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Theoretical study of the conditions of the maximum allowable slipping of wheel tractors

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Abstract. The process of tractor wheels slipping is accompanied by two forms of ground deformation: displacement and shearing. From the point of view of preserving the structure of the soil environment, wheel slip should be limited to displacement only. The limit of soil strength [σ_o] at this deformation can be a standardizing parameter. In this article an analytical dependence is developed, which allows using the parameter [σ_o] to establish the maximum permissible level of slipping of wheeled tractors. Of the soil parameters, the specified dependence includes the coefficient of sliding friction between the particles of soil medium and the coefficient of wheel rolling resistance on a particular agrotechnical background. Theoretical studies have established that the greater the value of this coefficient, the smaller should be the maximum permissible value of tractor slipping with a more economical effect on the soil environment. Compared to a tractor with a nominal drawbar pull of 14 kN, the use of a heavier tractor with a drawbar pull of 30 kN is possible with higher values of maximum permissible towing. This result is due to the magnitude of the vertical load on the wheel of the heavier tractor, which gives it a greater friction force between the tire wheel and the ground and allows the same contacting traction force to be realized at a lower level of slipping. The results of mathematical modeling using the developed analytical relationships indicate that with increasing the value of the angle of placement (slope) of the tractor wheel to the longitudinal axis of symmetry, the maximum permissible level of its slipping should be less. This will help to reduce the value of deformation (longitudinal shift) of the soil by the tractor during its working movement. When using the ground shear strength limit [σ_o] y as a limiting parameter for increasing the pitch and height of the tractor tire, as well as the width of the tractor wheel tyre, the maximum permissible level of its towing is more than 15%, which is an undesirable fact.

Key words: rolling resistance coefficient, soil conditioner attachment, soil shear strength, tangential driving force, tractor attachment.

INTRODUCTION

Preservation and improvement of soil fertility has been and will always be one of the most urgent problems of agricultural production. Since soil structure and fertility play a decisive role in this, the full potential of agricultural science should be directed to their systematic improvement. First of all, this concerns the engineering direction, since the negative man-made impact on the soil is one of the determining factors in the decline of its fertility.

One of the most destructive processes of soil structure is its compaction and deformation due to the towing of heavy tractors (Ansorge & Godwin, 2007; Medvedev, 2010; Antille et al., 2015; Shafaei et al., 2021). In the first place wheeled tractors. It should be noted that the study of these processes has received considerable attention from the world scientific community (Farrakh et al., 2013; Chamen et al., 2015; Damanauskas & Janulevičius, 2015; Moitzi et al., 2016; Abrahám et al., 2017; Antille et al., 2019; Bulgakov et al., 2022). As a result, scientists and practitioners have developed a fairly informative system of recommendations to reduce the negative impact of towing the running gear systems of machine-tractor units on the soil structure.

However, it should be noted that these recommendations bypass such a problem as determining the maximum permissible level of slipping of tractor wheels. On the one hand, according to scientific data, it is known that a tractor as a part of a machine-tractor unit has high towing performance of the undercarriage system at the level of 20–22% (Macmillan, 2002; Bulgakov et al., 2020). On the other hand, it can be argued a priori about the unacceptability of such a man-made impact on the soil in terms of preserving its structure. At the same time, we note that our conscious use of the term "a priori" is justified by the current absence of any restrictive-legislative documents concerning the permissible level of towing wheels of agricultural tractors.

The current document of similar purpose in Ukraine is DSTU 4521:2006 ‘Mobile agricultural machinery. Standard rates of impact on the soil by undercarriage’. It regulates the norms of maximum vertical pressure of agricultural machinery driving systems on the agricultural background $[Q_{max}]$ on its granulometric composition and moisture, as well as the terms of agricultural works in different soil and climatic zones.

The parameter $[Q_{max}]$ was used by us to establish the maximum permissible level of slipping δ_{max} of wheeled tractors, taking into account their deforming impact on the soil (Adamchuk et al., 2016; Battiato & Diserens, 2017; Nadykto et al., 2017; Bulgakov et al., 2020 and 2021). At the same time, the practical application of this parameter as a limiting parameter is rather problematic. Mainly due to the lack of methodological basis for the practical application of the requirements of the above DSTU. First of all, it concerns the practical determination of the specific pressure of the undercarriage system of wheeled power vehicles on the soil in kPa. The problem is that the value of such an indicator depends not only on the operating weight of the tractor, but also on the air pressure in the tires, their width and diameter, and most importantly on the hardness of the soil and its humidity. That is, in each case of using a particular tractor the specific pressure of its wheels on the ground will be different. Finally, everything is complicated by the problematic nature of measuring this indicator in the field in terms of determining the area of the bearing surface of the tractor wheels.

Given this, there is a need to find a compromise option for determining the maximum allowable slipping of wheeled undercarriage systems. This process is known to be accompanied by two forms of soil deformation: displacement and shearing. It is quite clear that in terms of preserving the structure of the soil environment wheels slipping should be limited only by displacement. The limit of soil strength at such a deformation can be a normative indicator. The nature of this parameter is quite clear, and the method of practical determination is widely known in scientific circles (Stefanow & Dudziński, 2020).

The aim of the study was determination of the maximum permissible slipping of wheeled tractors in the absence of shearing and manifestation of such a level of its shearing by the tyres, which does not exceed the specified strength limit.

THEORY AND MODELLING

As mentioned above, the process of slipping of wheel undercarriage systems is caused by displacement and shearing of soil by tyres of the soil in the direction opposite to the movement of the wheeled tractor. These deformations of the soil environment is its response to the action of the tangential force of wheel traction F_k (Fig. 1).

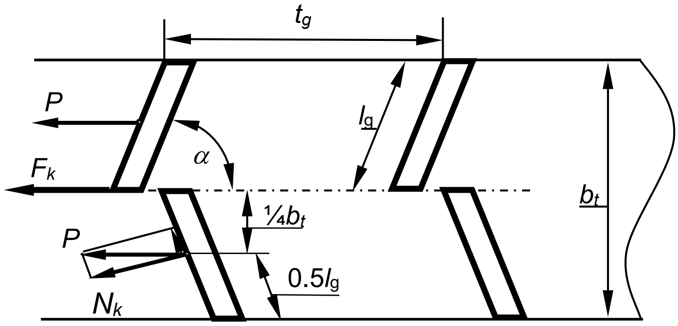

Figure 1. Scheme of the forces acting on the ground grips of the tyre of the tractor wheel (Nadykto et al., 2015).

In our opinion, the most complete connection between this force and the resulting shear and shear deformations of the soil is reproduced by the following analytical dependence:

$$F_k = \frac{f_{cl} \cdot k_\tau \cdot G}{\delta \cdot L}\left[\ln \mathrm{ch}\frac{\delta L}{k_\tau} - f_{sup}\left(\frac{1}{\mathrm{ch}\frac{\delta L}{k_\tau}} - 1\right)\right] + 2\tau_{sh}\frac{h_g \cdot L}{t_g}, \quad (1)$$

where f_{cl} – coefficient of sliding friction between particles of the soil environment; k_τ – coefficient of uniaxial soil deformation, m; G – vertical load on the wheel, N; δ – wheel slip coefficient; L – the length of the contact area of the wheel with the supporting soil environment, m; f_{sup} – given coefficient of friction; τ_{sh} – soil shear strength, Pa; h_g, t_g – the height and step of the ground contact, respectively, m.

The force F_k can be represented by the sum of its two components P_k (Fig. 1). Each of them, in turn, has tangential and normal N_k components. The latter (i.e. the force N_k) carries out the displacement of the soil medium by the ground hitch, located on the wheel tire at an angle α.

We used dependence (1) in Bulgakov et al. (2021) and Nadykto et al. (2015) to determine the maximum permissible slip δ_{max} of a wheeled tractor. The limiting factor in this case was the above-mentioned normative parameter $[Q_{max}]$, which was used not in the vertical (as provided by DSTU 4521:2006), but in the horizontal direction of soil deformation by tire shoes, located at an angle α:

$$[Q_{max}] \leq \left\{\frac{f_{cl}G}{k_\delta}\left[\text{lnch}k_\delta - f_{sup}\left(\frac{1}{\text{ch}k_\delta} - 1\right)\right] + 2\tau_{sh}\frac{h_g L}{t_g}\right\}\frac{\sin^2\alpha}{\text{Integer}\left(\frac{L}{t_g}\right)b_t h_g}. \quad (2)$$

In equation (2), the values of the components will be as follows:

$$k_\delta = \frac{\delta \cdot L}{k_\tau}, \quad (3)$$

and

$$L = R_k \cdot \left(\text{arctag}\frac{f_k \cdot \sqrt{1 - f_k^2}}{0.5 - f_k^2} + 2f_k^2\right), \quad (4)$$

where R_k – rolling radius of the wheel, m; f_k – coefficient of rolling resistance.

The subject analysis of analytical dependence (2) allows us to establish two important points. According to the first term of the expression in curly brackets $2\tau_{sh}h_g L \cdot t_g^{-1}$ is the ground shear deformation, which, in principle, should be made impossible in determining the maximum allowable wheel slip, and therefore in the further analysis is not necessary to consider.

The second point is related to the parameter k_δ. The analysis of equations (3) and (4) for tractors with rated drawbar pull of 14, 30 and 50 kN reveals that the value of hyperbolic cosine k_δ differs from the one by 5–6%. Taking it into account with sufficient accuracy for practice, we can also take into account in expression (2) that:

$$\text{ch}k_\delta = \text{ch}\frac{\delta \cdot L}{k_\tau} = \frac{e^{\frac{\delta L}{k_\tau}} + e^{-\frac{\delta L}{k_\tau}}}{2} \cong 1, \quad (5)$$

and

$$f_{sup}\left(\frac{1}{\text{ch}\frac{\delta L}{k_\tau}} - 1\right) \cong 0. \quad (6)$$

Taking into account dependences (5) and (6) and replacing in expression (2) the parameter $[Q_{max}]$ by a new normalizing parameter $[\sigma_o]$, we obtain a new dependence for determining the maximum permissible slipping of a wheeled tractor, taking into account such limiting factor as the limit of strength of the ground in the presence of its displacement:

$$[\sigma_o] \leq \frac{f_{cl} \cdot k_\tau \cdot G}{\delta_{max} \cdot L} \cdot \text{lnch}\frac{\delta_{max} \cdot L}{k_\tau} \cdot \frac{\sin^2\alpha}{\text{Intger}\left(\frac{L}{t_g}\right) \cdot b_t \cdot h_g}. \quad (7)$$

If we take into account that earlier for k_τ the following analytical dependence was proposed (Nadykto et al., 2015)

$$k_\tau = 0.4 \cdot t_g. \quad (8)$$

Taking this into account, we finally have a new analytical expression for determining a new normalizing indicator $[\sigma_o]$:

$$[\sigma_o] \leq 0.4 \frac{f_{cl} \cdot t_g \cdot G}{\delta_{max} \cdot L} \cdot \text{lnch} \frac{2.5 \cdot \delta_{max} \cdot L}{t_g} \cdot \frac{\sin^2\alpha}{\text{Integer}\left(\frac{L}{t_g}\right) \cdot b_t \cdot h_g}. \quad (9)$$

The obtained equation (9) together with dependence (4) allows us to determine the influence of soil and tractor parameters on the maximum permissible level of slipping of its wheels under the action of the limiting factor in the form of the landslide strength limit $[\sigma_o]$.

MATERIALS AND METHODS

The research methods are based on the use of sections of the tractor traction dynamics theory considering the process of rolling of an elastic traction wheel on a deformed ground surface. The theoretical calculations of the obtained analytical regularities were performed in the MathCad 15.0 software environment. The initial data were the parameters of a typical soil medium and construction parameters of the most common tractors with nominal drawbar pull of 14 and 30 kN in this area.

To conduct theoretical research of dependence (9) taking into account expression (4) to determine the maximum allowable slipping of wheeled tractors, let us define the nomenclature of their nominal drawbar pull. At the present time, in spite of proposed by us project of new type of wheeled tractors for Ukraine, though formally, but still valid GOST 27021-86 (ST SEV 628-85). Of the ten traction classes declared in it, tractors with nominal drawbar pull of 14 and 30 kN, represented in this study by type models of MTZ-892 and HTZ-170 series (HTZ-17221), respectively, are most common almost all over the country (Table 1).

Table 1. Construction parameters of wheeled tractors

Nominal drawbar pull category of tractor series	Type size tires	Structural parameters of the tractor and wheel					
		G, N	t_g, m	h_g, m	b_t, m	R_k, m	α,°
1.4 (MTZ-892)	16.9R38	25,260	0.23	0.038	0.43	0.770	43
3 (HTZ-170)	23.1R26	30,900	0.23	0.045	0.59	0.715	47

Wheeled tractors with smaller nominal drawbar pull (2, 6 and 9 kN) are used much less as part of traction machine-tractor units. In the recent past, they were generally regarded as non-systematic and for them a trail of appropriate agricultural machines and tillage and other implements were not even developed.

Tractors with nominal drawbar pull of 50, 60 and 80 kN develop satisfactory traction-energy indicators, as a rule, on technological operations on basic tillage. Usually it is in such aggregate state, when its resistance to shear in horizontal direction is much higher than that of agrotechnical backgrounds characterized by rolling resistance coefficient of 0.12–0.18. Practice shows that on agrotechnical backgrounds with such a characteristic, the optimal loading of tractors with drawbar pull of 50–80 kN is quite problematic.

As for some parameters of the soil environment, for loamy soils: f_{cl} = 0.72–0.79; f_k = 0.12–0.18. Their uniaxial deformation strength σ_o varies within a wide range (Macmillan, 2002). Moreover, the better the soil structure, the lower the value $[\sigma_o]$. At the same time, it is possible to assert this only a priori, since there is practically no experimental data on the nature of the relationship between the structure of chernozems or other soils and their landslide strength. From the small amount of available information (Torikov et al., 2016), it follows that for soils with medium structure the value of the parameter $[\sigma_o]$ is at the level of 100 kPa. It is this value of this parameter that was used in the theoretical calculations.

RESULTS AND DISCUSSION

According to calculations of dependence (9), taking into account expression (4), the maximum permissible value of wheeled tractor slipping δ_{max} significantly depends on the state of agricultural background, on which the wheeled tractor is moving. The quantitative characteristic of the background in this case is the value of the rolling resistance coefficient f_k. As it turned out, the intensity (steepness) of the function change $\delta_{max} = f(f_k)$ for both compared power tools (MTZ-892 and HTZ-17021 tractors) is practically the same (Fig. 2).

That is, if the increase of f_k coefficient from 0.12 to 0.18 for the tractor HTZ-17221 requires the reduction of the maximum allowable slipping by 35% (in relative measure), then for the tractor MTZ-892 it is 37%. The resulting difference of 2% (in absolute measurement) can be considered insignificant.

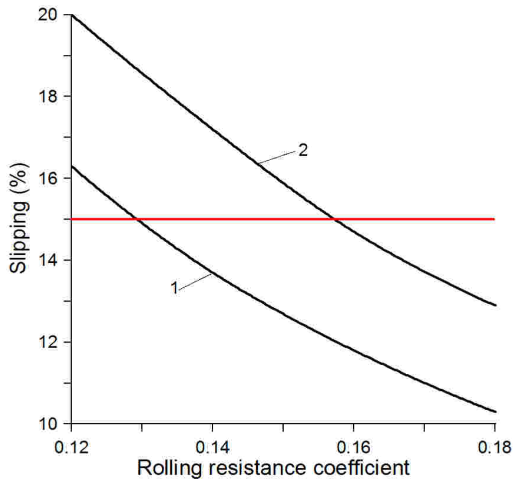

Figure 2. Dependence of the permissible slippage of the driver on the coefficient its rolling resistance: 1 – tractor MTZ-892; 2 – tractor HTZ-17221.

There is a reason to claim that the regularity of δ_{max} decrease with increase of rolling resistance coefficient f_k of wheeled drivers is quite logical. After all, the greater is the value of f_k, the lower is the agricultural background density, the fluffier it is, and therefore more sensitive to the deforming effect in the form of displacement. Based on this we have the conclusion: the greater the coefficient of rolling resistance of the wheeled mover on a particular agricultural background, the lower should be the maximum permissible value of its towing.

Analysis of comparison of calculation data for both tractors indicates that the use of tractor with nominal traction force of 30 kN (in this case - tractor HTZ-17221) is possible at high values of parameter δ_{max}. The reason of such result is caused by the value of vertical (or normal) load on the wheeled engine. Namely, it is by 23% higher in tractor HTZ-17221 than in tractor MTZ-892 (Table 1). Bigger value of G parameter in its turn causes bigger friction force between wheel tire and ground. And it allows one and the same contacting drawbar pull to be realized at lower level of wheel mover slipping.

Of the values included in expressions (4) and (9), a significant influence on the value of the maximum permissible slipping of wheeled power vehicle engines has the angle of position α of the tiller on the tire (Fig. 1). Fig. 3 shows the character of change of function $\delta_{max} = f(\alpha)$ at different values of rolling resistance coefficient f_k for wheeled power tool MTZ-892.

The results of mathematical modeling show that with increasing the value of the angle α the maximum permissible level of slipping of the wheel propeller should be less (curves 1 and 2, Fig. 3). This is explained by the location of the tire's hitch. As the value of α increases, it occupies a position close to the transverse with respect to the longitudinal axis of wheel symmetry. As a result, the tangential traction force component - force N_k, acting in the transverse (normal) direction to the side surface of the hitch (Fig. 1), increases. Because of this, the amount of shear deformation of the soil medium in the direction opposite to the tractor's movement increases.

As in the previous case, the intensity (steepness) of the function change $\delta_{max} = f(\alpha)$ for both variants of the coefficient value f_k is also almost the same (Fig. 3).

The cancellation is that with smaller values of f_k the value of the maximum permissible slipping of wheeled propellers may be greater. The result is quite logical, because at larger values of the coefficient of rolling resistance, the density of the soil environment, on which the tractor moves as part of a machine-tractor unit, is higher, its looseness is less, and the ability to resist shear is higher. Therefore, the greater the value of the coefficient f_k, the more sparing should be the impact on the agrotechnical background in the form of slipping of wheeled propellers of power vehicles. One of the technical options for solving this problem is the use of the latter with doubled or even tripled tires. Technological feasibility of such a technical solution is reflected quite substantially by Adamchuk et al. (2016).

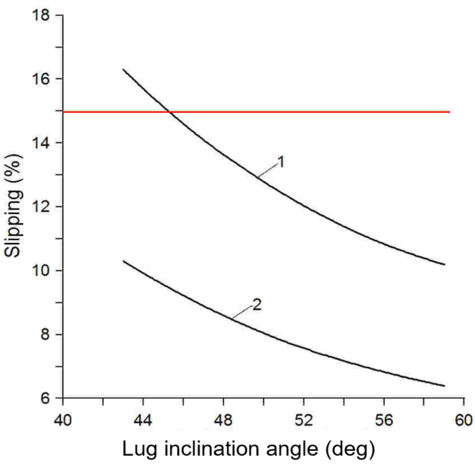

Figure 3. Dependence of the maximum permissible slipping of MTZ-892 tractor on the angle α of its tread on the tyre: 1) f_k= 0.12; 2) f_k= 0.18.

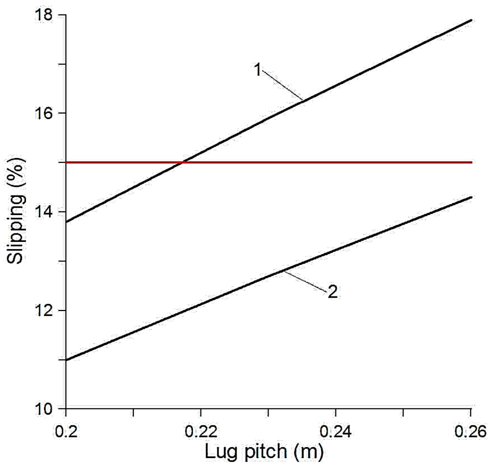

Figure 4. Dependence of the permissible skidding of the driver from the tread of the tyres: 1) tractor HTZ-17221; 2) tractor MTZ-892.

According to theoretical calculations we have that increasing the ground Clearance clearance pitch of the wheel propeller tyre allows us to increase the level of its permissible slipping. This level of tractor HTZ-17221 (curve 1, Fig. 4) is by 25% (in relative terms) higher than that of tractor MTZ-892 (curve 2).

The reason for this result is greater vertical load on the wheel of the tractor HTZ-17221. As already explained above, a larger value of parameter G causes greater friction force between the wheel tyre and the ground. And it gives an opportunity to realize more drawbar pull to the wheel at the same level of towing.

The height of the wheel hitch of both considered tractors qualitatively affects the value of maximum allowable slipping in the same way: the value of h_g max increases with increasing δ_{max} value (Fig. 5).

The logic behind this result is as follows. Increasing the height of the ground hook leads to a corresponding increase in the area of the side surface, which is located on the tire at an angle α and directly contacts the ground in the direction of the force N_k (Fig. 1). The increase in the specified area at the same value of force N_k causes a lower specific pressure of the trailing edge on the ground. This, in turn, leads to a decrease in the deformation of its displacement, which allows you to increase the maximum permissible value of towing the wheel.

As in the case with the pitch of the tractor tyre tread t_g, increasing its height h_g prefers increasing the value of δ_{max} to the heavier tractor (curve 1, Fig. 5) compared to the lighter tractor (curve 2, Fig. 5).

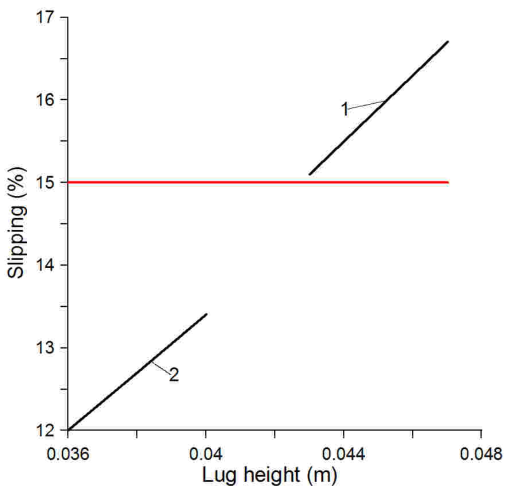

Figure 5. Dependence of the permissible slippage of the mover on the height of the tire ground hook: 1) tractor HTZ-17221; 2) tractor MTZ-892.

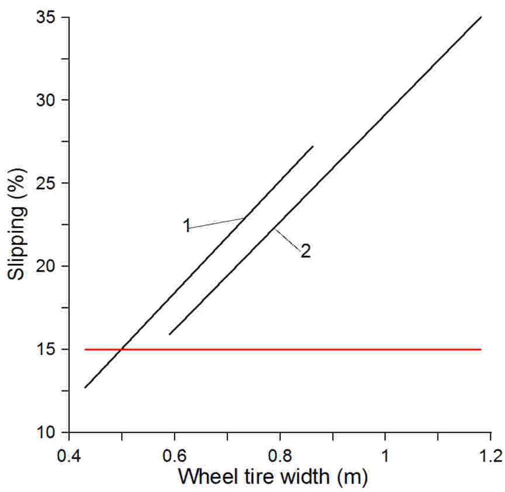

Figure 6. Dependence of allowable towing of mover on width of its tire: 1) tractor MTZ-892; 2) tractor HTZ-17221.

Now we will consider how the value of the maximum permissible wheel towing is affected by increasing the width of its tyre b_t. Increase of value of this parameter for both compared tractors twice causes corresponding increase of value of maximum permissible wheel towing (Fig. 6). This result is quite logical for the following reasons. The increase of the parameter b_t – is the corresponding increase in the length of the tyre tread l_g (Fig. 1), and therefore in the area of its supporting surface, directly in contact with the ground.

And the growth of bearing surface of the ground hook is the reduction of landslide value, which is the corresponding prerequisite for the increase of δ_{max} parameter. It should be noted that for the heavier tractor (in this case the HTZ-17221 tractor) the maximum permissible value of wheel slip for the reasons explained by us above is more.

Our preliminary studies have established that when using the normalization parameter $[Q_{max}]$ the maximum allowable value of towing of propulsion engines of wheeled power vehicles should not exceed 15%.

From the analysis of Fig. 2–6, where this limit is indicated by the red line, we see that when the shear strength of the soil $[\sigma_o]$ is used as a limiting parameter, the condition ($\delta_{max} \leq 15\%$) is not always satisfied. We will analyze this in more detail.

From Fig. 2 we see that the condition $\delta_{max} \leq 15\%$ almost completely corresponds to the tractor with a pulling force of 14 kN (tractor MTZ-892). For tractors with drawbar pull 30 kN (tractor HTZ-17221) this condition is true at their work on agricultural backgrounds with value of rolling resistance coefficient not less than 0.16 (curve 1, Fig. 2). It follows that on less loose (i.e., denser) backgrounds, the value of the maximum allowable slipping of these tractors can be increased up to 20%. But, as emphasized in (Nadykto et al., 2017), this should not be allowed in order to preserve the soil structure. That is, even when operating tractors such as HTZ-17221 on agricultural backgrounds with rolling resistance coefficient $f_k \leq 0.16$ the maximum permissible level of their slipping should not exceed 15%. It must be taken into account when assembling one or another machine-tractor unit on the basis of similar wheeled tractors.

Changing the angle of starters placement for both tractors under consideration within 43–59° practically does not contradict the requirement $\delta_{max} \leq 15\%$. Insignificant (by 1°) exceeding of this maximum allowable value of slipping takes place at α = 46° on the agricultural background with rolling resistance coefficient $f_k \leq 0.12$ (Fig. 3).

The values of pitch and height of ground hooks of MTZ-892 tractor wheels of 0.20 – 0.26 m (Fig. 4) and 0.036–0.40 m (Fig. 5) correspondingly fully meet the requirement $\delta_{max} \leq 15\%$. At the same time we have a different situation with the tractor HTZ-17221. Changing the height of its starters from 0.043 to 0.047 m allows you to set the maximum permissible value of wheel slip at the level of more than 15%, which, as has been repeatedly emphasized above, is unacceptable. As for the ground hooks pitch, only when their values are less than 0.22 m (curve 1, Fig. 4) the condition $\delta_{max} \leq 15\%$ is fulfilled. In practice, this means that the tyre tread of HTZ-17221 tractor type can be located in increments of more than 0.22 m, but the maximum permissible level of slipping of its wheels should not exceed 15%.

At width of the tire b_t > 0.5 m for tractor MTZ-892 and values of this parameter in the range of 0.59-1.18 m for tractor HTZ-17221, the considered condition of maximum permissible value of wheels slipping at a level no more than 15% is not satisfied. The use of doubled tires increases twice the area of the side surface of the tires, through which the ground is shifted. Therefore, as already emphasized above, a higher level of tractor wheel slip can theoretically be allowed. In practice, this cannot be done.

From the above analysis follows one logical question: why, when using the parameter $[\sigma_o]$ the maximum permissible level of tractor wheel slip δ_{max} can exceed the level of 15%, obtained when using as a limiting parameter $[Q_{max}]$? Such discrepancy of requirements on δ_{max} is caused, in our opinion, by the limited correct data on the value of σ_o parameter. Especially those that reflect the regularities of the dependence of the strength limit of the landslide on its structural-aggregate state. Obtaining such research information should be considered as one of the main research tasks of the nearest future.

CONCLUSIONS

The analytical dependence, which allows determining the maximum permissible level of towing of wheeled power tools, taking into account the limit of the soil medium strength for displacement, is developed.

Theoretical studies have established that the greater the coefficient of rolling resistance of a tractor wheel on a particular agricultural background, the less the maximum permissible value of its towing with a more economical impact on the soil environment.

In comparison with tractor with nominal drawbar pull 14 kN (tractor MTZ-892) the use of tractor with drawbar pull 30 kN (tractor HTZ-17221) is possible with higher values of maximum permissible towing. Such a result is due to the greater vertical load on the wheel of the tractor HTZ-17221. As a result, it provides him a greater friction force between the wheel tire and the ground and allows the same tangential traction force to realize at a lower level of slipping.

The results of mathematical modeling show that with increasing the angle of placement (inclination) of the hitch to the longitudinal axis of symmetry of the tractor wheel, the maximum permissible level of its slipping should be less. This will reduce the amount of deformation (longitudinal shear) of the soil by the tractor in the process of its working movement.

When using the limit of soil shear strength as a limiting parameter, increasing the values of the pitch and height of the tractor wheel and the width of the tractor wheel tire allows the maximum permissible level of its towing more than 15%, which is an undesirable fact.

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