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MODELING THE EFFECT OF WHEELED TRACTORS AND SKIDDED TIMBER BUNCHES ON FOREST SOIL COMPACTION

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An increasing demand for forest products incites a large number of log transportation operations, which may lead to negative consequences for the soil and the ecosystem as a whole. This paper is focused on establishing a mathematical model to estimate the soil deformation and compaction processes under tires of wheeled forest machines and individual components of the skidding system such as forwarder, limbs, butts, and tops of tree-lengths in high latitudes, permafrost soil and forests. The method applied is based on simulating the impact processes of elastic tires and the skidding system on the soil through a mathematical device for the measurement of the compaction parameters for different types of soil and the size of the shelterbelt. The effectiveness of the proposed models was evaluated according to experimental results. The influence of the rheological (elastic, viscous, and plastic) properties of soil were studied. The elasticity of tires and the running speed of forest machines can help to control the performance of forest machines. This can be done by reducing the pressure exerted on the soil and increasing the number of skidder passes 1.5-2-fold. Comparative analysis showed that the calculated data differ from the experimental ones by no more than 10%. The obtained results and the developed model will allow for a qualitative and quantitative assessment of technological impact on the soil during the projecting maps for logging operations.

Key words: high latitude forests, timber bunches, permafrost soils, reduction of environmental consequences

INTRODUCTION

Forests are considered not only a source of a timber and alternative energy source, but also ensure the environmental security of our planet. Forest is one of the main components of the human environment promoting biodiversity, which acquires undisputable importance for the full enjoyment of human rights [1]. Therefore, forest management, conservation, and regeneration methods must meet contemporary social, environmental, and economic human needs.

Therefore, in improving the efficiency of timber harvesting and reforestation processes, such multiple factors as physical and mechanical properties of the soil, parameters of tires, the vehicle body, loading capacity, etc., should be considered [2]. Soil compaction is considered the main harm caused by timber skidding [3]. Besides, value of the correlation between economic value added and environmental harm is of high importance as well [4]. The integral indicator of soil compaction at a felling area is one of the most important factors for estimating the environmental efficiency of harvesting processes [4, 5].

As the tire travels, it applies uneven pressure to the soil within the contact area [6]. This leads to the deterioration of the basic physical and physical-mechanical properties of the subsoil and topsoil layers, reducing soil fertility and increasing energy consumption. Numerous experimental studies present wheel and track designs for minimization of pressure on the soil [7-9]. A number of mathematical models of soil pressure distribution caused by tire have been proposed, which are based on the finite element model of soil compaction [10], smoothed-particle hydrodynamics [11], etc. Another important aspect in studying the environmental impacts of forest machinery on the soil is the interaction of skidding system with permafrost soils of cryolithic zone forests, which represent particularly susceptible forest ecosystems [12, 13], and, according to [14], significantly subjected to commercial exploitation. Skidding process is the most environmentally harmful operation in wood harvesting [15, 16], which may cause significant degradation of the soil at the interaction of the tractor's skidding and the dragging timber bunch [17]. Contemporary literature misses detailed studies on the

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The relationship between the time of rutting in elastic-viscous soils, the rut depth, and elastic tire deformation can be expressed as follows:

$$t = \left[\frac{\mu_0}{C} + [9\mu\beta P(32b^2R)^{-1}]^{\frac{1}{3}} C^{-2} \right] \ln \left[\frac{[9\beta P(32b^2R)^{-1}]^{\frac{1}{3}}}{[9\beta P(32b^2R)^{-1}]^{\frac{1}{3}} - C_x} \right] - x \tag{10}$$

At the beginning of the soil compaction process, the viscous component $(C_x + \mu x \frac{dx}{dt}) \ll \mu_0 \frac{dx}{dt}$ dominates;

therefore, $dt = \mu_0^{-1} dx$ and the rut depth is equal to:

$$x = [9\beta P(32b^2R)^{-1}]^{\frac{1}{3}} \mu_0^{-1} t \tag{11}$$

If $\mu_0 = 0$ and the initial conditions of rutting correspond to $C_x \ll \mu \frac{dx}{dt}$, then

$$x = (2\mu^{-1}t)^{\frac{1}{2}} \tag{12}$$

The expression (12) suggests that the equation for rut formation by elastic tires can be written as follows:

$$x_0 = [2\mu^{-1}[9\beta P(32b^2R)^{-1}]^{\frac{1}{3}} t]^{\frac{1}{2}} \tag{13}$$

From equation (14), the initial phase of rutting depends on both the elastic properties of the tire and the viscous properties of the soil. The asymptotic value of the rut depth can be found from the condition $t \rightarrow \infty$, which corresponds to the maximum rut depth:

$$x_m = [9\beta P(32b^2R)^{-1}]^{\frac{1}{3}} C^{-1} \tag{14}$$

It can be seen that the maximum depth of the rut under elastic tires linearly depends on the elasticity of the tire. Hence, the maximum sinkage depth of the wheel with the elastic tire in elastic-viscous soils can be determined by the following formula:

$$y_0 = \left(\frac{a^2}{2R} + \beta\mu^{-1}t \right) - \left[\left(\frac{a^2}{2R} + \beta\mu^{-1}t \right)^2 - 4 \left(\frac{a^2}{2R} \right)^2 \right]^{\frac{1}{2}} \tag{15}$$

whilst the first rut depth can be found using the formula

$$h_1 = \frac{a^2}{2R} - \left(\frac{a^2}{2R} + \beta\mu^{-1}t \right) - \left[\left(\frac{a^2}{2R} + \beta\mu^{-1}t \right)^2 - 4 \left(\frac{a^2}{2R} \right)^2 \right]^{\frac{1}{2}} \tag{16}$$

and the depth of the following ruts is to be found with the help of the equation

$$h_n = \left[\frac{a^2}{2R} - \left(\frac{a^2}{2R} + \beta\mu^{-1}t \right) - \left[\left(\frac{a^2}{2R} + \beta\mu^{-1}t \right)^2 - 4 \left(\frac{a^2}{2R} \right)^2 \right]^{\frac{1}{2}} \right] n^{\frac{1}{2}} \tag{17}$$

The presence of elastic deformability of the tire can be considered a degree of freedom manifestation, which, to a certain extent, makes it possible to control the performance of wheeled forest machines.

Methods of modeling the impact of skidding on the soil compaction

Most harmful effect on the soil during skidding is caused by turning and maneuvering operations while loading and transportation of timber bunches, which leads to additional shearing stress in a direction perpendicular to that of a normal forwarder's load [19]. Same great interest was aroused to studying the impact of a bunch weight on the soil which can cause an additional compaction during skidding [20].

Total forces acting while butt length immersion can be presented as follows:

$$Q = P + G \tag{18}$$

where Q is the gravity force of tree-length, P is the weight of tree-length acting on the tractor and amounting to $0.3Q$, G is the weight of tree-length acting on the soil when it is skidded at the top and amounting to $0.7Q$. At this, some part of a tree-length log can go into the soil to a certain value of primary immersion area h_0 .

The value h_0 can be determined as:

$$h_0 = \left(3^n \beta \frac{\pi h_k G}{AL\sqrt{d}} \right)^{\frac{1}{n+1.5}} \tag{19}$$

where d is the trunk diameter, L is the length of a tree-length log, the coefficient $\beta \geq 1$ is the relation of L to the maximum possible hanging part of the tree-length log, h_k is the distance from top point of the tree-length log support on the bolster to the supporting surface. A and n are the parameters of soil and press tool of weight G with contact area d in exponential functions $q = Ah^n$, i.e., in dependencies of press tool pressure q on the depth of its immersion h within the range from 0 to the depth H of the deformation area (Figure 2).

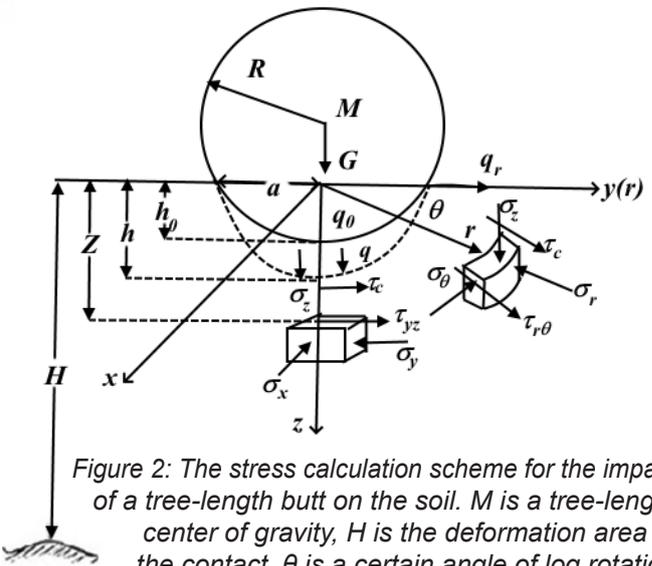


Figure 2: The stress calculation scheme for the impact of a tree-length butt on the soil. M is a tree-length center of gravity, H is the deformation area at the contact, θ is a certain angle of log rotation

The tree-length part operating on the soil with the bark volume V_x is determined by values L and d of the assortment tables and is calculated as an equivalent in volume and weight sphere with a radius by

$$R = \sqrt[3]{\frac{0,7V_x}{\pi}} \quad (20)$$

The mathematical model of area deformation based on the principles of contact fracture mechanics where the main characteristics of the indenter immersion into the area are the values of contact approach h_o and radius of the contact area

$$a = \sqrt{h_o R} \quad (21)$$

The initial uniform pressure averaged over the area operates

$$q_o = \frac{G}{\pi a^2} = \frac{G}{\pi h_o R} \quad (22)$$

The process of soil deformation outside the contact zone with depth h_o and radius a will be considered in a Cartesian coordinate system. As seen on Figure 2, the stress σ is determined as follows:

$$\sigma_x = \frac{\nu}{1-\nu} \sigma_z \quad (23)$$

$$\sigma_z = \left(-q_o \frac{z}{\sqrt{u}}\right)^3 \frac{a^2 u}{u^2 + a^2 z^2} \quad (24)$$

$$\sigma_z = q_o \left[\frac{1-2\nu}{3} \frac{a^2}{r^2 + z^2} \left[1 - \left(\frac{z}{\sqrt{u}}\right)^3 \right] + \left(\frac{z}{\sqrt{u}}\right)^3 \frac{a^2 u}{u^2 + a^2 z^2} + \frac{z}{\sqrt{u}} \left[\frac{(1-\nu)u}{a^2 + u} + (1+\nu) \arctg\left(\frac{a}{\sqrt{u}}\right) - 2 \right] \right] \quad (25)$$

Tangential stress is determined as follows:

$$\tau_{yz} = -q_o \frac{a \sqrt{u} z^2 (r^2 + z^2)}{(u + a^2)(u^2 + a^2 z^2)} \quad (26)$$

where u is the positive root of quadric equation; ν is Poisson's coefficient

According to the scheme presented in Figure 2, the ratio can be simplified to $\sigma_y = \sigma_r$. Then, from Eq. (23)-(25) follows that the stress state of the soil depends on the coordinates of the calculation contact point and the radius of the contact area a .

The combined action of the vertical force G and tangential force F_T of the tractor's traction initiate the force of resistance to tree-length log sliding F_n , which results in emergence of horizontal stress τ_c is formed perpendicular to the action of vertical stress σ_z :

$$\tau_c = \sigma_z \tan \varphi + C \quad (27)$$

At the moment when the tree-length log deviates from the given traffic direction to the angle θ , the components of the stress tensor in the cylindrical system of coordinates $zr\theta$ can be determined as:

$$\sigma_r = \frac{\sigma_y + \sigma_x}{2} + \frac{\sigma_y - \sigma_x}{2} \cos 2\theta; \sigma_\theta = \frac{\sigma_y + \sigma_x}{2} - \frac{\sigma_y - \sigma_x}{2} \cos 2\theta; \tau_{r\theta} = -\frac{\sigma_y - \sigma_x}{2} \sin 2\theta \quad (28)$$

The resultant value of tangential stress $\tau = \tau_c + \tau_{r\theta}$ characterizes the total shear stress and should meet the following condition:

$$\tau \geq q_s \quad (29)$$

If the given condition is fulfilled, the limit value of the contact approach or the maximum possible depth of the tree-length immersion area h_s corresponds to the value Z on Figure 2.

The dependence of τ on \bar{h} with a high determination coefficient ($R^2 > 0.93$) and considering the angle parameter θ for a single tree-length can be expressed as follows:

$$\tau = \lambda \bar{h}^\eta \quad (30)$$

where $\lambda = 0,7605\theta + 23,913$
 $\eta = -(0,0179\theta + 0,241)$

The Eqs. (29) and (30) show that the depth limit of the immersion area h_s can be defined as:

$$h_s = h_o \left(\frac{q_s}{\lambda}\right)^{\frac{1}{\eta}} \quad (31)$$

The value of a relative soil compaction within the trail is defined as:

$$\bar{\rho} = \frac{\rho}{\rho_o} = \varepsilon + 1 = \frac{h_s}{H} + 1 \quad (32)$$

where ρ is the achieved soil density and ε is the deformation of compression.

The radial stress q_r along the radius $r \geq a$ calculated from the boundary of a contact area is described by the ellipse equation:

$$q_r = q_o \sqrt{1 - (a/r)^2} \quad (33)$$

The maximum radial distance r_s , at which value q_r will exceed the soil bearing capacity q_s , can be interpreted as the size of the maximum compaction area in the radial direction from the track or as the width of a shelterbelt of undergrowth root system or cut-to-length wood:

$$r_s = a \sqrt{\frac{1}{1 - \frac{q_s^2}{q_o^2}}} \quad (34)$$

Experimental procedure

For estimation of initial parameters of contact and other parameters of soil compaction, the basic values and constants in the course of modeling were used, which are presented in Table 1.

The soil densification experiments on the side strands of a trail were performed under laboratory conditions using a metrologically verified DOS-3-I electronic compression dynamometer, which includes 101WN strain sensor and indicator station R320. The analysis results were processed by software and Excel application [21, 22].

For the tests, cylindrical wooden blanks were used, fabri-

Table 1: Basic soil loading data

| Parameter | Value | Parameter | Value |
|------------------------------------|---------|-----------|-------|
| L, m | 30.5 | E, MPa | 1 |
| d, m ³ | 0.24, | C, kPa | 12 |
| Vx, m ³ | 0.65 | v | 0.25 |
| hk, m | 1.8 | φ, ° | 15 |
| l, m | 1.525 | H, m | 0.4 |
| β | 1.05 | qs, kPa | 60 |
| ρ ₀ , kg/m ³ | 800-900 | Wp, % | 32 |
| WT, % | 44 | Wpl | 12 |

cated close to field conditions by shape and geometrical proportions. Experiments were performed on soil samples that correspond to three types of soils:

- Category I – sand, loamy sand, light clay (wet), top soil, and peat;
- Category II – loam, gravel fine and medium, and light clay (wet);
- Category III – clay medium or heavy, loosened, and dense loam.

Depending on the ratio of moisture values W versus its yield strength W_T , three categories can be defined: I – mild ($W > WT$), II – medium ($W = WT$), and III – solid soil ($W < WT$). The initial parameters for all soil categories are presented in Table 2.

The sample of a soil was placed into the tray so that the distance from the soil surface to the bottom of the tray was 0.16, 0.08, and 0.06 m for the first, second, and third categories of soil, respectively. A press tool was attached to a circular plate of 0.4 m in diameter and manually im-

Table 2: The initial parameters of contact deformation for different soil categories

| Parameters | Soil categories | | |
|------------------------------------|-----------------|-----------|-------------|
| | I | II | III |
| E, Mpa | 0.4 | 1 | 3 |
| v | 0.35 | 0.25 | 0.15 |
| C, kPa | 5 | 12 | 24 |
| φ, ° | 11 | 15 | 16 |
| ρ ₀ , kg/m ³ | 750 | 850 | 950 |
| qs, kPa | 40 | 60 | 80 |
| A, wt. (mass unit) | 0.0215 | 0.0564 | 0.1671 |
| n | 1 | 1.0206 | 1.0888 |
| H, m | 0.8 | 0.4 | 0.3 |
| h ₀ , m | 0.173 | 0.117 | 0.074 |
| a, m | 0.443 | 0.363 | 0.289 |
| q ₀ , kPa | 52.67 | 78.34 | 123.53 |
| ρ, kg/m ³ | 1350-1450 | 1450-1550 | 1550 - 1650 |

Note: ρ_0 is the initial density of soil samples and ρ is the density value of compacted soil samples

mersed into the soil placed in the tray. At that, the plate with the attached press tool tightly fitted to the soil surface. Afterward, the press tool and the plate were rotated to the specified angle θ , wherein the measuring equipment of the sensor recorded the value of force applied to the indicator part of the strain sensor from the side of the soil under deformation.

The main independent parameters to be monitored during the research were soil density used in the tests and consistency index. As variables were applied the die rotation angle θ and the distance from the die to the adjoining soil layer, for which the compressing force was measured at rotating the die. The output parameter was the maximum compressive force P occurring at the side soil layer adjacent to the die at its rotation. Based on the analysis, a three-level full-factor experiment was performed.

In order to test the model of rutting, three different categories of soil were sampled and then compacted using a standard compaction instrument. The plasticity limits of the soil were determined using the standard balancing cone of A.M. Vasilyeva. The soil elasticity and deformation moduli were determined using a tabletop lever press. The following data were found during the tests: a) diagrams of vertical soil stress vs relative soil deformation; b) the ultimate stress at failure of the soil sample and the corresponding relative deformation limits. Next, the influence of the cyclical vertical loads on the soil deformation process was evaluated. A load equal to 70-80% of the ultimate load was taken as a constant (fixed) one. Because the compacted soil samples had 1.8 to 2 times higher density than before the application of load (Table 2), the following assumptions were made: (1) this increase in soil density is associated with the application of the cyclic load; and (2) the true value of deformation is a combination of elastic deformation and residual (viscous-plastic) deformation.

RESULTS AND DISCUSSION

The results from the analysis of experimental data were converted to a graphical form to show the relationship between soil compaction at different moisture levels and variables such as the load acting on the soil specimens and load time (Figures 3 and 4). With these data, it is possible to determine the dependence of rut depth and running speed (v) at a given load (P). Let us take the moving wheeled tractor as an example. For this, it is necessary to determine what kind of deformations occur due to the tractor wheel passes. To begin with, let us determine the duration of wheel-soil interaction. Even with a rut depth equal to the radius of the tractor wheel, the length of the contact area will be less than 1.5 m. The tractor travels at the speed of 1-20 km/h. Therefore, the wheel-soil interaction will last $7 \div 0.45$ sec. The relationship between rut depth and load time is depicted in Figure 3. As it can be seen in the Figure 3 below, the viscous component is associated with the load time of 10 sec. Therefore, the mathematical model may be simplified by considering the viscous deformation alone.

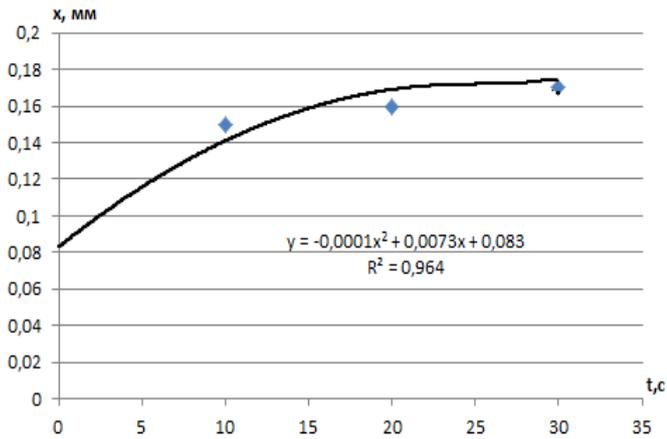


Figure 3: Changes in soil under vertical load of 0.2 MPa

The model of rutting in elastic soils derived from the general equation for soil deformation will take the form $P = \mu_0 \frac{dx}{dt}$, $\frac{dx}{dt} = \frac{V}{R} \xi$. The pressure acting on the soil

will be $P = \int_0^a Pbd\xi$, $P = \int_0^a \frac{bV}{R} \mu_0 \xi d\xi$. Consequently,

$\frac{P}{b} = \frac{\mu_0 V}{R} \cdot \frac{a^2}{2} = \mu_0 V h_1$. In this case, the rut depth after

the first wheel pass (h_1) will be $\frac{P}{b\mu_0} = h_1 V$, and, conse-

quently, $\frac{P}{b\mu_0 V} = h_1$.

The graph will show a hyperbolic relationship between rut depth and wheel speed for the n -th wheel pass

$h_n = \left(\frac{P}{b\mu_0 V} \right) n^{\frac{1}{2}}$. The plastic soil deformation will be

$$P = \mu_{0n} \frac{dx}{dt}, \quad \frac{P}{b\mu_{0n}} = h_n V, \quad h_n = \left(\frac{P}{b\mu_{0n} V} \right) n^{\frac{1}{2}}.$$

The calculation of total shear stress τ and stress tensor components showed that the soil deformation through shearing does not occur at skidding of a single tree-length log over the given soil without any maneuvers of a skidding system outside the primary immersion area ($z = h_0 - 0.047$ m). However, by log rotation ($\theta = 10-25^\circ$) the immersion area becomes larger, and h_s increases from 0.058 to 0.082 m, a radius of the contact area a expands in from 0.176 to 0.208 m. For a skidding of a single tree-length log the values q of the load exercised on the soil from the spherical indenter with radius R are changed to within the range $q = 27.3-48.33$ kPa. At initial parameters $q_s = 30$ kPa and $q_o = 41.64$ kPa for a single tree-length skidding the range of changes r_s is 0.25-0.30 m.

The results of similar calculations for a wider range of rotation angle ($\theta = 0-45^\circ$) showed that the maneuvers of the skidder significantly influence the value ε , which varies from 0.12 to 0.23 and the value of relative compaction. The size of a shelterbelt changes within a narrow range of $r_s = 0.23-0.33$ m.

The analysis of effect of cycling and skidder's maneuvers on the relative compaction $\bar{\rho}$ showed that a value $\bar{\rho}$ varied significantly even in case of a single tree-length skidding. The number of skidder passes (N) was deter-

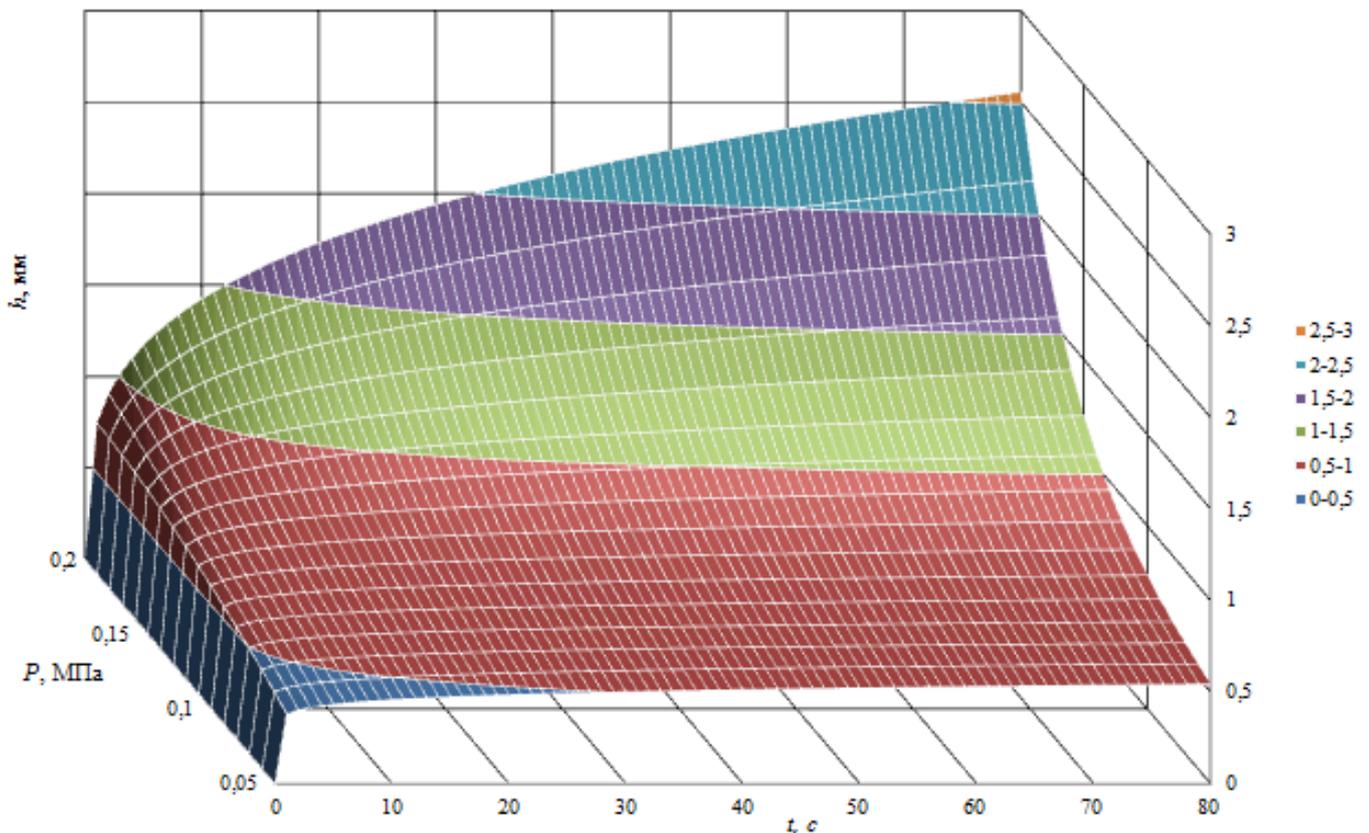


Figure 4: Changes in rut depth over time under different loads (moisture level, $W=40\%$)

mined by multiplying the value ε by the coefficient $\lambda_N = 1 + \lg N$.

The initial contact parameters for $N_x=10$, volume of $V_x = 6.5 \text{ m}^3$, and weight of $Q = 32.5 \text{ kN}$ ($G = 22.75 \text{ kN}$) were obtained as follows: $h_o=0,117\text{m}$; $a=0,363\text{m}$; $R=1,13 \text{ m}$; $q_o=78,3 \text{ kPa}$. Afterward, the soil compaction parameters $\bar{\rho}$ and the size of the shelterbelt r_s were established. The calculation results also showed that values of r_s increased substantially and varied within 1.1-1.6 m. The deformation of the soil compaction ε has also increased and reached a value of 0.8.

A comparison analysis of the calculation and experimental data of the density change ρ of the soil by ten double passage of the skidder over the trail while skidding a bunch of tree-length logs showed that the processes of soil compaction under a load of the forwarder and the bunch of logs have similar values of relative compaction $\bar{\rho}$ approximative to 2. This restriction indicated that the soil is compacted to the full depth H of the deformation area, and the rise in value N necessitates a substantial reduction of machinery maneuvers or a corresponding decrease of the weight of a skidded bunch.

The results of calculation of the values of $\bar{\rho}$ and r_s after a straight-line passage of a skidder for all soil categories are presented on Figure 5. As can be seen, the value $\bar{\rho}$ varies from 1.28 to 1.67, i.e., by 30.5%, the respective values of r_s differ by more than 2.5 times. This indicates the need to consider detailed characteristics of the soil in designing the skidding routes in order to determine the size of undergrowth shelterbelts.

Mathematical modelling allowed identifying the dependencies of $\bar{\rho}$ and r_s final values on the skidding parameters for all soil categories. Figure 6 presents the calculation results of values $\bar{\rho}$ and r_s at N_x changes from 1 to 10 and other parameters being constant.

As can be seen, the dependencies $r_s(N_x)$ have logarithmical nature of curves. The values $\bar{\rho}$ and r_s at the variation of other skidding parameters h_k , θ , and N were estimated based on these data. The analysis showed that when h_k is changed by 100%, the change of $\bar{\rho}$ does

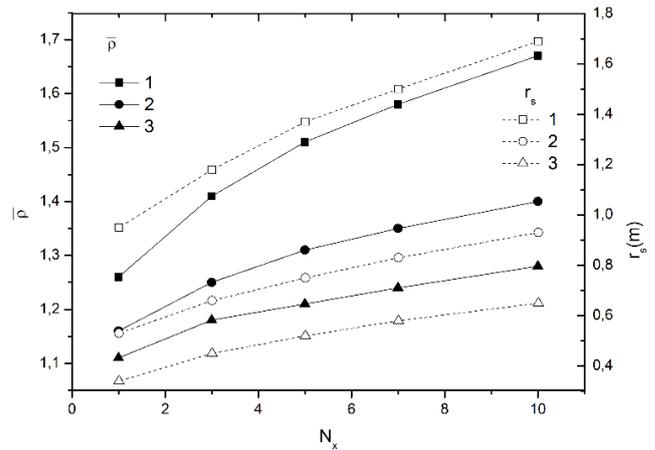


Figure 6: Compaction estimates for different soil categories with variable number of units in a bunch

not exceed 8%, i.e., the influence of h_k on the soil compaction process can be considered as not essential. A similar conclusion is made when estimating the effect of h_k on value r_s . Results of performed analysis revealed the significant influence of the skidder rotation angle θ on the compaction value $\bar{\rho}$ and value r_s for all soil categories.

Statistical processing of the samples of obtained values $\bar{\rho}$ and r_s allows establishing variation coefficients $K_v(\bar{\rho})$ and $K_v(r_s)$. With the possible deviations of θ and q_s , it is possible to establish allowable limits of $\bar{\rho}$ and r_s variation for each soil category studied. Thus, for the second soil category at $M(\theta)=10^\circ$, the variations of θ and q_s values within 20% provide $K_v(\bar{\rho}) = 5\%$ and $K_v(r_s) = 8\%$, which at $M(\bar{\rho}) = 1.5 \text{ m}$ and $M(r_s) = 1.08 \text{ m}$ sets a tolerable variation of $\bar{\rho}$ from 1.42 to 1.58 m, while r_s remains within 1-1.17 m. Noteworthy is that the 20% and lower variation is acceptable condition of skidding. Besides, the calculation analysis revealed that in milder soils, the variability of θ and q_s parameters determines wider limits of allowable variation ranges of $\bar{\rho}$ and r_s values. Thus, given mathematical model allows calculating parameters and indicators of the skidding system and allowable variation range for stabilization of indicators [23, 24].

The results of this research allows recommending the distance between the skidding trails, i.e., the areas between the skidding trails on which the machines can effectively use the boom, to be at least 20 m. Similar conclusions are drawn by other researchers [18, 25]. The 4-meter-wide skidding roads at a distance of 20 meters imply that at least 20% of the forest stand covered by forest machinery. This percentage may be reduced by laying access roads at a greater distance from each other. Trees outside the reach of a skidder can be cut down manually in the direction of the machine so that the trunk would be within the reach of harvesting arm. Moreover, machines should move without turning within one straight line as much as possible to prevent the soil wounding on the roadsides.

It is important to consider the balance between access roads and wood production areas. Narrower distance

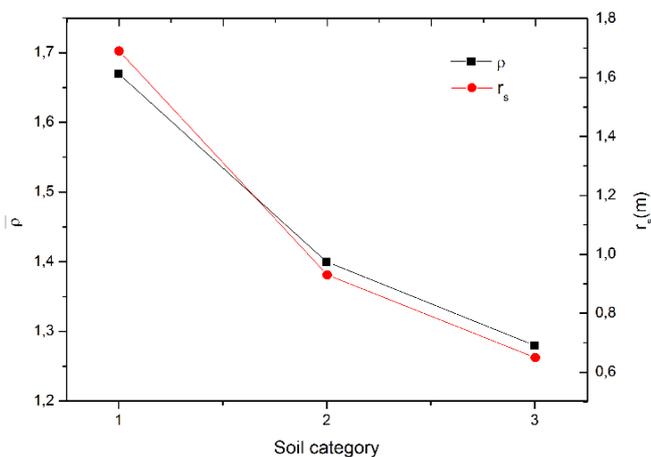


Figure 5: The $\bar{\rho}$ and r_s values at a straight-line passage of a skidder ($\theta=0^\circ$) for soils of I, II and III categories

between the tracks may lead to a reduction in the volume and value of production due to the soil compaction in the wood stands. However, wider spacing would increase the cleaning costs. Frutig et al. [25] found that a wider interval (optimum: 30-50 m) is advisable in the long-term perspective, as losses due to slower growth and less valuable wood are of great importance in calculating the entire turnover period. This conclusion coincides with the results obtained in this study.

With the shrub wood covers, the weight of the machine is distributed over a larger contact area than the landing area of machinery, thereby reducing the contact pressure on the soil. However, this method requires the tree-length logs to be carried, not skidded, out of the forest so that the brushwood cover remains intact [26].

However, the question of whether these wood covers provide sufficient protection in all situations is disputable. Another argument to consider is the displacement of nutrients in forest plantations, since, all organic matters usually spread throughout the plantation are now concentrated on the skidding trails.

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CONCLUSIONS

The results of the study allow concluding that the developed mathematical model for estimating the processes of soil deformation and compaction under the influence of the wheeled tractor and the skidded part of the timber bunch is quite accurate and effective. The behavior of soils under forest machines is influenced by a large number of factors, ranging from the rheological properties of soil to the forest machine design. The elasticity of tires and the running speed of forest machines can help to control the performance of forest machines. This can be done by reducing the pressure exerted on the soil and increasing the number of skidder passes 1.5-2-fold. Predicting the size of the shelterbelt at skidding a bunch of tree-length logs considering the results of the experiments, the calculation data differ from experimental by not more than 10%. Besides, the results of modeling showed that the deformation of the soil by the bunch of tree-length logs occurs due to shearing processes, wherein the initial vertical (compressing) stress exceeds the radial (stretching) stress by 30-40%. Performed analysis allowed determining correlation between the intensity of total shear stress reduction and the size of the soil compaction area. Estimating the dependency of the shelterbelt width on the number of tree-length logs in a bunch for three different soil categories (mild, medium, and solid) showed, that a limit values for logs amount to 4 till 6 units depending on the soil category, accordingly. The results of the study may be useful in predicting the behavior of soil under forest machines. Developed models can be applied to draw up a technological map

for projecting a logging area based on soil and skidding system specifics.

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