Comparison of the forest machine mover average and nominal pressure on the soil

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Abstract. The purpose of this article is to investigate the relationship between the estimated values of nominal and average wheeled mover pressure on the ground and a rigid bearing surface. Research methods are mathematical analysis, computational experiment, and calculated data approximation.

The article presents and compares methods of calculating average mover pressure in deformable soils, medium mover pressure on a rigid base, and nominal pressure on soil. According to the calculations results, it was found that the average mover pressure on firm soils almost corresponds to the estimate of the mover pressure on a rigid base. The nominal pressure is lower than the pressure on the rigid base by 40-50 kPa. The average pressure estimate on moderate soils is close to the nominal pressure. The average pressure on weak soils in the load range of 10-20 kN is close to the nominal pressure, at high values of wheel load the average pressure on the soils category is estimated to be twice less than the nominal pressure of the mover on the soils. It has been established by calculation that the average pressure of the wheeled mover on the deformable forest soils and on a rigid base is connected with the value of the mover nominal pressure on the soils, used by the foreign researchers. The dependences are linear and include correction factors, the values of which are determined by the mover parameters (wheel width and diameter, tyre pressure, and wheel load) and the forest soil category. The received equations allow simplifying the interaction estimates comparison process of forest machine movers on the soils, given within the domestic and foreign techniques limits.

Introduction

Contact spot pressure is one of the most important indicators that characterizes the machine's engine impact on the bearing surface (soils). There are various methods and models for calculating the track depth, soil compaction and logging equipment floatation, based on the comparison of the mover pressure and the soil bearing capacity [1], [2]. However, the authors use different approaches to determine the pressure: in foreign studies the nominal ground pressure (NGP) [3] - [7] is more frequent, in domestic studies the specific or average pressure of the mover on the contact spot \( p \) and on the rigid surface \( q \) [8], [9]. Based on the NGP value, the expected maximum pressure of the MMP (mean maximum pressure) [4], [5] is determined, and the maximum mover pressure on the ground \( p_{\text{max}} q \) is calculated using correction coefficients at \( p, q \) values [8], [9]. MMP, \( p_{\text{max}} \) values are also used to calculate the machine's interaction with soils. Moreover, in the scientific literature and periodicals there is not enough information on how to compare the values of NGP, \( p, q \) and, therefore, the recommendations of various authors.

The purpose of this article is to investigate the relationship between the design values of nominal and average wheeled mover pressure on the soils and a rigid support surface.

Research methods are mathematical analysis, computational experiment, and calculated data approximation.

Setting the objective and main results of the study

The equation for the average pressure on the wheeled mover rectangular spot with the deformable soils is written down as follows:
\[ p = \frac{G_w}{bl}, \]  
(1)

where \( G_w \) is the wheel load, \( b \) is the contact spot width, \( l \) is the contact spot length.

The contact spot width is found by the equation \([10]\):
\[ b = B + \frac{10h \cdot h_z}{1 - h + H_T - h_z}, \]  
(2)

where \( B \) is the tyre width, \( H_T \) is the tyre radial deformation, \( h \) is the track depth.

The contact spot length is found by the equation \([10]\):
\[ l = \sqrt{dh_z - h_z^2} + \frac{d \cdot (h_z + h) - (h_z + h)^2}{1 - h + H_T - h_z}. \]  
(3)

where \( d \) is the wheel diameter.

The track depth is found from the solution of the differential equation of pressing the stamp into the deformable soils, which, taking into account the compression deformation and the array shifting, has the form \([11]\):
\[ h = \frac{a b C_p J_p}{\sqrt{p_s(-C_p J_p + p_s - J_p)}} \arctg \left( \frac{p_s}{a b \sqrt{p_s(-C_p J_p + p_s - J_p)}} \left( H - h \right) \right). \]  
(4)

where \( a \) is a parameter that takes into account the deformable soils layer thickness, \( J \) is a parameter that takes into account the contact spot length and width ratio, \( H \) is the deformable soils layer thickness, \( p_s \) is the soils bearing capacity, \( C \) is the soils stiffness, determined depending on its rheological model.

The conclusion of the equation (4) and the rationale for its structure are detailed in the paper \([11]\). The parameters \( a, J \) are calculated according to the known formulas \([10]\):
\[ a = 0.64 \frac{b + H}{H}, \]  
(5)
\[ J = \frac{0.03b + l}{0.43b + 0.6l}. \]  
(6)

It was shown \([11]\) that the Maxwell Thompson’s rheological body model with equal modules of instantaneous and long-term deformation correctly describes the behavior of the forest soils under the machine load. The expression for the rigidity of such a model is \([12]\):
\[ C = \frac{2}{E} \exp \left( -\frac{E}{\eta} \right), \]  
(7)

where \( E \) is the deformation modulus, \( n \) is the soils viscosity, \( t \) is the exposure time.

The exposure time is determined by the formula:
\[ t = \frac{n}{v}, \]  
(8)

where \( n \) is the number of wheels passing successively along the track, \( v \) is the machine speed.

The equations analysis \((1) - (8)\) shows that the values of 12 variables are needed to determine the average pressure \( p \): \( G_w, B, H_T, d, p_s, v, n, E, \eta, p_s, h, h_z \). In this case, \( h \) is found in equation (4) by the iteration method, but an unknown quantity \( h_z \) is present in the equation.

The empirical equation allows calculating the elastic wheel pressure on the ground at a known radial deformation \( h \) \([10]\):
\[ p = \frac{p_n + q \cdot h_z}{2} \left( \frac{B}{H_T} + \frac{3H_T}{B} \right) \left( 1 - \frac{h_z}{B} \right), \]  
(9)

where \( p_n \) is the pressure in the tyre.

The pressure on the tyre contact spot with the rigid bearing surface can be expressed as follows:
\[ q = G_w \frac{h_z}{h_z^0}, \]  
(10)

where \( h_z, h_z^0 \) is the width and length of the wheel contact spot with a rigid surface according to formulas \((2), (3)\) at \( h = 0 \):
\[ h_z = B, \]  
(11)
\[ l_z = 2 \sqrt{dh_z + h_z^2}, \]  
(12)
where \( h_{z0} \) is the wheel radial deformation the one on a rigid surface, determined by the Heideckel formula [10]:

\[
h_{z0} = \frac{G_w}{mp_w \sqrt{Bd}}.
\]

(13)

The right parts of formulas (1) and (9) are equated; then, taking into account (2), (3), (10) – (13), an equation with the variables \( G_w, B, d, p_w, h \) and \( h_Z \) is obtained. The values \( G_w, B, d, p_w \) refer to the original data, then, at their given values, the equation will contain two unknown quantities, therefore, on its basis an expression for \( h_Z \) depending on \( h \) is obtained.

The calculations analysis with the initial data variation shows that the calculated values of \( h_Z \) are almost exactly expressed in terms of \( h \) with the help of the fourth degree polynomials:

\[
h_Z = a_0 + a_1 h + a_2 h^2 + a_3 h^3 + a_4 h^4,
\]

(14)

where \( a_0, a_1, a_2, a_3, a_4 \) are the approximation coefficients determined by the initial data \( G_w, B, d, p_w \).

The calculation procedure is as follows: after specifying the initial data \( (G_w, B, H_T, d, p_w, v, n, E, \eta, p_S) \) the equations (1) - (9) are solved taking into account (2), (3), (10) - (13) as a system with respect to \( h_Z \) when varying \( h \) in a given range, the calculated data is approximated and the function \( h_Z = f(h) \) as an expression (14) is obtained. Then, by iteration, the equation (4) with respect to \( h \) taking into account the formulas (1) – (3), (5) – (8), (14) is solved.

The influence of the parameters \( G_w, B, H_T, d, p_w, v, E, \eta, p_S \) on the pressure \( p \) in more detail is investigated. To do this, a computational experiment in the Maple 2017 environment is applied; the ranges of parameter-factors values changes are presented in table 1.

Table 1 - Range of changes in factors in the computational experiment to study the influence of the mover and soil parameters on the average pressure on the contact spot

| Parameter | Dimension | Minimum value | Maximum value |
|-----------|-----------|---------------|---------------|
| \( d \)   | m         | 1.2           | 1.8           |
| \( L \)   | m         | 0.5           | 0.8           |
| \( H_T \) | m         | 0.25          | 0.65          |
| \( P_w \) | MPa       | 0.15          | 0.55          |
| \( G_w \) | kN        | 10            | 70            |
| \( v \)   | m/s       | 0.25          | 1.5           |
| \( H \)   | m         | 0.2           | 1             |
| \( E \)   | MPa       | 0.4           | 3             |
| \( \eta \) | MPa s    | 1             | 10            |
| \( p_S \) | MPa       | 0.05          | 0.55          |

The calculations were performed with 1000 factor values combinations generated as random variables evenly distributed in the ranges according to table 1 (≈2⁵ combinations). According to the processing results the calculated data using the least squares method, excluding insignificant factors, \( p \) [kPa] for the pressure is obtained:

\[
p = 37.52d^{0.38}B^{0.41}P_w^{0.14}G_w^{0.43}E^{0.16}p_S^{0.35},
\]

(15)

The dimensions of the equation parameters (15) correspond to those specified in table 1.

So it can be concluded that the mover contact spot pressure with soils is determined by such factors as the wheel diameter \( d \), the tyre width \( B \), the internal tyre pressure \( p_w \), the wheel load \( G_w \), the deformation modulus \( E \) and the bearing soils capacity \( p_S \).

To calculate the nominal pressure \( NGP \) the formula is used [4], [5]:

\[
NGP = \frac{2G_w}{Bd},
\]

(16)
The compared results of calculations by formulas (10), (15), (16) for soils of three categories (I - firm \( E = 3 \text{ MPa}, \ p_S = 0.3 \text{ MPa} \); II - moderate, \( E = 1 \text{ MPa}, \ p_S = 0.1 \text{ MPa} \); III - weak, \( E = 0.4 \text{ MPa}, \ p_S = 0.04 \text{ MPa} \) at \( B = 0.7 \text{ m}, \ d = 1.6 \text{ m}, \ p_w = 0.35 \text{ MPa} \) are presented in table 2.

### Table 2 – Calculation results of nominal and average mover pressure on soils

| \( G_w \), kN | NGP, kPa | \( q \), kPa | \( p \), kPa |
|---|---|---|---|
| | weak (III) | moderate (II) | firm (I) |
| 10 | 18 | 61 | 25 | 39 | 69 |
| 20 | 36 | 87 | 34 | 54 | 94 |
| 30 | 54 | 106 | 41 | 65 | 113 |
| 40 | 71 | 123 | 46 | 74 | 129 |
| 50 | 89 | 138 | 51 | 81 | 143 |
| 60 | 107 | 152 | 55 | 88 | 155 |
| 70 | 125 | 164 | 59 | 95 | 166 |

The tabular data are illustrated by the graphs in figure 1.

![Figure 1](image_url)

**Figure 1.** Nominal and average mover pressure on the soils, depending on the load

The analysis of the calculation results shows that the average mover pressure on the soils category I \( p \) practically corresponds to the mover pressure estimate on the rigid base \( q \). The nominal NGP pressure is lower than the pressure on the rigid base \( q \) by 40-50 kPa. The average pressure assessment on the soils category II is close to the nominal pressure NGP. The average pressure on soils category III in the range of 10-20 kN load is close to the nominal pressure of the NGP. For the large load values on the wheel the average pressure on soils category III is roughly twice less than the nominal mover pressure on the soils, which can be explained by increasing the mover contact area with weak soils.

Processing the results of the calculations using equations (10), (15), (16), with variation of the initial data in the range specified in Table 1, shows that the average pressure on the deformable soil \( p \), pressure on a rigid base \( q \) and the nominal pressure of NGP can be correlated with high accuracy by simplified dependencies \((R^2>0.95)\):

\[ p = K_p \psi_p \text{NGP}, \]  
\[ q = K_q \psi_q \text{NGP}, \]  
\[ p = K \psi q. \]  

Where \( \psi_p, \psi_q, \psi \) are auxiliary coefficients depending on the mover parameters:

\[ \psi_p = B^2 d^2 G_w^{-1/2}, \]  
\[ \psi_q = B^2 d^2 G_w^{-1/2}, \]  
\[ \psi = B^2 d^2 G_w^{-1/2}. \]
\[ \psi_q = B^2 \frac{1}{2} d^2 \frac{1}{2} p^2 \frac{1}{2} G \frac{1}{2}, \quad (21) \]
\[ \psi = B^2 \frac{1}{3} p^2 \frac{1}{3}, \quad (22) \]

where \( K_q, K_p, K \) are numerical coefficients depending on the soils category, the values of which are presented in table 3.

| Coefficient | Soil category |
|-------------|---------------|
|             | weak (III)    | moderate (II) | firm (I) |
| \( K_p \)   | 3.8           | 6.0           | 10.5     |
| \( K_q \)   | 17.1          | 17.1          | 17.1     |
| \( K \)     | 0.30          | 0.47          | 0.83     |

In formulas (20) – (22), the quantities dimensions correspond to those specified in table 1.

**Conclusion**

It was found by calculation that the wheeled mover average pressure on the deformable forest soils and on the rigid base is associated with the nominal mover pressure value on the soils, used by foreign researchers. The dependences are linear and include correction factors, the values of which are determined by the mover parameters (wheel width and diameter, tyre pressure, wheel load) and the forest soils category.

The received equations will allow simplifying the estimates comparison process of forest machine movers interaction on the soil, given within the limits of domestic and foreign techniques.

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