influence of vibration on the angle of friction of the soil on the working body is established. The average value of the ground friction angle on steel was $\varphi = 0.548$ rad with an average square deviation of $\sigma = 0.003$ rad. Vibration reduces the friction angle to $\varphi = 0.463$ rad with an average square deviation of $\sigma = 0.01$ rad. The coefficient of friction acquires the values $f = 0.61$ without vibration and $f = 0.50$ with the vibration of the friction surface, respectively. These experiments have shown that vibration can reduce the coefficient of friction by 18%.
Currently, quite a lot of work has appeared in the field of vibrational tillage. Some developments are implemented and used on tillage tools. However, from the moment when academician V. P. Goryachkin put forward the idea of vibrational destruction of soil material, the nature of wave propagation in the ground under the vibration action of working bodies is not completely clear.

2. Materials and methods of research
Consider the movement and longitudinal vibration of the working body (Fig. 1).

An absolutely solid working body oscillates in an elastic ground having a constant linear mass \[ m = p \cdot A, \]  
(1)

where \( P \) is the density of soil material, kg / m\(^3\);
\( A \) is the cross-sectional area of the selected soil element, m\(^2\).

The equilibrium equation of the selected soil element (Fig. 2) writes as follows:

\[ \frac{dN}{dx} = -q, \]  
(2)

where \( dN \) is the increment of the longitudinal force on a section of length \( dx \), N;
\( q \) - the maximum distributed load on the ground from the vibration action of the working body, N.

If we replace \( N = E \cdot A \cdot \left( \frac{ds}{dx} \right) \) and differentiate this equality, we get

\[ \frac{d}{dx} \left( E \cdot A \cdot \frac{ds}{dx} \right) = -q, \]  
(3)

where \( E \) is the modulus of longitudinal elasticity of the soil, MPa.

In this case, the movement of the soil layer \( s \) along the \( x \) axis will depend on the \( x \) coordinate and time \( t \). Therefore, the derivative of the \( x \) function \( s(x, t) \) must be considered as a partial derivative, that is \( \left( \frac{d}{dx} \right) \). The load of the inertia force acting on the soil element is determined

\[ q = -m \cdot \frac{d^2s}{dt^2}. \]  
(4)

Then the equation of motion for longitudinal vibrations of the soil element (3) at \( E \cdot A = \text{const} \) is obtained as
\[ c^2 \cdot \frac{d^2 s}{dx^2} = \frac{d^2 s}{dt^2}, \]  
(5)

where \[ c = \sqrt{\frac{E \cdot A}{m}} = \sqrt{\frac{E}{\rho}}, \]  
(6)

Equation (6) is called the wave equation or the velocity of propagation of elastic longitudinal waves in the soil (Newton’s formula). Then for the propagation velocity of elastic transverse waves we write

\[ c_n = \sqrt{\frac{G}{\rho}}, \]  
(7)

where \( G \) is the shift modulus, Pa.

Equation (6) is more suitable for rod-shaped solids. For an unlimited medium, which can also include soil, the equation of the velocity of propagation of elastic longitudinal waves is written as [7.8]

\[ c = \sqrt{\frac{E \cdot (1 - \mu)}{\rho \cdot (1 + \mu) \cdot (1 - 2\mu)}}, \]  
(8)

where \( \mu \) is the Poisson’s ratio.

However, elastic waves in the soil environment do not cause residual deformations (i.e. they are reversible), so we will not get a result on the variability of mechanical characteristics. Based on the research, for example, for loam soil with a density of \( \rho = 1600 \text{ kg/m}^3 \): the propagation speed of elastic longitudinal waves is equal to \( C = 300 \text{ m/s} \), elastic transverse waves \( S_p = 140 \text{ m/s} \) [8].

All values of mechanical characteristics correspond to the material under static loading. If we affect the soil in the form of vibration, then the concept of dynamic characteristics is more appropriate here [7]. Then

\[ \mu_d = \frac{c^2 - 2c_n^2}{2 \cdot (c^2 - c_n^2)}, \]  
(9)

\[ E_d = \frac{c^2 \cdot \rho \cdot (1 + \mu) \cdot (1 - 2\mu)}{(1 - \mu)}, \]  
(10)

where \( \mu_d \) is the dynamic Poisson’s ratio; \( E_d \)-dynamic modulus of longitudinal elasticity, Pa.

After analyzing equations (9), (10) and using experimental data, we can conclude that the dynamic Poisson’s coefficient does not change during the vibration action of working bodies on the soil, and the dynamic modulus of longitudinal elasticity decreases by 4.5 or more times. Thus, for the same amount of force action, we get a greater absolute elongation of the material \( \Delta l \).

\[ \Delta l = \frac{N \cdot L}{A \cdot E}, \]  
(11)

where \( L \) is the initial length of the processed material, mm.

Absolute elongation and initial length are related by the ratio

\[ \varepsilon = \frac{\Delta l}{l}, \]  
(12)

If you take values of \( N, L, A, E \), and constants, and the relative longitudinal elongation \( \varepsilon \) increase linearly in proportion to the decrease in the modulus of elasticity \( E \), i.e. the soil is at lower deformation goes from elastic to a plastic condition will begin to collapse.

3. Results and discussions

Let us now consider the process of interaction of the working body with the soil (Fig. 3), which has a forward movement and a vibration speed of \( V \). For a short period of time \( dt \), the working body will pass the path \( \Delta s = V \cdot dt \), creating a longitudinal relative deformation in the soil \( \varepsilon \). From the working body,
this deformation will spread along the soil layer at a speed of \( C \) and during \( dt \) will create compression at the length \( l = C \cdot dt \). If we assume that the relative longitudinal strain \( \varepsilon \) is distributed evenly over this infinitesimal area, we will find the relative longitudinal strain and stress at the point where the working body interacts with the soil.

\[
\varepsilon = \frac{\Delta s}{l} = \frac{V dt}{c dt} = \frac{V}{c},
\]

\[
\sigma = \varepsilon \cdot E_o = \frac{V}{c} \cdot E_o.
\]

Thus, it can be concluded that contact stresses and relative deformation depend only on the speed of vibration of the working body.

\[
V = \frac{\sigma_d \cdot c}{E_o},
\]

where \( \sigma_d \) is the dynamic strength limit of the soil, Pa.

Then, in order to obtain residual deformations in the soil, it is necessary that the vibration speed of the working body \( V \) be at least 0.078 m/s, depending on the specified mechanical characteristics of the material.

4. Conclusions
The vibration effect of the working body on the soil creates waves in it that propagate to the value \( l \) and contribute to the destruction of the soil structure and the appearance of microcracks in it, as a result, the mechanical characteristics of the soil change, which leads to a decrease in the traction resistance of the tool.

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