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Theoretical justification of the parameters of the device for vertical measurement of soil hardness

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Abstract. When evaluating tillage machines, one of the important places is occupied by agrotechnical assessment of the quality of the technological process of tillage. The properties of the soil as an object of cultivation, as well as the processes occurring during the interaction of the soil with any materials, are studied by agricultural mechanics, created by V.P. Goryachkin. One of the most important characteristics of the soil condition is the hardness of the soil, or the resistance provided by the soil to the penetration of any deformer into it. This article describes the forces and stresses that occur when the plunger penetrates into the soil. According to the theoretical provisions, friction force F, drag force Q, total force P, stresses σ1 and hardness T are calculated, theoretical dependences of soil hardness on the tip diameter on compacted and loose soil are given.

1 Introduction

When evaluating tillage machines, one of the important places is occupied by agrotechnical assessment of the quality of the technological process – tillage, and includes the determination of indicators of the state of the soil before processing, as well as indicators of the quality of the technological process, determined on already treated soil [1–3].

The properties of the soil as an object of cultivation, as well as the processes occurring during the interaction of the soil with any materials, are studied by agricultural mechanics, created by V.P. Goryachkin. One of the most important characteristics of the soil condition is the hardness of the soil, or the resistance provided by the soil to the penetration of any deformer into it [4, 5].

2 Materials and methods

To determine this indicator, devices for vertical measurement of soil hardness are used, the main working body of which is a plunger buried in the soil, and, as a rule, having a replaceable tip. Manual hardness testers used in tests have replaceable tips in the form of a flat disk with a base area of 1; 2 and 3 cm^2 with a plunger diameter of 1 cm. The size of the tip is selected depending on the density of the soil. However, the processes occurring in dense and loose soil are different, and the ratio of the diameter of the tip and the diameter of the plunger of the hardness tester is not justified.

If the tip has an equal diameter with the plunger or close to it, then the force required to bury the plunger will be greater, that is, the readings of the hardness tester will be overestimated, since the effect of soil exposure on the lateral surface of the rod is not taken into account.

Studies by a number of scientists [7-9] have proved that the soil has elastic properties, that is, the soil is characterized by partial recovery of volume when the applied load is removed.

We consider the penetration of a flat tip into the soil and its movement at a constant speed. If the depth is large enough in comparison with the width of the deformer, then the stress field in which the soil movement occurs and the stresses caused by it can be considered constant during the period of deepening. [9]

We consider two cases: the first is when the diameters of the plunger d and the tip *D* are equal, and the second is when the diameter of the tip *D* is greater than the diameter of the plunger *d*. Since we are interested in determining the effect of the ratio of the plunger and tip diameters on the accuracy of hardness determination, in the second case we will consider two options: immersion in loose soil and in untreated.

3 Results and discussion

The deepening of a flat cylindrical tip into the soil is accompanied by the appearance of a stress zone under it. Stresses cause the movement of structural soil particles, partial destruction and their mutual displacement. The theory of soil destruction assumes that when a certain load occurs on the surface, a certain array of stresses arises under it. A model formulated by Coulomb is known and used to describe the destruction of soil. According to this model, the load applied to the soil causes the destruction of the soil, the boundary of which is formed at an angle of $(45^0 - \varphi/2)$ to the soil surface,

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where φ is the angle of internal friction of soil particles, deg. (fig. 1).

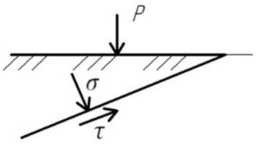

Fig. 1. Stresses arising in the soil sample during shear

According to Coulomb's law, the shear stress required for fracture must exceed the adhesion force of soil particles in the fracture plane and the friction force between surfaces at the fracture boundary. The calculated value of the required shear stress is:

$$\tau = c + \sigma_n tg\,\varphi, Pa, (1)$$

where c is the adhesion tension, Pa;

σ_n is the normal stress on the plane of destruction, Pa.

Adhesion tension c and angle of internal friction of soil particles φ depend on the mechanical composition of the soil, moisture content, porosity.

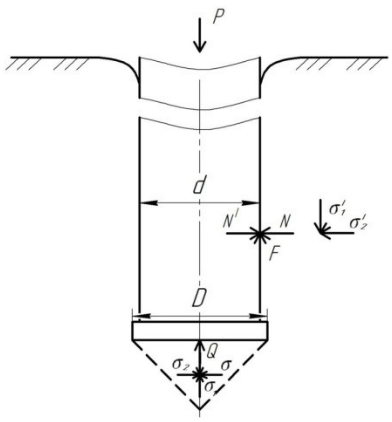

Fig. 2. Diagram of forces and stresses arising when the plunger penetrates into the soil

Let the tip of the hardness tester have a diameter D, and the diameter of the plunger d (fig. 2). Consider the case in which $D = d$. When the flat tip is immersed with the applied force P, according to the Coulomb-Mohr law, the normal stress in the stressed zone having the shape of a wedge (shown by the dotted line) is equal to:

$$\sigma_1 = \sigma_2 tg^2\left(45 - \frac{\varphi}{2}\right) + 2c\,tg\left(45 - \frac{\varphi}{2}\right), Pa, (2)$$

where σ_1 is the vertical stress acting on the tip surface, Pa;

σ_2 is the horizontal voltage, Pa.

The total force Q acting on the tip will be equal to:

$$Q = \sigma_1 S, N, (3)$$

$$S = \frac{\pi D^2}{4}, m^2, (4)$$

where S is the tip area, m^2.

$$Q = \sigma_1 \frac{\pi D^2}{4}. (5)$$

A cone-shaped zone with a base on the top surface appears on the surface of a solid material (tip) penetrating into an isotropic material. Such zone is called a compacted core with a taper angle $\gamma = 2\varphi$. When the tip moves, this compacted core acts on the soil and causes it to move sideways and compact under the action of the applied load. The stress σ_1 inside the core determines the force with which it acts on the surrounding masses of soil. If we take an element of the soil mass lying outside the zone of the compacted core at some depth h under the steady-state mode of sinking, then there will also be stresses arising due to the pressure of the overlying layers: σ_1' – vertical stress and σ_2' – horizontal stress.

The vertical stress acting on the soil element from the own weight of the soil is [11]:

$$\sigma_1' = ph, Pa. (6)$$

where p is the soil density, kg/m^3;

h is the location depth of the considered point, m.

The stress acting in the horizontal direction on the soil mass is equal to:

$$\sigma_2' = \xi \sigma_1', Pa. (7)$$

where ξ is the coefficient of lateral pressure in natural occurrence, depending on the type and condition of the soil.

Then:

$$\sigma_2' = \xi ph. (8)$$

During penetration, the side surfaces of the plunger and the tip from the side of the contacting soil are affected by the force of normal pressure N and the friction force F, directed against the direction of movement. The resultant of these forces R deviated from the normal by the angle of friction, this is the force with which the soil acts on the side surface of the plunger. Also, the plunger surface acts on the soil with the force R' directed in the opposite direction, and, accordingly, with the force N'. The force N' is equal to:

$$N' = \sigma_1' S', N. (9)$$

where S' is the area of the lateral surface of the plunger and tip, m^2.

Then the friction force will be equal to:

$$F = fN', N. (10)$$

where f is the friction coefficient of the soil on the material of the plunger.

$$F = f\,\xi ph\pi dl, N, (11)$$

where l is the length of the immersed part of the plunger, m.

Since l is the depth of the considered point of action of the force, the expression (11) can be represented as:

$$F = f\,\xi p h^2 \pi d,\ N. \quad (12)$$

The friction force from the side of the soil will also act on the side surface of the tip, but since its height is rather small compared to the length of the plunger, it can be neglected.

Assuming that from the equilibrium condition, $\sigma_2 = \sigma_2'$, we get that:

$$\sigma_1 = \sigma_2'\left[tg^2\left(45 - \frac{\varphi}{2}\right) + 2c\,tg\left(45 - \frac{\varphi}{2}\right)\right] =$$

$$= \xi p h\left[tg^2\left(45 - \frac{\varphi}{2}\right) + 2c\,tg\left(45 - \frac{\varphi}{2}\right)\right]. \quad (13)$$

Then:

$$Q = \frac{\pi D^2}{4}\xi p h\left[tg^2\left(45 - \frac{\varphi}{2}\right) + 2c\,tg\left(45 - \frac{\varphi}{2}\right)\right]. \quad (14)$$

Friction force F and the normal pressure force of compressive resistance (frontal resistance) Q balance the penetration force P, i.e.:

$$P = F + Q. \quad (15)$$

$$P = f\,\xi p h^2 \pi d + \frac{\pi D^2}{4}\xi p h\left[tg^2\left(45 - \frac{\varphi}{2}\right) + 2c\,tg\left(45 - \frac{\varphi}{2}\right.\right.$$

$$P = \xi p \pi\left\{f h^2 d + \frac{\pi D^2}{4}\left[tg^2\left(45 - \frac{\varphi}{2}\right) + 2c\,tg\left(45 - \frac{\varphi}{2}\right)\right]\right\}$$

Hardness (or soil resistivity) by its definition is the ratio of the resistance force to the area of the tip:

$$T = \frac{P}{S},\ Pa, \quad (16)$$

or

$$T = \frac{\sigma_1 S + \sigma_2 S'}{S}. \quad (17)$$

$$T = \sigma_1 + \frac{F}{S}. \quad (18)$$

That is, σ_1 is the specific drag force, then it is a value that does not depend on the area *S*. Since when finding *T*, σ1 does not depend on *S*, the friction force *F* on the side surface of the plunger has a greater influence on the value of *T*.

Now we consider the plunger movement in the case when the plunger diameter is smaller than the tip diameter: *d*<*D* (fig. 3).

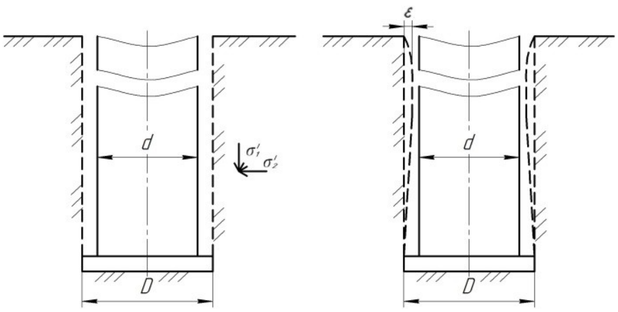

Fig. 3. Plunger immersion scheme with a tip (D>d): a) in dense soil; b) loose soil

If the soil has a high density, then the angle of internal friction of the soil in this case will have a smaller value, and the adhesion force will have a larger one. The force transmitted by the tip as it passes will compress the walls of the hole. It has been proven [7–9] that the soil belongs to the media with elastic-plastic properties, that is, it is able to restore, partially or completely, its initial volume after the application and removal of a short-term load. The process of volume restoration after applying a certain load under any conditions lasts no more than 15 sec., and the time during which a significant part of the volume is restored is 3–6 sec. [12]. That is, this value is comparable to the time during which the process of immersion of the hardness tester plunger takes place. In this case, the nature of the volume recovery proceeds according to the law described by the logarithmic dependence:

$$p_i = p_{max} e^{-bt},\ kg/m^3, \quad (19)$$

where p_i is the value of soil density in the process of unloading, kg/m^3;

p_{max} is the maximum value of density during loading, kg/m^3;

b is the experimental coefficient;

t is the time of unloading, sec.

The change in the value of decompaction ε from 0 to ε_{max} of the soil sample subjected to the action of the load and compaction p_{max} occurs within 3...6 sec. Let us assume that the load applied to the walls of the hole with diameter *D* formed during the passage of the tip compacts the walls (ε=0). According to the law of elastic deformations, the value of ε will increase according to dependence (17), acquiring the value of ε_{max} within 3 sec.

It can be assumed that when the tip reaches the maximum depth in the upper part of the plunger at a depth h', the friction force F' will act. Taking into account the average immersion time and the distance traveled, it can be assumed that h'=¼*h*, in this section of the hole ε will be equal to ε_{max}, and in the lower layers it will be zero.

Thus, if the ratio *D*–*d*<2ε, then with an increase in ε in the upper layer, a friction force F' is equal to:

$$F' = f\,\xi p (h')^2 \pi d. \quad (20)$$

In the case when *D–d*>2ε (fig. 3), it is theoretically possible to take the friction force *F* equal to zero, since the hole wall does not act on the side surface of the plunger. The force of friction on the side surface of the tip is neglected.

In the second and third cases, we assume that with an increase in *D*, and, accordingly, *S*, σ_1 remains constant, and *P* increases in proportion to *S*.

Now consider the movement of the tip in loose soil. The tip, plunging, compresses the soil and deforms it in lateral directions. In this case, a compacted core is created, which perceives the frontal resistance to penetration and tangential friction forces along the side surface of the tip. The soil from the impact of the tip is compacted, and a well with compacted walls is formed. The degree of their compaction depends on the initial compaction of the soil and its properties - the adhesion force and the angle of internal friction.

Theoretically, we assume that in the case of both *D*=*d* and for *D*>*d*, the forces *F*, *Q*, *P* and the values σ_1 and $\sigma_2^{¿}$ will be determined according to the above expressions. That is, if the soil is loose and the force N_1 applied in the lateral direction is less than the cohesive forces of the soil, then soil particles, crumbling from the walls of the well, will act on the side surface of the plunger (fig. 4, b).

According to the theoretical provisions, the calculation of the friction force *F*, the frontal resistance *Q*, the total force *P*, the stress σ_1 and the hardness *T* was carried out, with the following parameters corresponding to the moisture content of the medium loamy black soil of 24%: for movement in solid soil with c=400·10^3 kg/m^2, φ=22^0; ξ=0,7, p=1.2·10^3 kg/m^3. When calculating in the case of movement in loose soil, the density was taken equal to 0.9·10^3 kg/m^3, c=300·10^3 kg/m^2, φ=26^0.

Calculations were carried out for the following points: *D*=*d*=11 mm; *D–d*<2ε (*D*=13 mm, *d*=11 mm) (in this case, it was assumed that within 3 sec the precipitation *ε* reaches the value *ε*>(*D–d*)/2 in the upper 50 mm layer. So friction force *F*, and in the underlying ones – *F*=0, let's say that *F* will be recorded when the tip of the lower layer passes 30 cm); *D–d* >2ε (*D*>13 mm), in this case *F*=0 was taken.

The results of calculating the soil hardness are shown in fig. 4, 5.

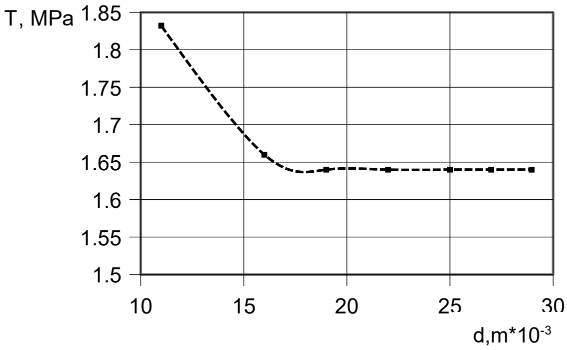

Fig. 4. Theoretical relationship between soil hardness and tip diameter (compacted soil)

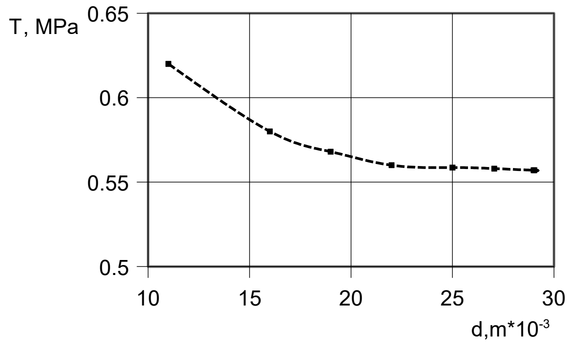

Fig. 5. Theoretical relationship between soil hardness and tip diameter (loose soil)

4 Conclusion

On the basis of the theoretical studies, the following conclusions can be drawn.

Calculations performed according to theoretical provisions showed that the decrease in soil hardness with an increase in the cross-sectional area of the measuring device tip is explained by the decrease in the *F*/*S* value in formula (1), due to the fact that the plunger diameter *d* remains constant, and the ratio *D*/*d* increases. The stress that occurs on the surface of the tip remains constant with a change in its diameter, which means that the total force *P* is more influenced by the friction force along the side surface of the plunger, which decreases with increasing *D*/*d*.

References

1. M.A. Kanaev, O.V. Karpov, S.A. Vasiliev, M.R. Fathutdinov. *Theoretical research of the scaffolder and soil interaction*, Bulletin of Samara State Agricultural Academy **3**, 19-23 (2017)

2. O.N. Chernikov, A.P. Bychenin, D.S. Sazonov, *Soil structure and hardness change resulting from the depth of a tractor track under different wheel drive towing strength*, Bulletin of Samara State Agricultural Academy **1**, 22-27 (2019)

3. M.P. Erzamaev, D.S. Sazonov, E.S. Nesterov, S. N. Zhil'tsov, *The influence of tillage longline process parameters for energy outlay*, Bulletin of Samara State Agricultural Academy **2**, 3-12 (2018)

4. G. Eudoxie, D. Phillips, R. Springer, *Surface Hardness as an Indicator of Soil Strength of Agricultural Soils*, Open Journal of Soil Science, 341…346 (2012)

5. T.S. Nugmanova, *Improvement of methods and technical means for determining soil condition indicators during testing of tillage machines*, Diss. cand. tech. sciences. Samara (2002)

6. V.F. Babkov, V.M. Bezruk, *Fundamentals of soil science and soil mechanics*. Moscow, Higher School (1986)

7. V.M. Matsepuro, *Investigation of the laws of soil and*

soil resistance, Diss. cand. tech. sciences. Minsk (2002)

8. V.N. Savinykh, *Investigation of the regularities of stress relaxation and soil resistance to deformation as the basis of technological design of earthworking processes*, Diss. cand. tech. sciences. Minsk (1971)

9. S.S. Nugmanov, S.I. Vasiliev, T.S. Gridneva, *Methods and technical means for measuring soil hardness in coordinate agriculture*, Monograph (2009)

10. A. Kulen, H. Kuipers, *Modern agricultural mechanics*. Moscow, Agropromizdat (1986)

11. N.A. Tsytovich, *Mechanics of soils*. Moscow, Higher School (1979)

12. Yu.A. Saveliev, P.A. Ishkin, *Improving the efficiency of soil decompression using shallow autumn strip treatment*, Monograph (2017)

13. Yu.A. Savelyev, Yu.A. Kirov, P.A. Ishkin, M.A. Petrov. *Optimization of parameters of powered tillage tool with soil spikers*. Bulletin of Samara State Agricultural Academy **3**, 30-38 (2021)