Bearing floatation of forest machines (theoretical calculation)

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Abstract. The purpose of the article is to summarize the calculation procedure and calculate the forest machines floatation depending on the type of mover and soil conditions. Research methods are analysis of literary sources, numerical methods of applied mathematics during calculations and calculated data approximation. Formulas and the procedure for calculating the track depth, the coefficients of resistance to movement, adhesion and traction of the forest machines movers are given. In the compiled mathematical model, slipping is not an input parameter; its value is determined by calculation comparing the resistance forces to movement and the mover adhesion to the bearing surface. According to the calculations results, it was found that forestry machines with a caterpillar mover have greater cross-country ability compared to wheeled vehicles. On weak and moderate soils, the bearing floatation loss of tracked vehicles due to insufficient mover adhesion to the bearing surface does not occur. A factor limiting the pressure of the caterpillar mover on the bearing surface should be recognized as the track depth, since at a pressure of more than 0.04 MPa, the track depth exceeds the machine clearance. To ensure the bearing floatation of wheeled vehicles on weak soils, the pressure of the wheeled mover should be limited to 0.6 MPa. To ensure the bearing floatation of wheeled vehicles on moderate soils, the pressure of the wheeled mover should be limited to 0.95 MPa.

Introduction
The bearing floatation of forest machines is usually estimated by the traction coefficient, which is the difference between the adhesion coefficient and the resistance coefficient to movement [1], [2]. A positive value of the traction coefficient means that the machine is able to move along the bearing surface, a negative value indicates the loss of bearing pass ability [1], [2]. A theoretical assessment of the thrust, adhesion, and drag coefficients is the most complicated task for forest engineering [2] - [5]. To date, based on the methods of road transport theory in off-road conditions, studies have been carried out to model the interaction of the forest machines movers with various soils and forest soil [1], [2], [6] - [10]. As a result, engineering dependencies were obtained for assessing track formation, traction and adhesive properties, and equipment floatation in predetermined soil conditions. At the same time, the authors note [1], [2], [6] - [10] that further research is required for the further development and improvement of the presented mathematical models. In particular, in the well-known works [1], [2], [6] - [10], the skidding coefficient of the mover is considered an input parameter of the models, which is not entirely correct, since the skidding coefficient value is a derivative that depends on the interaction parameters of the mover with deformable soil [11], [12].

The purpose of the article is to summarize the calculation procedure and perform the calculation of the forest vehicles floatation depending on the type of mover and soil conditions.

Research methods are analysis of literary sources, numerical methods of applied mathematics in calculations and computational data approximation.

Problem setting. As it was noted in the introduction, the basic machine floatation will be evaluated using the traction coefficient $\varphi_p$ [11], [12]:

$$\varphi_p = \varphi_r - \mu,$$

where $\varphi_p$ is the movement resistance coefficient, $\mu$ is the adhesion coefficient.
The movement resistance coefficient is found by the formula [11], [12]:

$$\varphi = \frac{F_r}{G_w},$$  \hspace{1cm} (2)

where $F_r$ is the resistance force to movement, consisting of the deformable soil resistance, the sticky soil resistance to the mover separation, the mover deformation resistance, $G_w$ is the reduced load on a single mover.

At this stage of the study only the deformable soil resistance is taken into account.

The mover adhesion coefficient to the support surface is calculated by the formula [11], [12]:

$$\mu = \frac{F_T}{G_w},$$  \hspace{1cm} (3)

where $F_T$ is the mover adhesion force to the support surface.

The force with which the soil resists the mover movement is defined as the integral [11], [12]:

$$F_r = B \int_0^p F dh ,$$  \hspace{1cm} (4)

where $p$ is the mover normal pressure on the soil (the average on the contact spot), $B$ is the contact spot width (assuming a rectangular contact shape), $h$ is the track depth (soil sediment).

Here are the formulas for calculating the track depth (sediment). It is based on the equation for the upsetting of a stamp pressed into a deformable half-space [10]:

$$h = \frac{J_{pa}B_p}{(p_s - p)\sqrt{E(E - J_p)}} \arctg \left( \frac{E(H - h)}{aB \sqrt{E(E - J_p)}} \right),$$  \hspace{1cm} (5)

where $J$ is a coefficient of accounting for the rectangular contact spot aspect ratio, $a$ is a power factor of the deformable soil layer, $H$ is the thickness of the deformable soil layer, $E$ is the modulus of the total soil deformation, $p_s$ is soil bearing capacity.

The coefficients $J$, $a$ are calculated by the formulas [1], [11], [12]:

$$J = \frac{0.03 + \frac{L}{B}}{0.6 + \frac{0.43 \frac{L}{B}}{B}} ,$$  \hspace{1cm} (6)

$$a = \frac{0.64 \frac{B + H}{H}}{B} .$$  \hspace{1cm} (7)

where $L$ is the mover contact spot length and the ground.

For a crawler, the contact spot length is taken as the input parameter of the model. For a wheeled tractor, the contact spot length is approximately determined by the formula [13]:

$$L = \frac{d}{2} ,$$  \hspace{1cm} (8)

where $d$ is the wheel diameter, for a more accurate calculation of the contact spot length, the joint deformations of the elastic mover and the ground should be considered.

To calculate the load-bearing capacity, the refined formulas are proposed [14]:

$$p_{so} = \alpha_{z} \exp \left\{ \right. \left. \begin{array}{l} p_{so} = 0.5K_1N_2 \beta B + N_3 \gamma h + K_3N_4C \\ K_1 = \frac{L}{L + 0.4B} ; K_3 = \frac{L + B}{L + 0.5B} \\ N_1 = \frac{1 - T^4}{T^5} ; N_2 = \frac{1}{T^2} ; N_3 = \frac{2(1 + T^2)}{T^3} ; T = \cos \left( \frac{\pi}{4} - \frac{\varphi}{2} \right) \\ \alpha_z = 1 + \frac{H h}{2H \cdot (H - h - 0.25H^*)} ; H^* = \sqrt{\frac{2H}{2H - (H - h + 0.25H^*)}} \exp \left( \frac{\pi}{4} + \frac{3\varphi}{4} \right) \tan \frac{3\varphi}{4} B \cos \frac{3\varphi}{4} - \frac{1}{4} \tan \varphi \right\} \left. \right\} .$$  \hspace{1cm} (9)

where $p_{so}$ is soil bearing capacity with unlimited capacity of the deformable layer, $\alpha_z$ is the power factor of the deformable soil layer, $K_1$, $K_3$ are the ratio coefficients of the mover’s contact spot length and width with the bearing surface, $N_1$, $N_2$, $N_3$ are the coefficients of the soil internal friction angle, $C$ is the specific soil adhesion, $\varphi$ is the soil internal friction angle, $\gamma$ is the specific soil gravity, $T$, $H^*$ are the auxiliary notations.

The mover adhesion force to the ground is found as an integral [1], [11], [12]:

$$F_T = B \int_0^p F dh ,$$  \hspace{1cm} (4)
where \( x \) is the horizontal coordinate measured along the contact spot length, \( \tau \) is the tangential shear stress distributed over the contact spot.

The tangential stress is calculated by the equation [1], [11], [12]:

\[
\tau = \frac{JG \tau_{max}}{JG + t_g \tau_{max}},
\]

where \( j \) is the soil shear strain, \( G \) is the soil shear modulus, \( t_g \) is the lug pitch, and \( \tau_{max} \) is the maximum soil shear resistance.

The shear deformation is found by the formula [1], [2]:

\[
j = Sx,
\]

where \( S \) is the slip coefficient.

The maximum resistance to the soil shear is found by the formula [1], [11], [12]:

\[
\tau_{max} = p \tau g \phi + C \left(1 - \frac{j}{t_g}\right),
\]

The dependence integration (10), taking into account expressions (11) – (13), results in the formula:

\[
F_T = \frac{BG^2L(p \tau g \phi + C)}{(G - C)^2} \cdot S - \frac{BCG^2L}{2 \gamma (G - C)^2} \cdot \frac{1}{S} \cdot \frac{L(G - C)}{(G - C)^2} \ln \left(1 + \frac{S}{L(G - C)} \right)
\]

The input parameters of the mathematical model characterizing the soil are: the total strain modulus \( E \), the shear modulus \( G \), the specific adhesion \( C \), the internal friction angle \( \phi \), the specific gravity \( \gamma \), the power (thickness) of the deformable layer \( H \). The mover parameters: the reduced load \( G_w \) or the average pressure on soil \( p \), the contact width \( B \) and the contact spot length \( L \) (depending on the mover’s geometrical parameters), the lug pitch \( t_g \).

When the initial data are received, the average pressure range \( p \) is divided into intervals with a given pitch \( \Delta p \). The system of equations (5) - (9) is solved numerically for each pressure value \( p \). As a result, a table of the correspondence between the average pressure \( p \) and the track depth \( h \) is obtained. Using the table numerically (e.g., using the trapezoids method) the approximate value of the integral formula is found (4), then the resistance factor \( \phi \), according to the formula (2) is calculated. For each pressure value \( p \) two slipping coefficient values \( S \) are defined. The first value is found as the solution of equation (14) at \( F_T = F_r \) (slipping is sufficient to ensure adhesion). Then, for each \( p \) value, the function maximum (14) and the corresponding value of the slipping coefficient \( S \) are numerically determined (at this coefficient value, the mover adhesion with the support surface is maximum). The adhesion coefficient is found by the formula (3). The traction coefficient is calculated by the formula (1).

**Calculation results and conclusions**

For the calculation in this study the following initial data is taken: 1) wheel width \( B = 0,7 \) m, wheel diameter \( d = 1,6 \) m, lug pitch \( t_g = 0,14 \) m, average mover pressure \( p = 0,1 \ldots 0,1 \) MPa, pressure pitch \( \Delta p = 0,1 \) MPa; 2) caterpillar width \( B = 0,6 \) m, the caterpillar contact spot length with bearing surface \( L = 6 \) m, lug pitch \( t_g = 0,15 \) m, average mover pressure \( p = 0,01 \ldots 0,1 \) MPa, pressure pitch \( \Delta p = 0,01 \) MPa. The forest soil properties are taken in accordance with table 1.

| Parameter               | Soil conditions category |
|-------------------------|--------------------------|
|                         | Weak soil, category III  | Moderate soil, category II |
| \( \gamma \), MN/m³     | 0,0075                   | 0,0085                     |
| \( E \), MPa             | 0,4                      | 1                           |
| \( C \), MPa             | 0,0053                   | 0,0108                      |
| \( G \), MPa             | 0,22                     | 0,25                        |
| \( \phi \), °             | 12                       | 14                           |
| \( H \), m              | 0,8                      | 0,4                          |

The calculation results are presented in figures 1-3.
Figure 1. Track depth (sediment) under the influence of a wheeled and caterpillar mover

Figure 2. Slipping coefficient at maximum traction of the wheeled and caterpillar mover with the supporting surface
Figure 3. Traction coefficient of wheeled and caterpillar mover

Research results
By the calculation results it is established that:
1. Forest vehicles with a caterpillar engine have a greater floatation compared to wheeled vehicles. For the weak soils and the moderate soils the loss of the bearing terrain tracked vehicles because of the poor mover adhesion with the bearing surface does not occur. The factor limiting the caterpillar mover pressure on the bearing surface should be recognized as the depth of the track, since at a pressure of more than 0.04 MPa, the track depth exceeds the machine clearance.
2. To ensure the wheeled vehicles on the weak soils, the wheeled mover pressure should be limited to 0.6 MPa. To ensure the wheeled vehicles basic floatation on the moderate soils, the wheeled mover pressure should be limited to 0.95 MPa.

In the compiled mathematical model, slipping is not an input parameter; its value is determined by calculation based on the results of comparing the movement resistance forces and the mover adhesion with the bearing surface. This builds on the results obtained in previous studies on the forest vehicles floatation. The mathematical model uses a simplified expression to determine the contact spot length; in the long term it is expedient to clarify the calculation procedure when taking into account the influence of the wheel drive elasticity on the contact spot shape.

References:
[1] Lukhmnsky V.A. Improving models and methods for predicting the tracked forest machines floatation. Diss. Cand. tech. sciences. Place of protection: Arkhangelsk, NArFU 2018 p 179.
[2] Khakhina A.M. Methods for predicting and increasing the wheeled forest machines floatation. Diss. Doct. tech. sciences. Place of protection: Arkhangelsk, NArFU 2018 p 318.
[3] Anisimov G.M. The main directions of the logging industry scientific and technological progress Bulletin of the St. Petersburg Forestry Academy. SPb. FTA. No. 169. 2003 pp. 129-140.
[4] Anisimov G.M. Forecasting methods of the logging machines technical level. SPb. Izvestia SPb FTA. 2005 pp. 4-10.
[5] Anisimov G.M., Bolshakov B.M. New concepts of the logging machines theory. SPb FTA, 1998 p 114.
[6] Bozhbov V.E. Improving the skidding process efficiency by justifying the forwarders' workload. Abstract of diss. Cand. tech. sciences. Arkhangelsk: NArFU, 2015 p 20.
[7] Dmitrieva M.N. Modeling the interaction of a wheeled mover of small-sized forestry machines with weak bearing soil. Abstract of diss. Cand. tech. sciences. Arkhangelsk: NArFU 2018 p 20.
[8] Kalistratov A.V. Modeling of cyclic compaction in the problems of reducing the negative impact of forest machines on the soil. Abstract of diss. Cand. tech. sciences. Arkhangelsk: NArFU 2016 p 20.
[9] Peskov V.B. Improving models for assessing soil rutting and compaction under the wheeled forest machines movers’ influence. Abstract of diss. Cand. tech. sciences. Arkhangelsk: NArFU, 2018 p 20.
[10] Kochnev A., Khitrov E. Theoretical models for rut depth evaluation after a forestry machine’s wheel Passover. International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM 18. 2018. pp. 1005-1012.
[11] Ageikin Ya.S. All-terrain wheeled and combined movers. Theory and calculation. M. Mechanical Engineering 1972 p 184.
[12] Ageikin Ya.S. Cars passability. M. Mechanical Engineering 1981 p 232.
[13] Saarilahti M. «Development of a protocol for ecoefficient wood harvesting on sensitive sites (Ecowood). Soil interaction model». University of Helsinki, Department of Forest Resource Management, 2002. 39 p.
[14] Larin V.V. Prediction methods of multi-axle wheeled vehicles bearing floatation on the ground: Diss. Doct. tech. Sciences: 05.05.03.-M., 2007 p 530.