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Analysis of research on soil destruction criteria during its interaction with working bodies

Vladimir I. Konovalov*

Chair "Processes and machines in agribusiness" of the faculty of mechanization of Kuban State Agrarian University named after I.T.Trubilin, 350044, Krasnodar, Russia

Abstract. Under the action of the working surface of the tillage unit, three mutually perpendicular stresses and corresponding deformations occur in the soil layer, which are characterized by different time functions. The finding of these functional relationships is the fundamental task of agricultural mechanics, with the help of which the process of soil crumbling with different physical and mechanical properties can be described in interaction with working bodies. The article presents an analysis of the results of studies of domestic and foreign scientists of the process of soil destruction in its interaction with working bodies. When considering the process of soil destruction from the point of view of stress theory, the Coulomb-Mohr theory of destruction is most often used. It is proposed to expand the consideration of the process of soil destruction by adding elements to the theory of strength that will describe the rate of change of the acting loads.

1 Relevance of research

Intensive population growth in the global space, as well as the peculiarities of the global economic model, inevitably leads to stricter requirements for the efficiency of any agricultural production. Not so long ago, the main task of the agricultural industry was considered to be obtaining a given volume of a particular product with specified quality parameters. However, in recent years, the requirements have shifted somewhat, and the requirement to minimize the reduced costs in the production of agricultural products has been added to this task [9, 10, 19].

Crop production is considered the most important element of the agricultural sector of the Russian Federation, which uses an interconnected set of technologies for soil treatment, fertilization, plant protection, harvesting, etc. [4, 6, 13, 14]. In the world, disk working bodies are increasingly used for tillage, which cut off, crumble, shift and partially wrap the treated layer in the process of work [12, 15, 16, 18].

2 Problem statement

Strict requirements to the quality of soil crumbling are made according to the agrotechnical requirements in the process of working bodies operation, in addition to the requirements to

* Corresponding author: konovalov.v.i@mail.ru

the depth of processing. Many domestic and foreign scientists, including Goryachkin V. P., Zheligovsky V. A. et al, were engaged in the problems of soil crumbling, or rather its deformation in the process of interaction with working bodies [2, 3]. The results obtained by them clearly state that the fundamental task of agricultural mechanics is to study and build a model of the process of interaction between the working body and the soil, in order to minimize its energy intensity. Despite such a seemingly simple task, many scientists have been struggling to solve it for more than a dozen years, which is explained not only by the great variety of working bodies and soil types, but also by its significantly changing physical and mechanical properties, even on a single site within one year. In addition, the case is complicated by the variety of approaches and methods for solving it, so at the initial stage, it is necessary first of all to analyze them, to choose the most rational algorithm for achieving the goal and determine the necessary elements for research.

3 Presentation of main research material

Most scientists associate the interaction of the working body with the soil with the work of a dihedral or trihedral wedge. In the general case, three mutually perpendicular stresses arise in the soil under the action of the working bodies on the soil aggregates, which are characterized by their magnitude and are called the main, minimal and medium or medium, and are also invariants of stress state. The voltage value is determined by the dependence [5]:

$$\lim_{dA\to 0}\frac{\sum F}{dA} = p, \tag{1}$$

where $\sum F$ – sum of all forces acting on an elementary area dA;

dA – elementary area (point) in which present stresses are considered.

Most often, the stresses that occur in any plane are considered as stresses acting on all the faces of the elementary cube for simplification. Under the current stresses, an elementary cube can condense, deform, collapse, and move like a solid. As A. Kulen and H. Kuipers point out that the compression and deformation of such cubes can be considered from the point of view of stress theory [5]. At the same time, there is a relationship between the resulting stresses and deformations of the elementary cube, which can be attributed to the characteristics of each type of soil [11, 17, 18].

In the general case, stresses and deformations are functions of time, and their general relationship is determined by the expression [5]:

$$\begin{bmatrix} \sigma_x(t) & \tau_{xy}(t) & \tau_{xz}(t) \\ \tau_{yx}(t) & \sigma_y(t) & \tau_{yz}(t) \\ \tau_{zx}(t) & \tau_{zy}(t) & \sigma_z(t) \end{bmatrix} = f(\begin{bmatrix} \varepsilon_x(t) & \varepsilon_{xy}(t) & \varepsilon_{xz}(t) \\ \varepsilon_{yx}(t) & \varepsilon_y(t) & \varepsilon_{yz}(t) \\ \varepsilon_{zx}(t) & \varepsilon_{zy}(t) & \varepsilon_z(t) \end{bmatrix}) \tag{2}$$

where σ_x, σ_y, σ_z – normal stresses;

τ_{yx}, τ_{zx}, τ_{xy}, τ_{zy}, τ_{xz}, τ_{yz} – stresses of shift (tangential components);

ε_x, ε_y, ε_z – normal deformations;

ε_{yx}, ε_{zx}, ε_{xy}, ε_{zy}, ε_{xz}, ε_{yz} – deformations of shift (tangential deformations);

The left and right parts of expression (2) are called the stress tensor and the strain tensor, respectively.

Academician Goryachkin V. P. in his works pointed out that during the interaction of the working body with the soil, there are deformations of tension, compression, shear, torsion and bending, but only tension and compression can be considered the main ones, and the rest of the stresses are derivatives. Bending is reduced to a complex strain of compression and tension, shear stress and torsion are reduced to equal compression and tension in the direction of diagonals [2].

At the same time, according to the works of Coulomb and Mohr, the maximum and minimum have decisive values for determining the magnitude of destructive stresses, and the average ones determine only the plane of destruction, which always passes through the direction of the average stress. In other words, the destruction of the soil always occurs in two definite directions, which are located at a certain constant angle $\theta /2$ to the minimum of the main stress and passes through the middle ones. The relationship between the limit values of stress k^1, compression k^2, torsion k^3, net shear stress k^4 and the angle of failure θ is determined by the dependencies [2]:

$$\frac{1}{k_3} = \frac{1}{k_1} + \frac{1}{k_2}, \tag{3}$$

$$\cos\theta = \frac{k_2 - k_1}{k_2 + k_1}, \tag{4}$$

$$tg\frac{\theta}{2} = \sqrt{\frac{k_1}{k_2}}, \tag{5}$$

$$k_4 = \frac{1}{2}\sqrt{k_1 k_1}, \tag{6}$$

where k_1, k_2, k_3, k_4 – the limit value of the net tension, compression and torsion, respectively;

θ – with the angle of destruction

For the graphical representation of stresses on any plane through a point, the 'Mohr circle' method is used (Fig. 1), in which the area includes the geometric location of the points that satisfy the expressions [5]:

$$\begin{aligned} \sigma &= \sigma_1 \cos^2\theta + \sigma_3 \sin^2\theta, \\ \tau &= (\sigma_1 - \sigma_3)\sin\theta\cos\theta, \end{aligned} \tag{7}$$

where σ – normal stress on the plane under consideration;

τ – shear stress at the point in question;

σ_1 – main normal voltage;

σ_3 – minimum normal voltage;

θ – angle between the plane and the horizontal.

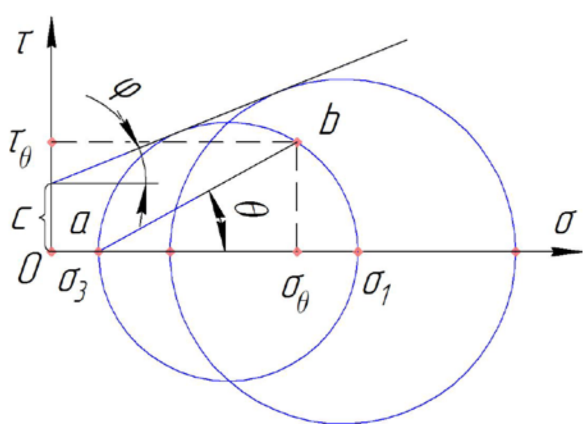

Fig. 1. Graphical method for representing stresses by the Mohr circle

The specified method is used in the following sequence:

1) selection and construction of a rectangular coordinate system σ and τ;

2) plotting the values of the main σ_1 and minimum σ_3 of the normal stress on the axis σ;

3) plotting a circle through the obtained points σ_1 and σ_3 with the center on the axis σ;

4) plotting the segment *ab* from the point σ_3 at the angle θ to the axis σ and obtaining the point *b* of the intersection of the segment with the circle;

5) determination of coordinates of the point *b*, which will have the value of the effective stresses σ and τ.

Thus, it is possible to determine the normal stress σ and the shear stress τ at any angle θ at known values σ_1 and σ_3. Different combinations of stresses σ_1 and σ_3 at different physical and mechanical properties of the soil, for example, at different humidity, give different strength indicators. At the same time, if we draw a general tangent to obtained circles, it will be a graphical representation of the Coulomb-Mohr law and will show the angle of internal friction of the soil φ as the angle between the tangent and the axis σ, and its intersection with the axis τ will determine the connectivity of the soil *c* [5]. In this case, the Coulomb-Mohr law for saturated soil will be written by the expression (8), and for unsaturated soil by the expression (9):

$$\tau_f = c' + (\sigma_n - p_\omega) tg\varphi', \tag{8}$$

$$\tau_f = c' + (\sigma_n + \chi s_\omega) tg\varphi', \tag{9}$$

where τ_f – shear stress at destruction in the plate of rupture;

c' – real cohesion;

σ_n – normal stress on the plane of rupture;

p_ω – pressure of soil moisture;

φ' – real angle of inner friction;

χ – degree of soil moisture saturation;

s_ω – prevailing suction pressure of soil moisture..

The disadvantage of the Coulomb-Mohr theory includes the rate of the load's change which is not taken into account.

Academician Zheligovsky V. A. pointed out that the cultivated soil layer is destroyed in two stages: disintegration into large blocks and into small-lumpy soil elements. In the process of working, the wedge presses on the soil with its working surface, and the soil can deform under external pressure and resist deformation, and in the process of deformation the resistance forces of the soil increase as the wedge compaction takes place. In the process of lifting the layer on the working surface, the soil crumpling at the base of the raised layer increases. At the same time, as soon as deformation of crumpling reaches the day surface, the formation layer ceases to increase the resistance to crumpling and the growth of pressure of the working surface on it and its further compaction stops. As a result of this interaction, the overlying soil layer will shift relative to the underlying layer, i.e., the shear deformation will occur. Due to the different speeds of soil elements movement relative to the contact plane of the working body and the processed layer, the destruction due to shear deformations and the resulting tangential stresses occurs from the day surface to the furrow. It should be noted that this process of soil breaking into large blocks takes place by a different mechanism on soils with different soil conditions. For example, when the soil is very wet or blackened, when the rupture resistance (soil adhesion) is high, the block may not move relative to the underlying layer, resulting in solid shavings. The process of soil destruction into small-lumpy soil elements, according to the hypothesis of Zheligovsky V. A., occurs due to the potential energy of dispersed, pinched and compressed soil air under the influence of the working body [3]. In addition, Zheligovsky V. A. indicated that the bending of the soil formation does not have a strong effect on its crumbling.

The vectors of interaction of the pressure force of the surface of the working body on the soil are deviated from the normal to the surface by the angle of the soil friction φ over the material of the working body.

Buromsky V. I. investigated the degree of crumbling of the soil formation depending on the location and place of the concentration of pressure forces on the soil. According to the data obtained by him, the best crumbling of the formation occurs if the concentration of pressure forces on the soil from the working body is located in the first third of the thickness of the processed layer from the day surface. The most unsatisfactory variant is shown by cases when the concentration of pressure forces on the soil is located below the bottom of the furrow or on the day surface [1].

Novikov Yu. F. conducted studies on the distribution of stresses in the soil formation and its density during the soil plowing by various types of units, according to which, the destruction of the formation occurs in the area of the ploughshare and the chest of tillage, i.e., in the place of soil compression and pinching of soil air, and the rest of the dump is mainly the transportation of soil and its partial destruction due to partial collapse downwards under its own weight [7, 8]. Thus, the results of researches of Novikov Yu. F. also confirm the hypothesis of Academician V. A. Zheligovsky.

The results obtained are consistent with the elements of the theory of the total specific potential energy of deformation, which is used in the resistance of materials, but it also does not take into account the rate of occurrence or change of the stress state. At the same time, it should be noted that most researchers claim an increase in the stress state of the body with an increase in the speed of the load action, or, in the case of agriculture, with an increase in the speed of the unit movement [3, 4].

4 Conclusion

The process of soil crumbling is best considered with the application of the Coulomb-Mohr law for materials that are not equally resistant to compression and tension. At the same time, the study and construction of the process's model of interaction between the working body and the soil must be carried out taking into account the rate of load change. The main stresses, compressions, and stretches should be considered, in which the difference between the minimum and maximum stresses is of the greatest importance, and the average determines the distruction plane. All researches confirm a direct relationship between the moisture content, the granulometric soil composition and the degree of its crumbling, and also note an increase in the degree of crumbling with an increase in the speed of the unit. The optimal humidity is the humidity corresponding to the ripeness of the soil, which is 40-60% of its total moisture capacity, depending on the type of soil.

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