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The Mathematical Model of Forestry Machines Impact on Cryolitozone Forest Soils

Sergej Rudov*, Ol'ga Kunickaya[1], Albert Burgonutdinov[2], Igor Kruchinin[3], Alexey Prosuzhih[4], Nikolay Dolmatov[5], Natalia Dmitrieva[6] and Igor Grigorev[1]

Military Academy of Communications named after Marshal of the Soviet Union S.M. Budyonny
Saint-Petersburg, Russian Federation
[1]Yakut State Agricultural Academy, Yakutsk, Russian Federation
[2]Perm National Research Polytechnic University, Perm, Russian Federation
[3]Ural State Forestry University, Ekaterinburg, Russian Federation
[4]Ukhta State Technical University, Ukhta, Russian Federation
[5]Don State Agrarian University, Novocherkassk, Russian Federation
[6]Petrozavodsk State University, Petrozavodsk, Russian Federation
✉ rudovser@rambler.ru

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Abstract: In the Russian Federation, the permafrost zone are gaining increasing importance due to wood procurement operations. Active timber harvesting, accompanied by the simultaneous development of wood processing enterprises in the Far Eastern Federal District, leads to the depletion of available and exploitable forests in southern and central Siberia, Buryatia, and Khabarovsk territory. The exploitation of modern forestry machines, wheeled forwarders, in particular, broadens the question of their effectiveness. In specific production and geotechnical conditions, the cross-country ability and technological productivity of wheeled forwarders are of particular relevance. These circumstances, combined with the need to minimise technological pressure on the ecological environment raise the problem of optimisation of the forest machines. We developed a mathematical model for calculating parameters of the defrosting soil destruction process occurring at the border with the permafrost zone. The mathematical model allows assessment of the possible value depth of the induced track at the stage of the project design. The assessment is conducted with the account of the forest machine's technical and maneuvering capabilities in specific natural and industrial conditions.

Key words: Forestry machines, forests, mathematical model, wood, wood processing.

Introduction

The harmful forest machines' effect on the cutting areas' ecosystems induced by tracked vehicles' soil packing and deformation is widely known (Antoniade et al., 2012; Grigorev et al., 2018; Han et al., 2009; Ivanov et al., 2018; Lepilin et al., 2019; Nawaz et al., 2012; Shegelman and Budnik, 2019; Terinov et al., 2016). Cryolithozone forests are particularly vulnerable to such an impact. These forests are characterised by harsh natural conditions, low annual growth, and extremely poor biota of the fertile soil layer (Grigoreva et al., 2018).

The exploitation of modern forestry machines, wheeled forwarders in particular, in the first place, raises the question of their effectiveness, cross-country ability and technological productivity in specific production and geotechnical conditions.

*Corresponding Author

These circumstances, combined with the need to minimise the effect of the technogenic load on the environment, raise the problem of optimising the number of skidding systems' passes along the same strip road and actualise it to the level of high priority.

The study results of Kotlyarenko (2008) indicate that a single passage of the skidding system with the low average pressure on the ground (no more than 47 kPa) leads to separate ruptures of the continuous soil mass; a double passage destroys up to 30% of the ground, and a triple passage destroys up to 80% of the contact volume layer. For a particular soil, the tensile strength value (σts) is on the average 5-10 times less than the compressive strength value (σcs) and 2-5 times less than the shear strength value (σss).

Irreversible ultimate deformations develop under excessive tensile strength and also due to the breakage of structural bonds. Whereas under compression and shear strength, some parts of the structural bond resist external loading. As a result, the soil mass can be deformed though not destroyed. For this reason, tensile stress is defined as one of the significant factors destroying the soil mass prone to the formation of internal rupture cracks in it.

Objects and Research Methods

Special conditions for skidding systems' exploitation occur during logging operations conducted on frozen and thawed soils.

In the first case, the bulk deposition of ice is largely present in the soil massif. Its presence has a significant effect on the increase of the soil bearing capacity under the influence of the initial vertical load (q_o, kPa) of the skidding system.

In the second case, the frozen ground is oversaturated with water due to defrosting; therefore, the natural bonds between solid particles weaken, which results in loosening of the original value from the physical and mechanical properties of the ground.

Moreover, if the working stress leads to the formation of rupture cracks, then the released water will intensively fill them in up to the border with the frozen soil. Almost zero water permeability of the border soil will result in surplus water concentration at the border with the thawed soil. The excess water concentration, in its turn, will lead to an increase of the soil's total humidity (W), and the decrease in its adhesion and bearing capacity as a whole.

This conclusion is confirmed by the obtained research data (Roman et al., 2018), which characterise the effect of the increase in the parameter W (%) on the process of the adhesion value decrease C (kPa) and the angle of the internal friction φ(°). If the angle φ in the soil mass and at the permafrost soil boundaries changes insignificantly (the difference is no more than 7–13%), then the cohesion value C for the sands decreases by five times, and for other soils – on the average by 25-35%.

The technological requirements limiting the forwarder's load-bearing capacity and reducing resistance to its movement determine the maximum permissible track depth ($h_к$) after the first passage within the following limits $h_к \leq 0.10$ *m*. These limitations are closely followed for the operations conducted in frozen soils. For thawing soils, technological limitations are not as closely followed and are violated toward increasing values. As a result, the track depth values reach $h_к$ = 0.25–0.3 m or more.

The moving forest machine forms a track in the immediate area of contact of the wheel with the soil. The larger is the size of this zone, the greater forces are transferred to the soil to realise necessary traction.

The horizontal feed force can be used to overcome the force of resistance to motion and realise the necessary traction. The maximum thrust and the resulting surface friction influence the effect of the amount of soil resistance to shear τ, which depends on the normal (vertical) load q, C and φ values according to the generalised Coulomb-Mohr equation:

$$\tau = C + q.\ tg\varphi \quad (1)$$

We assume that the depth of the thawing zone is equal to H (*m*). Beyond its boundaries, the frozen ground constitutes a very solid waterproof base. The physical and mechanical properties of the soil within and beyond the depth H significantly differ from each other. The integral characteristic of this difference can be expressed by the value of the total strain modulus (E, MPa).

The research work of Cerato and Lutenegger (2006) for three categories of soils with a fairly wide range of changes in their physical and mechanical properties provide the obtained correlation ratio for the following parameters C, φ, H and E:

$$C = 10.774E^{0.7737},$$
$$\varphi = 13669E^{0.1818},$$
$$H = 0.4714E–0.479 \quad (2)$$

Moreover, the value of the modulus E for weak soils (first category) is E = 0.4 MPa, for medium soils (second category) - E = 1 MPa, and for strong soils of the third category, it is E = 3 MPa.

For frozen soils, the E indices differ from these values significantly upwards. According to the obtained data (Velli et al., 1963), for the frozen silt sandy loam under external pressures from 100 to 700 kPa and humidity W = 28–29%, the value E depends on the temperature T: for T = –0.3°C, the module E = 5.7-8, 2 MPa, for T = –1.4°C – it increases to E = 9.2–18.5 MPa, for T = –3.6°C it increases to E = 14.7– 24 MPa. With such E values, the adhesion C increases to 100 kPa or more, and the depth H decreases to 0.10 m or less.

Moreover, the analysis of the graphic data (Velli et al., 1963) indicates a significant effect of humidity W on characteristics of the frozen soil elastic properties. Namely, in the variation range of W from 10 to 30%, the elastic modulus Ey increases. The resulting oversaturation of soil with moisture leads to a sharp decrease in Ey by 40-50%. The general deformation modulus E experiences a similar effect from the parameter W. At the same time, it is noted that frozen soils significantly differ from thawed and thawing soils precisely by the criterion of indicators of the modules Eu and E, in case the bearing capacity of the soil exceeds the strength of the foundations created in them.

As it follows from equation (1), the value of the ultimate soil resistance to shear depends on the normal pressure. In other words, it depends on the external load on the soil, on the pressure brought by the skidding system. At the same time, the range of its carrying capacity is a random variable determined by the parameters of the forest bundle (Shegelman and Budnik, 2019).

The exploitation of the 8-10-wheeled forestry machines equipped with caterpillars with a load of P=19-20t creates pressure q_o=35-37 kPa. This pressure is two times less than the working pressure q_o=68-80 kPa when using the 4-6-wheeled systems without caterpillars. The use of the latter in a six-wheeled system reduces the exercised pressure by almost 33% from 40 to 27 kPa.

Let us estimate the shear resistance value of the soil τ, depending on the initial pressure q_o and considering humidity W.

Since the value τ is a variable according to the ratio (1) and data presented in Table 1, and one of the criteria for the destruction of the soil mass, therefore, it is important to provide a generalised quantitative assessment of the effect caused by W on the value τ with the increase of the track depth and its approach to the frozen ground boundaries.

For this purpose, the obtained data (Roman et al., 2018) for two types of frozen soils (sandy loam and clay loam) are presented in a non-dimensional form. The basic scale unit is presented by the data of the minimum moisture content W = 15%.

The calculation results showed that the behaviour of the functions of the non-dimensional quantities $\bar{C}(\bar{W})$ and $\bar{\varphi}(\bar{W})$ coincides. It provides an opportunity to perform adequate calculations in absolute values.

Transition to the absolute values of W, C, and φ, taking into account the initial pressure q_o, allows us to calculate the dependencies between the decrease in tensile strength τ and the increase in humidity W. Therefore, the high reliability are described by the exponential dependencies in the form:

$$\tau = k1e \quad (3)$$

With high reliability (R^2 exceeds 0.95) for the coefficients k_i included in equation (3), we can accept:

$$k1 = 2.2q_0 + 30.64,$$
$$k2 \approx 0.075 \quad (4)$$

This allows us to calculate the value τ as a function of two variables - q_o и W:

$$t = (2.2q0 + 30.64)e^{-0.075W} \quad (5)$$

The data analysis shows that at the maximum possible pressure equal to q_o=80 kPa, a three times increase in W (from 15 to 45%) leads to the decrease in tensile strength τ by more than an order of magnitude from 67 to 5.6 kPa. This in turn, significantly affects the process of soil destruction and track formation. Under the load P *(m),* a contact area with a radius $a(m)$ is formed on the surface of the soil, The size of the contact area equals $s = \pi a^2$ and the depth of the contact approach - h_o.

Based on the provisions of the research work of Morozov and Zernin (2010), the parameters a and h_o are defined as:

$$a = \sqrt[3]{\frac{3p(1-v^2)R}{4E}};\ h_0 = a^2/R \quad (6)$$

where R is the radius of the wheel, m, v is the Poisson's ratio.

The process of soil deformation caused by the action of the external pressure q_o under the load P occurs in the spatial Cartesian reference system $Oxyz$. The stress tensor acts on an arbitrary elementary site of the massif. The components of the stress tensor are defined as:

$$\sigma_z = q_0\psi_z(r, z) = -q_0 \frac{z^3}{\sqrt{u}} \frac{a^2u}{u^2 + a^2z^2},$$

$$\sigma_x = a\sigma_z = \frac{v}{1-v},\ \sigma_y = q_0\psi_y(r, z)$$

where α is the coefficient of the lateral thrust; the functions of two variables $\psi_z(r, z)$, $\psi_y(r, z)$ и $\psi_{yz}(r, z)$ are called coordinate functions equal to:

$$\psi_y(r,z) = \frac{1-2v}{3}\frac{a^2}{r^2+z^2}\left[1-\left(\frac{z}{\sqrt{u}}\right)^3\right] + \left(\frac{z}{\sqrt{u}}\right)^3 \frac{a^2u}{u^2+a^2u^2}$$

$$+\frac{z}{\sqrt{u}}\left[\frac{(1-v)u}{a^2+u} + (1+v)\, arctg\left(\frac{a}{\sqrt{u}}\right) - 2\right]$$

$$\tau_{yz} = -q_0\frac{a\sqrt{u}z^2(r^2z^2)}{(u+a^2)(u^2+a^2z^2)},\ r=\sqrt{x^2+y^2} \quad (7)$$

Part of the equation (7) parameter u is a positive root of the following quadratic equation: $\frac{r^2}{a^2+u}+\frac{z^2}{u}=1$

In the main axes of tension, (the mains) are taken from the following inequalities:

$$\sigma_1 > \sigma_2 > \sigma_3 \quad (8)$$

In that case, the tangential stresses are absent.

Let us perform calculations based on the correlations (7) in the soil zone, which is directly below the first indenter. The goal is to determine the stress tensor components σ_x, σ_y, σ_z using the following initial data:

P = 19 т, q_o= 58 kPa, E =1 MPa, W = 35%, v = 0.35.

The correlation data in (2)–(6) give: a = 0.175 м, h_o= 0.068 м, H = 0.47 м, C = 10.774 kPa, φ = 13.67°, τ = 24.88 kPa, $\sigma_p \approx \tau/2$ = 12.44 kPa.

As the analysis showed, the main stress σ_1 is an alternating sign. Positive (tensile) stresses develop in the zone near the contact surface with the indenter ($z = h_p \leq$ 0.128 m). They significantly exceed tensile strength σ_p values. The fulfillment of the fracture criterion in this zone leads to the formation of rupture cracks.

Beyond the area of the rupture zone, the level of tensile stresses is insufficient to destroy the soil; however, negative (compressive) stresses σ_2 и σ_3 lead to the appearance of maximum tangential stresses:

$$\tau_C = 0.5(\sigma_2 - \sigma_3) \quad (9)$$

They can exceed the value of shear strength τ, thereby determining the depth of the zone h_c, which can be considered as the most probable track depth from the action of the first indenter.

The differentiated approach employed to identify the mechanism of continuous medium destruction, the solid woods, in particular, was developed in the research work (Gazizov et al., 2008). The principles of this approach can be also used in the study of the deformation of soils with the corresponding elastoplastic and strength indicators.

At the moment of forest machine maneuvering and its deviation from the given trajectory through the angle θ, the soil deformation occurs under the action of the stress tensor with the following components:

$$\sigma_y = \sigma_1,\ \sigma_z = 0.5(\sigma_2 + \sigma_3) + 0.5(\sigma_2 - \sigma_3)\cos 2\theta$$

$$\sigma_x = 0.5(\sigma_2 + \sigma_3) + 0.5(\sigma_2 - \sigma_3)\cos 2\theta,$$

$$\tau_{zx} = 0.5(\sigma_2 - \sigma_3)\sin 2\theta \quad (10)$$

According to the correlations (10), it follows that at θ = 0 the stress tensor components act as principal components, therefore, we have:

$$\sigma_y = \sigma_1,\ \sigma_z = \sigma_2,\ \sigma_x = \sigma_3,\ \tau_{zx} = 0 \quad (11)$$

Thus, the criterion for the destruction of the soil mass is the fulfillment of the following terms:

In the fracture zone by fracture: $\sigma_y > \sigma_p$.

In the fracture zone by shear: $\tau_E = \tau_c + \tau_{zx} > \tau$, (12)

where τ_Σ - the summarised tangential stresses.

Along with the general strain modulus E, the elastoplastic properties of the soils are also characterised by the Poisson's ratio ν.

Taking into account that the coefficient ν affects both the components of the stress tensor and the contact parameters of the interaction of the indenter with the soil mass, we estimate the dependence of ν upon moisture W.

According to the data of Tsytovich (1983), the indicated effect for the frozen and thawing soils, namely, for the sand, sandy loams, loam and clay is well described by the exponential dependence. In the range of W from 15 to 35%, this dependence has the form (R^2 = 0.9729):

$$v = 0.0887^{0.0442W} \quad (13)$$

For the values of W > *35%,* the Poisson's ratio is controlled by the value limit v = 0.5. The dependence v *(W)* is expressed through the form:

$$v = 0.2234\ln W - 0.4463 \quad (14)$$

Thus, in case of high humidity $v \rightarrow 0.5$, i.e., the lateral thrust coefficient $\alpha = v/(1-v)$, which connects components of the vertical σ_z and horizontal σ_x compressive stresses, tends toward 1. It means that the soil mass is in the state of the quasi-incompressible fluid and experiences maximum tensile stress only in the surface zone resulting in soil fractures.

As the calculations showed, the values of the rupture zone h_p substantially depend on the magnitude of the total strain modulus *E* while the parameters of humidity and initial load have little effect on the value h_p (relative changes do not exceed 8-10% when changing *P* from 19 to 12 t and *W* from 35 up to 15%).

Calculations aimed to determine the fracture zone by shear indicate a certain dependence of the value h_c upon the load parameter P, the angle of the frame rotation θ, and humidity *W*.

When a forest machine moves along its given trajectory, all maneuvering with the steering angle θ reaching 10° is assessed as quite natural, however, in some cases, the angle of steering may reach 15-20° or more. The maximum possible values of θ reach 42-44°. This negatively effects the soil mass as evidenced by the results of studies (Ding et al., 2017).

In soils with high moisture content (*W* about 35% or more), it is difficult to maintain the size of the fracture zone within $h_c \leq 0.1$ m even when the load is reduced to 12 t.

It is practically possible to maintain the limit of the track depth under large loads *P*=19 t. when moving a forest machine along the soils with *W* = 25-30%, With the increase in *W* to 35-45%, the track depth reaches 0.25 m. Reduction of the load to 12 t meets the track depth restrictions for more humid soils with *W* reaching 30%.

Considering characteristics of stress changes associated with the increase in the track depth, their correlations within the main stresses, and accepted fracture criteria (formulas 5-10), the depth of the track upon the first indenter is equal to:

$$h_{\kappa} = a\sqrt{q_o \frac{(1-\alpha)(1+\sin 2\theta)}{2\tau}}, \qquad (15)$$

where τ is determined following equation (5).

The analysis of dependences $h_k(E)$ for three q_o=35, 58, and 80 kPa and 80 kPa showed that for a wide range of changes in the parameter q_o is the value $h_k \sim \sqrt[3]{E}$, herewith, the proportionality coefficient is logarithmically dependent upon q_o.

The impact degree comparison of such factors as humidity, deformation modulus, pressure and load on the depth of the track showed that the climatic (first two) factors dominate technological (last two) factors. Since the magnitude of the deformation modulus depends on the moisture parameter *W*, therefore, the latter indicator significantly affects the process of soil mass deformation.

Under the impact of static pressure, thawed soils saturated with moisture in the area of the first indenter will enhance water filtration processes. They will be activated beyond the zone of destruction, which is deeper than the induced track. The action of the first indenter can be considered instantaneous. If the speed of the forest machine is equal to 2.5 km/h and the distance between indenters reaches 2 m, then the time interval for the start of the second indenter effect will not exceed $\Delta t_{\phi} = 3$ sc. However, the interval provides ample time for some volume of water to move in the direction of the permafrost zone boundary.

Let us consider the Darcy model of linear fluid filtration under the impact of the vertical current pressure *q* in the direction z = *h*:

$$v_h = -\frac{k}{y}\frac{\partial q}{\partial h} \qquad (16)$$

where: *k* – is filtration coefficient, m/s, γ is liquid density.

The values of the filtration coefficient are defined following the State Standards (GOST) 25100-2011 “Soils Classification”.

The partial derivative $\frac{\partial q}{\partial h}$ ∂q is taken as the ratio between the pressure drop in the area of the fracture zone h_c and the size of the site itself. Thereafter, for 1 unit of time (s) the volume of liquid V_z within the area of the contact spot *s* will move down and amount to:

$$V_z = \frac{\pi k}{\gamma}\frac{\partial q}{\partial h}\cdot a2\frac{1}{1+h_c/a} \qquad (17)$$

After attributing to the corresponding volume V_z for the period Δt_{ϕ} to the volume of water V_c in the soil zone with the depth of (H-h_c), we obtain the value λ (%) of the additional volume of liquid entering the soil from the fracture zone with the depth h_c into the thawing zone with the depth H-h_c. The value of total humidity will increase by λ (%). This approach was used in the work of Lepilin et al. (2019) to study the process of dehydration in modified materials.

Calculations, conducted for the hawing sandy loam with filtration coefficient $k = 10^{-6}$ ms, showed that at *E* = 0.4 MPa the increase in q_o from 35 to 80 kPa, other things being equal, leads to the increase in *W* from 2 to 4 absolute%. It means that the filtering factor in this case can be neglected.

However, in stronger soils at *E* = 1 MPa, humidity indicators increase more significantly and the increase in W reaches 8% at q_o exceeding 58 kPa. In strong soils at E = 3 MPa, an increase in W over the entire range of q_o changes reaches 8.2-18.8%. It significantly affects the decrease in the strength of the massif and the increase in the track depth under the second indenter influence.

Let us consider the process of water movement into the permafrost zone under the influence of external load. The bound high-density (up to 1200-1400 kg/m^3) water, which makes up to 40 % or more of the total volume, is practically not compacted under the influence of static loads. To provide the gradient of the water movement in the direction of growth of the z coordinate is not easy. To secure the water movement in this direction is challenging too since up to 95% of the bound water remains in its original state. Such water transfers into the solid-state of ice at low water freezing temperatures of $-4 \div -6°$ C.

Unbound water consists of gravitational and capillary components. Capillary water freezes at temperatures T close to the freezing temperature of the bound water. The process of unbound water transition into the solid-state of ice occurs at any negative temperature $T \geq 0^o$ C.

Let the initial distribution of the unbound and bound water in the unit of soil volume be determined by the corresponding components of the vector.

$$\overline{v_o = (\omega_1, \omega_2)},\ \omega_1 + \omega_2 = 1 \quad (18)$$

According to the matrix of transition states P_c with the square dimension of 2×2; p_{11} can be expressed as

$$p_{11}=1\text{-}\lambda/100, \text{ and } p_{22}= 0.95,$$

which means that the matrix of transition states has the form:

$$P_c = \begin{pmatrix} 1-\lambda/100 & \lambda/100 \\ 0{,}05 & 0{,}95 \end{pmatrix} \quad (19)$$

Then, according to Markov's theory and the principles of its applications developed in the work of Shapiro and Shapiro (2007), the multiplication of the vector $\vec{v}_o$ by the matrix P_c determines the vector $\vec{v}_1$ - the distribution of water states after the first exposure the cycle of impacts (passage of the first wheeled pair of the forest machine). Thus, the multiplication of vector (18) by the matrix (19) gives the vector of the new state of water.

As calculations showed, the first passage of forest machines with low tyre pressure (q_o up to 39 kPa) and, in particular, with the initial state $\vec{v}_o$ = (0.6; 0.4) leads to the vector $\vec{v}_1$ = (0.58; 0.42). It means that the relative change does not exceed 5% and the process of filtration can be neglected. When forest machines with high tyre pressure are used on the forest soil (up to 80 kPa), quantitative changes in the components (ω_1, ω_2) cannot be neglected. Consideration of the increase in humidity is a significant factor. As the skidding system passes along the same strip road, the revealed features will be cyclically reproduced in the static mode as well as under possible dynamic manifestations (Dvoynikov et al., 2020; Khitrov and Andronov, 2019).

Conclusion

The use of forest machines with high tyre pressure on thawed soils with high humidity (35% or more) increases the depth of the track to the values (0.8 ÷ 1) H, practically almost to the borders with the permafrost zone. It means that the employment of this type of forest machines in such climatic conditions is very low.

The use of machines with low tyre pressure significantly reduces the depth of the track, especially in soils where moisture content does not exceed 30%. In this case, the value of h_k is close to the regulatory restrictions of 0.1 m. The use of these systems should be considered effective in these conditions.

The developed mathematical model for calculating parameters of the destruction process in the area of the thawing soil at the border with the permafrost zone allows us to assess the possible depth of the induced track. The technical capabilities of forest machines and their maneuverability in specific production conditions should be taken into consideration. The obtained results allow us to establish acceptable ranges of effective operations for various skidding systems when classifying logging sites by moisture parameters.

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