Article

Maximum Admissible Slip of Tractor Wheels Without Disturbing the Soil Structure

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Abstract: One of the most important parameters that characterize the traction-coupling properties of a wheeled tractor is its slip. The more tractor's gross traction, the higher its traction-coupling properties. But, this gross traction should not exceed its maximum possible value, which, in turn out, is to be determined by the maximum permissible slip δ_{max}. This article provides the equation to calculate this crucial parameter and establishes the dependencies between the tractor's slip and soil structure coefficient. It was shown that the value of δ_{max} basically depends on such soil characteristics as the bulk deformation coefficient and the coefficient of rolling resistance. Calculations showed that for the average value of the soil bulk deformation coefficient at 4000 kN·m^{-3}, the average value of rolling resistance coefficient at 0.16, the ratio value of the maximum permissible soil pressure to the tractor wheel rolling radius at 222 kPa·m^{-1} the maximum permitted amount slip of the tractor wheels should not exceed 15%. With more slip, the soil structure deteriorates significantly. In this case, its structure coefficient may be less than critical, equal to 0.4.

Keywords: slip, gross traction, soil structure, soil bulk deformation

1. Introduction

The drive wheel's main rolling problem is to provide it with a large traction force due to the high adhesion of its tyre to the supporting surface. In our case, this is soil.

The action of the following forces causes the adhesion of the drive wheel tyre to the soil: i) frictional forces between the soil and the tyre's supporting surface; ii) the force generated by the pressure of the tyre vertical lug side on the soil; iii) the force acting along the tyre-soil contact surface located between lugs. These forces' impact is accompanied by the displacement (sliding) of the wheel's tyre relative to the soil, commonly called slip.

From the above, it follows that slip should be considered as acombintion of two processes: i) slip due to circumferential deformation of the pneumatic tyre (δ_t); ii) slip due to soil deformation (δ_s).

The circumferential deformation of an elastic pneumatic tyre is caused by the torque applied to the wheel. The latter causes the wheel hub to turn at some angle relative to that part of the tyre that is in contact with the soil. As a result, both the entire wheel and its axle, simultaneously rolling forward, partially move backward by a distance equal to the tyre's deformation. It should be noted that it is complicated to measure δ_t separately [1]. Because of this, in practice, this slip is most often determined together with slip δ_s.

Of the above three forces, the last two carry out the greatest deformation of the soil. All three forces form the gross traction of the wheel. The nature of its change from slip depends on the type of soil.

Multiple studies have proven that on loose soils, the wheel's gross traction, as its slip increases, reaches its maximum value. Further, in most cases, it remains practically constant [2-4].

On firm soils, the nature of the gross traction dependence on its slip is somewhat different. At first, this force rises to its maximum value. A further increase in wheel slip causes a decrease in its gross traction to some steady-state value [5-7].

It turned out that, regardless of the soil type, in almost all cases, the maximum value of the wheel's gross traction is achieved when its slip is 15% or more. But due to the intensive slip of the wheel lugs relative to the supporting surface, there is a shift, crushing, and significant abrasion of the soil.

As a result, it loses its structure due to compaction [8-9], the permeability of air and moisture in it deteriorates [10]. Simultaneously, the restoration of these soil properties to a normal state is a very time-consuming, labor-intensive, and expensive process.

Hence it follows that the maximum value of the tractor wheels slip (δ_{max}) should be such that the destructive effect on the soil is minimal. One way to decrease the tractor wheels slip is ballasting [11-14]. As practice shows, such a decision leads to an increase in soil compaction, which is undesirable and harmful.

In another variant decision to this problem, it is proposed to equip the wheeled tractor's tyres with lugs in the form of spikes or blades [15-16].

It should be noted that in off-road conditions, this complication of the wheeled tractor can be justified. Under normal field conditions, the effectiveness of its application will depend on the value of δ_{max}. The value of this parameter can be such that the tractor operation with the slip of the wheels no more than δ_{max}. It will be really provided by doubling the tyres [10],[17] or decreasing air pressure in them [13], [18-20].

The main problem it follows above is determining such a value of δ_{max}, which allows the tractor to develop high tractive properties without disturbing the soil structure.

One of the attempts to solve this issue was established [11], that the soil cutting with the tractor wheel's lugs occurs when slip is varied from 10 to 17%. With this in mind, the article's authors propose considering such values of wheel slip as approximate-limit values.

Simultaneously, these tractor wheel slip levels can and obviously will be different in other soil conditions. Moreover, the maximum permissible value of δ_{max}, in our opinion, should be such as to i) exclude a soil cutting in general; ii) allow soil deformation (shearing or crushing) in the longitudinal direction only up to a specific limit. The latter has not been established in [11].

The article [18], [21] proposed the following algorithm for decision this problem. In Ukraine, there is a state standard DSTU 4521: 2006 'Mobile agricultural machinery. Standard rates of impact on soil by undercarriage'. It establishes the requirements for limiting the vertical pressure (Q, kPa) of the agricultural tractor's wheels on the soil depending on its moisture content, density, and fieldwork period: spring-summer and summer-autumn.

Having applied this restriction to the effect of the wheel lugs side surfaces on the soil in the horizontal plane, we obtained an analytical dependence that allows us to determine the value of δ_{max} [18],[21]:

$$\delta_{max} = \frac{Q}{k_o \cdot R_k \cdot \left(arctan \dfrac{f_k \cdot \sqrt{1 - f_k^2}}{0.5 - f_k^2} + 2 \cdot f_k^2 \right)}, \tag{1}$$

where k_o – coefficient of soil bulk deformation, N m⁻³; R_k – rolling radius of the wheel, m; f_k – rolling resistance coefficient.

A feature of equation (1) is that it allows you to determine the value of the maximum permissible wheel's slip δ_{max} without cutting the soil by the lugs and with such a level of their pressure on it in the longitudinal direction, which is limited by the value of Q.

Besides, this equation allows establishing the regularity of influence on the value of δ_{max} such soil parameters as the coefficient of bulk deformation k_o and the coefficient of rolling resistance f_k. The latter's influence on the maximum permissible of the wheel slip with the constancy of the remaining parameters included in the formula (1) is described in the articles [18],[21].

At the same time, functional dependence $\delta_{max} = f(k_o)$ has not yet been determined. It is essential for practice since the bulk deformation coefficient (k_o) is rather closely correlated with its density. Obviously, there is a specific relationship between the values of the parameters f_k and k_o too. But its point is not yet known.

Finally, to determine the maximum permissible slip value of the tractor wheels, it is essential to know the regularity of this process's influence on the soil structure. But the methodology for assessing such effect has not yet been developed.

An attempt to provide answers to these problematic questions is the aim of this article.

2. Materials and methods

To assess the effect of tractor slip on the soil, the coefficient of its structure k_s was adopted. To define it, we have proposed the following expression:

$$k_s = \frac{M_{sa}}{M_t},$$ (2)

where M_{sa} – mass of agronomically valuable soil aggregates in the soil sample, kg;
M_t – the total mass of soil sample, kg.

The agronomically valuable soil aggregates are considered those with a diameter of 0.25-10 mm [22].

Before field studies, the initial value of the soil structure coefficient k_s, as well as its moisture and density in the 0-10 cm layer, were determined. The studies were carried out in the Zaporizhzhia district's conditions (southern Ukraine) on dark chestnut soil with physical clay content up to 55%, physical sand up to 35%, humus up to 3%.

To determine the coefficient k_s the dry method of sieving the soil was used. For this purpose, a kit of three sieves stacked, one on top of the other, was used. The top sieve had holes 10 mm in diameter. The hole diameter of the middle sieve was 1 mm.

This decision was due to the following considerations. Firstly, holes with a diameter of 0.25 mm are difficult to implement and are prone to clogging with soil. Secondly, we use the coefficient k_s to assess the influence degree of tractor wheels slip on the soil structure. Considering this, the middle sieve holes' diameter equal to 1 mm is entirely acceptable and technically feasible. The bottom sieve was without holes.

The soil sample mass was equal to 1 kg. After handshaking sifting, the soil remained on the upper sieve, the particles of which had a diameter of more than 10 mm. Soil aggregates with a diameter of more than 1 but less than 10 mm remained on the middle sieve. Soil particles less than 1 mm in diameter spilled onto the lower sieve.

Thus the agronomical valuable soil aggregates were concentrated on the middle sieve. Since in our case $M_t = 1\ kg$, the soil mass in this sieve M_a, determined in kg, automatically selected, as follows from expression (2), the value of the soil structure coefficient k_s.

For the weighting of the selected soil samples, we used an SF-400-D3 (PROK, Ukraine) electronic laboratory scales with a weighing limit of 3 kg and an accuracy of ± 0.1 g.

The measurement of soil moisture in the 0-10 cm layer was carried out with an SHS-1 device (Kharkiv, Ukraine), which was connected to a laptop via an Arduino Uno device (China) (Fig. 1). The error in measuring soil moisture's absolute value with this device did not exceed ± 1%.

The data received from the Arduino Uno were formed on the laptop using the CoolTerm program in a form suitable for processing in the Microsoft Excel environment.

After 100 soil moisture measurements, carried out every 3 m along the field diagonal, its average value was calculated.
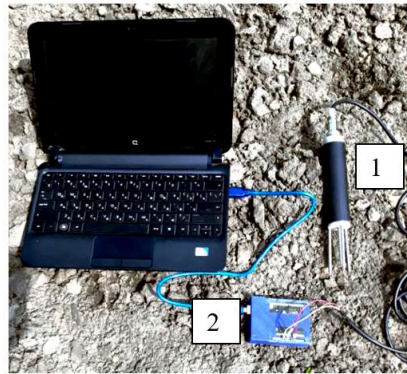
Figure 1. Soil moisture measuring kit: **1** – SHS-1; **2** – Arduino Uno

Figure 2. Soil bulk density measuring kit

Measurement of soil bulk density was carried out as follows [21]. A soil sample was taken with a 28.35 cm^3 cylinder (Fig. 2) and weighed on the scales. The latter were configured to measure in ounces (oz.). Because 1 oz. = 28.35 g, the scale displayed the soil mass, corresponding to its density in g cm^{-3}.

The influence of the tractor wheels slip on the soil structure coefficient was studied with a plowing unit. It included the HTZ-17021 (Kharkiv, Ukraine) 4WD tractor and the five-furrow plow (Fig. 3). The main technical characteristics of this plowing unit are presented in Table 1.

Figure 3. Tractor HTZ-17021 with five-furrow plow

Table 1. Main technical characteristics of the plowing unit

Index	Value
Tractor operating mass, kg	8480
Nominal engine power (BF6M1013E, DEUTZ), kW	132.3
Wheelbase, m	2.860
Track, m	1.860
Tyres	23.1R26
Coefficient k_d, m^{-1}	0.21
Plow operating mass, kg	800
Number of plow bottoms	5
Width of plow bottom, m	0.35
Operating width (B), m	1.75

The plowing unit's research program provided three modes of its movement with wheel slip: i) up to 15%; ii) up to 20%; iii) up to 25%. For these three levels of slip, the required plow traction resistance (R_p) was determined according to the passport traction characteristics of the HTZ-17021 tractor. To provide approximate R_p values for each level of tractor's slip, the plowing depth (h, m) was changed. The required value of this parameter was determined from the equation:

$$h = \frac{R_p}{k \cdot B},$$

(3)

where k – plow specific resistance coefficient. For soil conditions of south Ukraine mean of this parameter is equal to 60 kN m^{-2}.

For studies of the plowing unit movement in the field, 9 sites (3 test conditions with 3 replicates for each of them) were prepared. The length of each site was equal to 300 m. The first 25 m of each site were used to accelerate the plowing unit. On the site $S_p = 250\ m$ during the time t_p it carried out a working stroke with a given plowing depth. The time t_p was measured with an FS-8200 electronic stopwatch. Its measurement accuracy is equal to ± 0.1 s. Then the operating speed of the plowing unit V_p was calculated by the formula:

$$V_p = \frac{S_p}{t_a}$$

(4)

The last 25 m of each site were used to stop the plowing unit. On the same area in the track of the tractor rear wheels, soil samples were taken to determine its structural coefficient at the corresponding value of slip HTZ-17021. To determine the coefficient k_s the above method and expression (2) were used.

Tractor wheels slip was calculated using the formula:

$$\delta = 1 - \frac{n_{wx} \cdot V_p}{V_x \cdot n_{wp}},$$

(5)

where n_{wx}, n_{wp} – number of a tractor's driving wheels revolutions with idling and working strokes of plowing unit respectively; where V_p, V_x – the speed of the tractor with draft traction and without it, respectively.

For most agricultural tractors with sufficient practice accuracy, the ratio $k_d = \frac{n_{wx}}{V_x}$ on their main working gears can be taken approximately constant, i.e., $k_d = \frac{n_{wx}}{V_x} \approx const.$

For the HTZ-17021 tractor, this ratio is equal to 0.21 (see Table 1).

In each experiment, the number of revolutions of the tractor's rear wheels (n_{wp}) was recorded using IMD-2N rotary magnetic encoders (IMD Ltd, Kyiv, Ukraine), with the following main technical features: 10-30 VDC voltage supply and $\pm 0.15°$ absolute accuracy. Its electrical signals entered into an analog-to-digital converter and then to the laptop.

Having determined the values of V_p, n_{wp} and k_d HTZ-17021 wheels slip was calculated from equation (5). The influence of this parameter on the soil structure coefficient was estimated from the obtained experimental dependences $k_s = f(\delta)$.

3.   Results and discussion

Analysis of equation (1) shows that the slip of the tractor wheel depends on only one constructive parameter of a tractor – the rolling radius of the wheel R_k. In the real conditions, the greater its value, the more significant the wheel's contact area with the supporting surface, i.e., soil.

But in such case, it is possible to take a correspondingly more value of the allowable pressure Q. Taking into account the growth of this parameter while increasing the wheel radius R_k, we can assume in the first approximation that the ratio of the values Q and R_k remains practically constant, i.e.,

$$\frac{Q}{R_k} \approx const \tag{6}$$

Having taken this into account, the maximum permissible value of the tractor's wheels slip, as shown by equation (1), is determined by only three parameters of the soil. They are: 1) the permissible pressure Q (N·m^{-2}); 2) soil bulk deformation coefficient k_o (N·m^{-3}); 3) the rolling resistance coefficient f_k.

In Ukraine, the value of Q is regulated by the state standard DSTU 4521: 2006 "Mobile agricultural machinery. Standard rates of impact on the soil by undercarriage". The maximum value of this parameter for the spring-summer period is 160 kN·m^{-2}.

Tractors of traction classes 30 and 50 kN are the most common in Ukraine and other European countries. The average value of their operating mass is approximately 8000 and 12000 kg, respectively. In Ukraine, tractors of traction class 30 kN are equipped with tyres 23.1R26, and traction class 50 kN are fitted with tyres 28,1R26. The rolling radius of the wheels with these tyres is $R_k = 0.72$ m.

The value of the soil bulk deformation coefficient (k_o) depends on its type, structure, etc. In southern Ukraine, for example, the average value of this parameter (determined by us) for dark chestnut soils is about 4000 kN·m^{-3}.

As to the coefficient of rolling resistance f_k its value in the field conditions is usually considered for two agrotechnical backgrounds: 1) *stubble* and 2) *field prepared for sowing*. If

$f_k = 0.08 - 0.12$ for the first of them (i.e., *stubble*), then for the other (i.e., *field prepared for sowing*), this parameter varies from 0.12 to 0.20.

If we consider the separate influence of the coefficients k_o and f_k on the value of slip(δ_{max}), then we will obtain the following result. The analysis of equation (1) shows that increasing the rolling resistance coefficient (Fig. 4) and soil bulk deformation one (Fig. 5) requires less value of the slip δ_{max}.

Function $\delta_{max} = f(f_k)$ (Fig. 4) was obtained at $Q = 160\ \text{kN·m}^{-2}$, $R_k = 0.72\ \text{m}$, $k_o = 4000\ \text{kN·m}^{-3}$, and $f_k = 0.08 - 0.20$ [22]. Calculation of the equation $\delta_{max} = f(k_o)$ was conducted at $Q = 160\ \text{kN·m}^{-2}$, $R_k = 0.72\ \text{m}$, $f_k = 0.16$, and $k_o = 3500 - 5500\ \text{kN·m}^{-3}$.
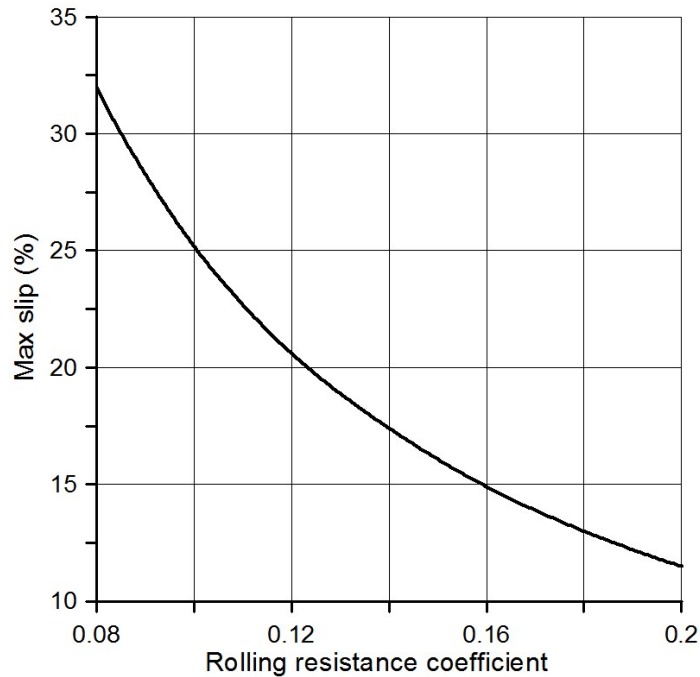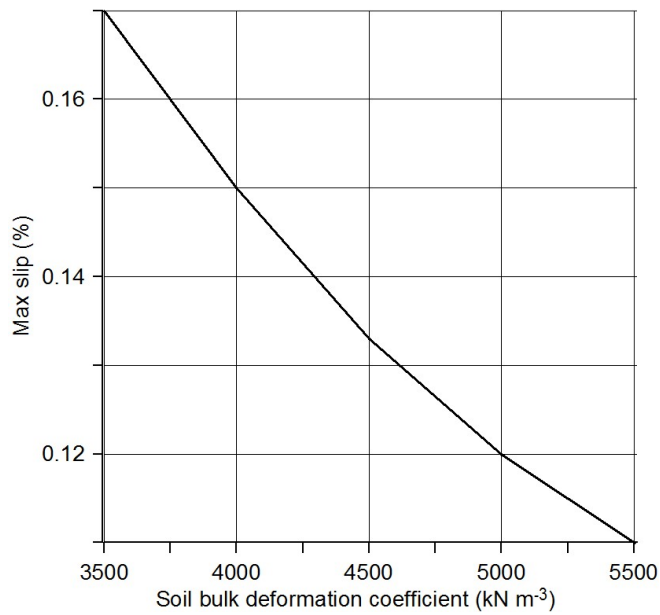

Figure 4. Dependence the maximum tractor's wheels slip δ_{max}
from the rolling resistance coefficient f_k

It should be noted that Fig. 4 shows the dependence of the coefficient f_k not on the operating tractor wheels slip but the maximum allowable slip δ_{max} which does not lead to a destroyed soil structure and is determined from equation (1). Indeed, the larger the coefficient f_k, the lower the strength of the soil, and the less admissible the tractor wheels slip (δ_{max}) can be realized on it.

Simultaneously, if the first result (Fig. 4) is, in principle, logical, then the second one (Fig. 5) is not. The reason for this disagreement is the interrelationship between the coefficients k_o and f_k. The analysis of the equation (1) and research results of other authors [5] show the larger the soil bulk deformation coefficient, the lower value of the rolling resistance coefficient (Fig. 6).

Figure 5. Dependence the maximum tractor's wheels slip δ_{max} from the soil bulk deformation coefficient k_o
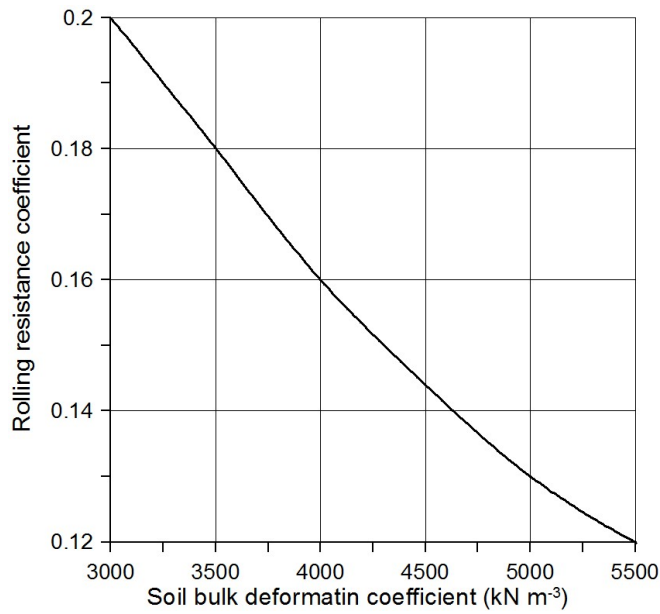
Figure 6. Dependence between coefficients k_o and f_k

Really, the value of the coefficient k_o, as well-known, is larger for density (solidity) soil. In this case, it has less value of the coefficient f_k [7].

Practically this means that an increase/decrease in the rolling resistance coefficient's value will be compensated by a corresponding decrease/increase in the value of the soil bulk deformation coefficient. As a result, the value of the maximum slip δ_{max} will be determined only by the accepted values (but not variations) of the mentioned above coefficients and by the value of the ratio (6).

It should be remembered that changing the parameter R_k to a greater or lesser side should not have a significant effect on the value of δ_{max}. In this case, it is possible to change (i.e., increase or decrease) the value of the parameter Q in such a way that the condition (6) was correct.

It follows from equation (1), for such soil and tractor characteristics as $Q = 160 \text{ kN·m}^{-2}$, $k_o = 4000 \text{ kN·m}^{-3}$, $f_k = 0.16$ and $R_k = 0.72 \text{ m}$ the maximum slip δ_{max} of the tractor's wheels should not exceed 15%. If the initial data $[Q]$, k_o, f_k, and R_k differ from these, then the maximum slip value δ_{max} will be different too.

For practice, it is interesting to know how the correct equation (1) is. Under real test conditions on dark chestnut soil with a bulk density of 1.29 g·cm⁻³ and a moisture content of 12.4%, the initial value of the coefficient of its structure k_{sin} was equal to 0.6. The minimum value of this coefficient k_{smin} at which soil structure is considered satisfactory is equal to 0.4 [23].

If the value of the coefficient k_s is in the interval between k_{smin} and k_{sin} soil structure can be considered satisfactory.

Experimental studies had shown that when the wheels of the HTZ-17021 tractor slipped 12.2% (plowing depth 0.26 m), the coefficient of soil structure k_s was equal to 0.51 (Fig. 7). It is slightly less than the original value k_{sin} but more than the minimum acceptable k_{smin}.
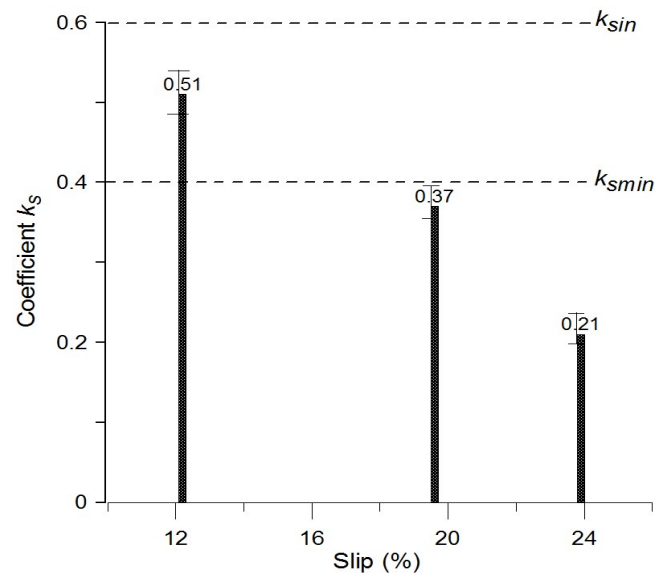
Figure 7. Influence of tractor wheels slip on the coefficient k_s

Simultaneously, when the tractor wheels slipped 19.6% (plowing depth 0.29 m), the soil structure coefficient decreased to 0.37. This means that soil structure has deteriorated and passed into the category of unsatisfactory.

The soil quality became even worse when the tractor wheels slipped at 23.9% (plowing depth 0.32 m). In this case, agronomically valuable soil particles in the HTZ-17021 track were no more than 21% (see Fig. 7).

Hence, it follows that to preserve the soil structure, the tractor wheels' slip should be strictly limited to the value determined from expression (1). For the soil conditions described in this work, the value of δ_{max} should not exceed 15%.

4. Conclusions

One of the most important parameters that characterize a wheeled tractor's traction-coupling properties is its slip when operating in a particular machine-tractor unit. To reduce destructive effect on the soil, the tractor's wheels' maximum permissible slip should not exceed the value calculated by the formula (1).

For the soils average bulk deformation coefficient at 4000 kN·m^{-3}, the average value of the rolling resistance coefficient at 0.16, the ratio value of the permissible soil pressure to the rolling radius of the wheel at 222 kPa·m^{-1} the maximum permitted value slip of the tractor wheels δ_{max} should not exceed 15%.

Experimental studies have confirmed the validity of equation (1). When tractor wheels slip more than 15%, the aggregate state of the soil deteriorates. Under experimental conditions, even with a value of the parameter δ close to 20%, the actual value of the soil structure coefficient 0.37 was less than the minimum permissible (0.4). With wheel slip close to 25%, this coefficient's value was even less, which cannot be acceptable in practice.

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