Determination of the Maximum Allowable Slipping of the Wheel Tractors

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Abstract: *One of the most important parameters that characterize traction-coupling properties of a wheeled tractor is its slippage when operating in a particular machine-tractor unit. The article gives a formula that allows to determine practically the reliable value of this parameter. The difference between this formula is that it does not take into account the loss of speed of the tractor due to the reduction in engine speed, which occurs under the influence of traction load. Overcoming this load, the tangential traction force of the tractor should not exceed the maximum possible adhesion to the soil Pkmax. In the paper, the condition is used that the ratio of this force to the sum of the vertical projections of the stubborn surfaces of the tractor's tractors should not exceed a given pressure on the soil [Q]. On the basis of this, an equation is derived that allows to determine the maximum permissible level of slipping of the wheel tractor δmax. In this equation, the value of δmax basically depends on such characteristics of the soil as the coefficient of volume collapse and the coefficient of rolling resistance. The ratio of permissible pressure on the soil [Q] to the rolling radius of the tractor wheels can be regarded as practically constant. Calculations showed that for soils with an average collision rate of about 4000 kN·m-3, the average rolling resistance coefficient is – 0.16, and the ratio of permissible soil pressure to the rolling radius of the wheel – is at 222 kPa/m, the maximum permissible value slippage of the tractor wheels δmax should not exceed 15%.*

Keywords*: slipping, wheel tractor, coefficient of rolling resistance, bulk deformation of soil.*

INTRODUCTION

Since the wheeled tractor is a traction machine, slipping of its wheels is not an exception, but the norm. Theoretically, this process occurs at the moment when the wheel starts to move under the influence of the torque applied to it, which creates the tangential force of the thrust (P_k).

Studies have established (Guskov V.V. et al., 1988) that the tractor in the traction machine-tractor aggregate achieves the highest traction-coupling properties when the wheels (δ) have slippage at 20-22%. But because of the intensive slippage of the tires and the soils of the wheels with respect to the bearing surface, there is a shift, crushing and considerable abrasion of the soil. As a result, it loses its structure and fertility (Battiato, A. et al., 2011, Noréus, O. & Trigell, A., 2008), the restoration of which is a very long, laborious and expensive process.

Consequently, the maximum value of skidding of the tractor wheels (δmax) should be such that the destructive effect on the soil is minimal. At first glance this problem can be solved by appropriate ballasting of the tractor (Damanauskas, V., Janulevicius, A., 2015, Spagnolo, RT., Et al., 2012; Janulevicius, A., Giedra, K., 2008).

However, as practice shows, this method leads to an increase in soil compaction, which is the result of undesirable and harmful.

In another variant of the solution to this problem, it is proposed to equip the tires of the wheeled tractor with lugs in the form of spikes or blades (Abrahám R. et al., 2014). It should be noted that in off-road conditions, this complication of the construction of the tractor running system can be justified. In 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 work of the tractor with skidding of the wheels no more than δ_{max} will really be provided by simply doubling the tires.

From the foregoing it follows that the main problem is to determine the value of δ_{max}. Up to now, an attempt has been made to solve this problem (Nadykto V. et al., 2015) by applying in the horizontal plane the restriction of the pressure of the wheels of tractors to soil ([Q]), which is regulated by Ukraine's standard in the vertical plane (DSTU 4521: 2006 '

Mobile agricultural machinery. Standard rates of impact on the soil by undercarriage).

As a result, it was found that to substantially reduce the destruction of the soil structure in the spring field, the maximum permissible slipping (δ_{max}) of the wheels of tractors of traction classes 5, 3 and 1.4 should be 15%, 12% and 9%, respectively. In the autumn-summer period, the values of δ_{max} can be large and accordingly make up 20%, 16% and 13%.

The difficulty lies in the fact that Nadykto V. et al. (2015) the expression for the definition of δ_{max} contains many design parameters for both the wheels and the tractor itself. And this not only significantly complicates the process of determining the value of δ_{max}, but also requires its determination for each specific traction facility.

In the real conditions of the tractor's movement, the crushing and shearing of the soil occurs under the action of the tangential force of the thrust P_k. The maximum value of its adhesion value (P_{kmax}) should be such that the pressure of the tractor wheels on the soil in the horizontal plane and their slippage does not exceed the maximum permissible values: [Q] and δ_{max}, respectively. In this case, it is quite obvious that the values of P_{kmax}, [Q] and δ_{max} are connected with certain parameters of the soil in a certain way. Determining the nature of this relationship with the subsequent determination of the maximum allowable slippage of the wheels of the tractor δ_{max} is devoted to this article.

MATERIALS AND METHODS

According to Professor E.D. Lviv, the maximum possible traction with traction of the tractor wheel (P_{kmax}) can be represented as follows:

$$P_{kmax} = \delta_{max} \cdot F_v \cdot k_o \cdot L, \quad (1)$$

where F_v is the sum of the vertical projections of the thrust surfaces of the tractor wheels immersed in the soil, m^2; k_o – the coefficient of bulk crushing of soil, $N{\cdot}m^{-3}$; L – the length of the traction tractor clutch traction with soil, m.
It follows from (1) that

$$\delta_{max} = \frac{P_{kmax}}{F_v \cdot k_o \cdot L}. \quad (2)$$

The expression for determining L is:

$$L = R_k \cdot \left(arctg \frac{f_k \cdot \sqrt{1 - f_k^2}}{0.5 - f_k^2} + 2 \cdot f_k^2 \right), \quad (3)$$

Where: R_k is the dynamic rolling radius of the wheel, m; f_k – the coefficient of rolling resistance of the tractor wheel.

As in the work of Nadykto V. et al. (2015), we assume that the ratio of the force P_{kmax} to the area F_v is a voltage that can be limited by the value of [Q] ($N{\cdot}m^{-2}$), which is defined by DSTU 4521: 2006 'Mobile agricultural machinery. Standard rates of impact on soil by undercarriage '. I.e:

$$P_{kmax} / F_v = [Q], \quad (4)$$

Substituting the value of L from expression (3) into formula (2) and taking into account expression (4), we finally obtain:

$$\delta_{max} = \frac{[Q]}{k_o \cdot R_k \cdot \left(\operatorname{arctg} \frac{f_k \cdot \sqrt{1 - f_k^2}}{0.5 - f_k^2} + 2 \cdot f_k^2 \right)}. \qquad (5)$$

RESULTS AND DISCUSSION

Analysis of expression (5) shows that the maximum allowable slippage of the tractor wheel depends only on one structural parameter – of the rolling radius R_k. In real conditions, the larger its value, the greater the contact area of the wheel with the supporting surface, i.e. soil. But in such a case it is possible to take a correspondingly larger value of the allowable pressure [Q]. Taking into account the growth of this parameter, with simultaneous increase in the radius of the wheel R_k in the first approximation, we can assume that the ratio of the quantities [Q] and R_k remains practically constant. i.e

$$\frac{[Q]}{R_k} \approx const. \qquad (6)$$

Taking this into account, the maximum permissible value of skidding of the tractor wheels, as shown by the relationship (5), is determined by only three parameters of the soil. They are: 1) the permissible pressure [Q] ($N \cdot m^{-2}$); 2) the coefficient of volume collapse k_o ($N \cdot m^{-3}$); 3) rolling resistance coefficient f_k.

In Ukraine, as noted above, the value of [Q] is regulated by the state standard DSTU 4521: 2006 'Mobile agricultural machinery. Standard rates of impact on soil by undercarriage '. The maximum value of this parameter for the spring-summer period is 160 $kN \cdot m^{-2}$.

The most common not only in Ukraine but also in other European countries are tractors of traction classes 3 and 5. Their operating weight is approximately 8.2 and 12.0 tons respectively. Tractors of traction class 3 are equipped with tires 23,1R26, and traction class 5 – with tires 28,1R26. The rolling radius of the wheels with these tires is $R_k = 0.72$ m.

The value of the coefficient of volumetric soil compression k_o depends on its type, aggregate state, etc. In southern Ukraine, for example, the average value of this parameter for sod-podzolic soils is about 4000 $kN \cdot m^{-3}$.

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., the field prepared for sowing) this parameter varies from 0.12 to 0.20.

At [Q] = 160 $kN \cdot m^{-2}$, $R_k = 0.72$ m and $k_o = 4000$ $kN \cdot m^{-3}$, the dependence of the maximum permissible skidding of the tractor wheel δ_{max} on the rolling resistance coefficient f_k according to the expression (5) has the form shown in Fig. 1.

\From his analysis it follows that on a more loose soil background, characterized by a larger value of the rolling resistance coefficient f_k, the maximum permissible skidding of the tractor wheels should be less. The value of this coefficient against the background of the "field prepared for sowing" changes, as indicated above, from 0.12 to 0.20. The average value of f_k is 0.16. Taking this into account, it follows from equation (5) that for soil conditions with characteristics [Q] = 160 $kN \cdot m^{-2}$, $k_0 = 4000$ $kN \cdot m^{-3}$ and $f_k = 0.16$, the maximum skid (δ_{max}) of tractors with a rolling radius their wheels at the level of $R_k = 0.72$ m should not exceed 15%.

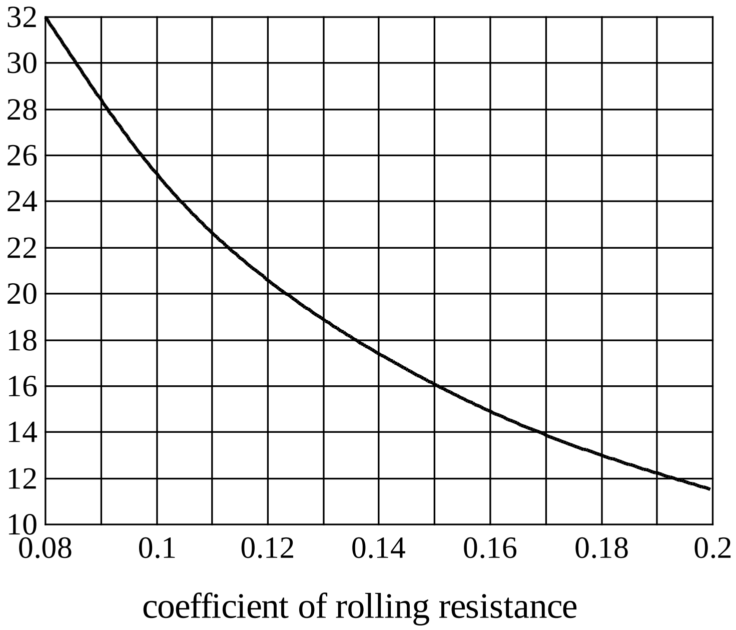

Fig. 1 Dependence maximal slipping of wheel tractor (δ_{max})
from coefficient of rolling resistance (f_k)

Moreover, the change in the parameter R_k to a greater or lesser side should not have a significant effect on the value of δ_{max}, since in this case it is possible to change (ie, increase or decrease) the value of the parameter [Q] corresponding in such a way that the condition (6).

In order to apply the maximum permissible value of slipping (δ_{max}) in practice, it is very important to be able to determine correctly in the field conditions its actual value, i.e. δ. Very often to calculate this parameter, the following formula is proposed (Lu Zhixiong, 2013; Bin, Z., Yu, Q., 1997):

$$\delta = \frac{V_x - V_p}{V_p}, \qquad (7)$$

Where: V_p, V_x - the speed of the tractor with traction load and without it, respectively. However, the formula (7) is valid only in the case when the values of V_x and V_p are obtained at the same engine speed of the tractor when it moves under load (n_{ep}) and without it (n_{ep}). Those are:

$$n_{ex} = n_{ep.}, \qquad (8)$$

The problem is that when the tractor moves at idle speed, that is, without traction, condition (8) can not be ensured. In this case, there will always be $n_{ep} > n_{ex}$. In the presence of traction, the actual speed of the tractor's forward speed is reduced both by skidding of its wheels and due to the mandatory reduction in engine speed. But the second circumstance is not caused by skidding, and therefore should be properly taken into account. This can be done by increasing the value of the working speed V_p by a certain amount (K_1). Theoretically, using expression (7), it looks like this:

$$\delta = \frac{V_x - V_p \cdot K_1}{V_x} = 1 - K_1 \cdot \frac{V_p}{V_x}., \qquad (9)$$

If this is not done, then using formula (7) if condition (8) is not fulfilled leads to the definition of an overestimated value of δ.

The second known expression for determining slippage is the loss on the same path segment (Stajnko, D. et al., 2012; Macmillan RH, 2002) of the total number of revolutions of the tractor's driving wheels with idling (n_{wx}) and working strokes (n_{wp}):

$$\delta = \frac{n_{wp} - n_{wx}}{n_{wp}}, \qquad (10)$$

We emphasize that the quantity n_{wp} is simultaneously a function of skidding of the wheels and the reaction of the engine to the traction load. In order to exclude the second circumstance when calculating δ, the number of turns of the tractor wheels when it is moving under load must be corrected by some amount (K_2). In this case, from equation (10) we have:

$$\delta = \frac{n_{wp} \cdot K_2 - n_{wx}}{n_{wp} \cdot K_2} = 1 - \frac{n_{wx}}{n_{wp} \cdot K_2}, \qquad (11)$$

Note that the values n_{wp} and n_{wx} are functions of the path traversed by the tractor and have the dimension [turns/m]. In practice, their definition has some difficulties. In order not to burden ourselves with the necessity of dividing the field into sections of a fixed length (especially when there are a large number of them), it is more convenient to register the quantities n_{wp} and n_{wx} as functions of time n_p and n_x, having dimensions of [turns/s].

It should be borne in mind that

$$n_{wp} = n_p \cdot V_p;$$
$$n_{wx} = n_x \cdot V_x, \qquad (12)$$

Taking into account expression (12), formula (11) can be rewritten as follows:

$$\delta = 1 - \frac{n_x \cdot V_x}{n_p \cdot V_p \cdot K_2}. \qquad (13)$$

Equating the right-hand sides of formulas (9) and (13), after the transformations we obtain:

$$K_1 \cdot K_2 = \frac{n_x}{n_p} \cdot \left(\frac{V_x}{V_p}\right)^2. \qquad (14)$$

Taking into account the fact that the coefficients K_1 and K_2 are dimensionless, from the expression (14) we have:

$$K_1 = n_x / n_p;$$
$$K_2 = (V_x / V_p)^2. \qquad (15)$$

If now we substitute the expressions for K_1 and K_2 in (9) and (13) into formulas (9) and (13), we obtain the same dependence, which allows us to calculate the loss of tractor speed when it operates in the traction mode only due to skidding of the wheels i.e. without taking into account the engine speed reduction):

$$\delta = 1 - \frac{n_x \cdot V_p}{n_p \cdot V_x}. \qquad (16)$$

In the field conditions, the parameters included in the formula (16) can be easily fixed using an analog-to-digital converter and a computer. Moreover, for most agricultural tractors with a sufficient accuracy for practical accuracy, the ratio of n_x/V_x in the main working transmissions can be assumed to be approximately constant, i.e. $n_x/V_x \approx$ const.

Let's consider a practical example of an estimation of skidding of wheels of a tractor by formulas (7) and (16). Thus, when testing a tractor of traction class 3 HTZ-17021 with a five-hull plow PLN-5-35, it was found that with the traction resistance of the tiller 34.4 kN, the real speed of the plowing unit (V_p) was 2.43 $m \cdot s^{-1}$. The average wheel speed of this tractor (n_p) was equal to 0.568 s^{-1}.

As for the parameters of idling of the arable unit, then on the same gear they were: V_x = 3.00 $m \cdot s^{-1}$, and n_x = 0.591 s^{-1}.

When calculating according to formula (16), the slipping of the wheels KhTZ-17021 with plow PLN-5-35 was equal to 15.7%. In the case of calculating the same parameter by formula (7), it was found that δ = 19.0%. In absolute terms, the difference (i.e., the excess) is 19.0 – 15.7 = 3.1%, and in the relative – 21.0%.

The question arises: is this a lot or a little? To get an answer, let's turn to the factory traction characteristics of the tractor HTZ-17021. When driving over the stubble, the difference between the tractive forces developed by this tractor when skidding 15.5 and 19.0% is approximately 8 kN. At the nominal tractive effort of this tractor 32 kN this is 25%. From this it follows that incorrect determination of the slippage of the tractor wheels according to formula (7) in practice can lead to its substantial underload by tractive effort. To avoid such a result, calculate slippage using formula (16).

CONCLUSIONS

One of the most important parameters that characterize traction-coupling properties of a wheeled tractor is its slippage when operating in a particular machine-tractor unit. For the practical determination of the reliable value of this parameter, the formula (16) is proposed, which does not take into account the loss of the tractor's speed due to the reduction of its engine speed due to the effect of the traction load.

In order to reduce the tractor's destructive effect on the soil, the maximum permissible slipping of its wheels should not exceed the value calculated by formula (5). For soils with an average collision rate of about 4000 $kN \cdot m^{-3}$, the average rolling resistance coefficient is – 0.16, and the ratio of permissible ground pressure to the rolling radius of the wheel – is at 222 kPa/m, the maximum permissible value of slipping of the tractor wheels δ_{max} should not exceed 15%.

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