International Journal of Advanced Science and Technology
Vol. 28, No. 9, (2019), pp. 179-197

Method of Variational Calculation of Influence of the Propulsion Plants of Forestry Machines upon the Frozen and Thawing Soil Grounds

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Abstract

The forests, which grow in the conditions of complete expansion of the perpetually frozen ground, are unique forests in accordance with their taxational characteristics, quality indicators of the felled timber, and the ecological functions, which these forests perform in the nature. They are characterised by the low biological productivity, as well as by the high vulnerability due to climatological changes and human economic activities. It is fair to say that conservation of the permafrost is one of the main functions of the forests, which grow within the cryolithozone. Because of this, it is necessary to ensure special regimes for the forestry management and forest exploitation within the forests of the cryolithozone. We formulated the variational problem in order to determine influence of the changeability of the physical and mechanical properties of the thawing soil ground at the boundary with the permafrost ground.

***Keywords**: Variational Calculation, forest, cryolithozone, stress tensor components*

Introduction

We consider the following digits as the very illustrative parameters: dry weight of the phytomass within the high-producing tropical forests achieves 500 metric tonnes per one hectare, while annual increment achieves 50 tonnes. Within the light coniferous forests of the cryolithozone, where larch-trees are the main and dominating timber species, reserves of the dry phytomass per one hectare is only equal to 2.5 tonnes (Karavaiev & Skriabin, 1971).

The forests of the cryolithozone grow on the multi-year permafrost, which is only thawing at the little depth and which has the form of the subsurface earth's formations and of the grounds that are continuously in the frozen state for a long stretch of time. Magnitude and temperature of the perpetually frozen ground are different in various regions and they depend on many factors: air temperature, local topography, depth of the snow cover, and so on. For example, magnitude of the multi-year permafrost within the southern regions of the Republic of Sakha (Yakutia) is equal to several tens of metres, while within the northern regions of the Republic it is already equal to several hundreds of metres. The permafrost with the depth more than 1 km was found in certain regions. Average yearly temperature of

ISSN: 2005-4238 IJAST

the permafrost at the depth from 10 to 15 metres varies from 0 °C down to -10 °C. There is no permafrost under beds of large rivers, as well as under deep lakes (Karavaiev & Skriabin, 1971)..

The forests of the cryolithozone grow due to the seasonally active layer, that is, the layer of the permafrost, which thaws during the warm time of the year. Depth of the seasonally active layer (as well as the depth of the permafrost itself) depends on the climate, terrain relief, and on the top soil. In this case, rate of thawing (as well as temperature of the seasonally active layer) exerts direct influence upon the rate of growth of various plants, as well as upon the processes of soil formation (Karavaiev & Skriabin, 1971)..

Formation of the permafrost in the springtime is connected with the sharply continental climate, which is characterised by small amount of precipitations, significant changes in the annual temperatures, and prolonged winter. As concerns the Republic of Sakha (Yakutia), degree of the climate continentality increases in the direction from south to the northeast. At the same time, amount of precipitations decreases in the same direction in the appropriate manner. Therefore, we observe gradual decline of the biological productivity of forests. They begin to thin, become more homophyllous, and transform into the shunted wood.

As it was already mentioned above, larch-trees are the main and dominating timber species of forests within the cryolithozone. Various kinds of the larch-trees are the most adapted to these harsh environmental conditions. Pine forests are on the second place in the forests of the Republic of Sakha (Yakutia). They occupy 6% of the forest-covered area within the Republic and 11% of reserves of the standing timber. The next timber species (in respect of the forest-covered area) is the Asian white birch, stands of which often arise at the places of the burnt larch forests. The Siberian spruce is on the forth place among the forest-forming species within the forests of the cryolithozone. As a rule, these trees grow within the bed sections of the river valleys (Karavaiev & Skriabin, 1971)..

It should be noted that forests of the cryolithozone consist predominantly of the old-aged trees, and this fact is both economic problem, and ecological problem. It is common knowledge that forests of the cryolithozone have very great importance in carbon sequestration. However, as it was established in accordance with the results of the comprehensive investigations, the over-mature forest does not already deposits carbon adequately. Because of this, environmental scientists strongly recommend to renew the forest stands, while at the present time any "renovations" are achieved with the help of fires (as a rule). It is common knowledge that forests burn in the places, where forests are not cut. Economic significance of the over-matured forests is not high as well, because of quality characteristics of timber of the over-matured trees decrease in the course of time.

At the present time, as concerns the Republic of Sakha (Yakutia), actual volume of utilisation of the annual allowable cutting rate (except for harvesting of wood for the routes of various linear objects) does not exceed 5 %. This is largely connected with the extremely weak development of the road network. This is precisely why almost one-half of all forests in the Republic of Sakha (Yakutia) are included to the category of the reserved forests.

As it was already mentioned above, conservation of the permafrost is one of the main tasks of forests within the cryolithozone. It is well known that permafrost modes of various soils (within the harvesting areas and burnt areas of forests of the cryolithozone) are essentially different as compared with the permafrost mode of the soils under the forest canopy. In accordance with the data of article (Utkin, 1965), depth of the soil thawing on the burnt and harvesting areas of the Central Yakutia exceeds depth of the soil thawing in the forest by 0.4-0.6 metre (while in accordance with the data of article (Lytkina, 2010) this difference is equal to 0.3-0.8 metre). This is explained by the fact that favourable environments for the intensive heating of soil exist on the deforested areas during several first years at the expense of good consumption of the solar radiation (due to decrease of shadowing from the crowns of trees, and this fact ensures increase of the direct solar radiation (Korkhodkina, 1975; Savvinov, 1989).

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In accordance with the data, which were found in the course of investigations (Lytkina, 2010), it is probable that due to the fact that scarification of soil in the conditions of forests within the cryolithozone is the powerful factor, which stimulates subsequent natural forest regeneration, while processes of the natural forest regeneration under the forest canopy are not satisfactory.

The following numerical data are very significant: following scarification of soil on the burnt harvesting areas, there are essential changes in the heat mode and water mode of soils. Therefore, at the early stages of succession temperature of soil at the depth from 0.3 metres increases by 4.3-6.2 °C, moisture content of soil increases by 2.3 times, while magnitude of the seasonally active layer increases by 0.3-0.8 metres (Lytkina, 2010) (as compared with the areas, which are covered by forests). These essential changes are observed during the first ten years following fire or harvesting. The younger harvesting area or burnt area, the more significant changes occur. In the course of the next succession, that is, in the course of regeneration of the cutover stands on the harvesting areas or on the burnt areas, these indicators are stabilised and they become equal to the indicators of the surrounding stands.

It is well known that natural succession of the coniferous boreal forests (which include the forests within the cryolithozone) envisages alternation of generations within these forests at the expense of the pyrogenic factors. This is precisely why natural coniferous boreal forests are even-aged forests (as a rule). It was also proved that clear-cut harvesting operations within the forests do not create any obstacles for conservation of the biological diversity of forests, especially on the condition of correct separation and conservation of the key objects for conservation of the biological diversity of various level (conservation of the key biotopes and so on (Grigorev et al., 2013; Grigorev & Grigoreva)).

Consequently, it can be said that the clear-cut harvesting operations will not cause any destructive changes in the case of compliance with the regulatory requirements (provided that these requirements would correspond to the conditions of forests within the cryolithozone) in respect of the areas of various timberlands, their cutting cycles, and other organisational and technical indicators, which are established for performance of the cutting area works.

Moreover, it is necessary to take into account the fact that due to presence of the permafrost, as well as due to small depth of thawing of the seasonally active layer, the main mass of roots of the tree and shrubbery vegetation in the forests within the cryolithozone is situated at the depth of one-half metre from the surface of the soil ground (Timofeyev, 1976; Dokhunaiev, 1988). Moreover, once again, it was established in the article (Lytkina, 2010) that distribution of moisture in the soil at various depths is sufficiently uniform under the canopy of the permafrost forests. However, moisture content in the upper horizons is usually higher. This fact is explained by the capabilities of the forest litter and humus horizon of the soil ground to retain moisture. It means that in the case of the selective logging of the forests, the greatest part of the trees, which would be left as the standing timber, would have the depressed root systems due to compaction of the soil ground, as well as due to the sharp changes in the filtration and water-carrying capabilities of the soil ground (Grigorev et al., 2018; Rudov et al., 2019) (due to influence of machines upon the soil ground).

In the course of calculation of the degree of negative influence of the forestry machines upon the soil grounds of forests within the cryolithozone, it is necessary to take into consideration the following specific features of the soil texture: ice is present between various aggregates of the soil ground and certain particles of these aggregates. This ice exerts influence upon all indicators of the physical and mechanical properties (Rudov et al., 2019). In the course of thawing, properties of the permafrost soil grounds change very essentially (Rudov et al., 2019b).

As the basis of our investigations, we will utilise the materials, which were obtained earlier in the articles (Grigorev, 2018; Ivanov et al., 2018; Manukovsky et al., 2018; Rudov et al., 2018; Shapiro et al., 2018; 2018b; Zhuk et al., 2018) and which describe behaviour of the soil ground massive under the influence of the propulsion plants of the forestry machines and other special forest equipment.

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Operation of the forestry machines in the conditions of the frozen soil grounds is characterised by high degree of variability of the physical and mechanical properties of such grounds even within the certain limits of one and the same timberland.

One of the main reasons of such situation is essential dependence of the carrying capacity of the soil ground from the factors of temperature (T) and moisture content (W).

There are the following trends of the previous years: increase in T values during the period between seasons (in summer), decrease in duration of the period of the stable negative temperatures, and traditionally high indicators of T during the summer work period. These trends have caused increase in the depth of the thawing zone of the ground, increase in the moisture content at large depths, and (as a consequence) increase in the tracing rut depth (wheel spacing) in the course of yarding-and-loading of the timber wood in the process of multiple runways of the yarding-and-loading system.

These circumstances in combination with the necessity to ensure minimisation of the anthropogenic impact on the environment move the problem of optimisation of number of runways of the yarding-and-loading system over one and the same skidding track to the category of the most topical problems.

Results of investigations of the article (Kotliarenko, 2008) demonstrate that even the single runway of the yarding-and-loading system at the not so high pressure on the soil ground (no more than 47 kPa) causes certain damages of the continuous and compact massive. The twofold runway will damage already up to 30 %, while threefold runway will damage up to 80% of volume of the upper fertile layer of the soil ground.

Specific conditions of exploitation of the yarding-and-loading systems must be complied with in the course of the cutting area works on the frozen soil grounds, as well as on the soil grounds, which are at the stage of thawing.

In the first case, massive of the soil ground contains quite great volume of ice, which exerts essential influence upon the increase in the carrying capacity of the soil ground under the action of the initial vertical load ($q_{initial}$, kPa) of the yarding-and-loading system.

In the second case, in the course of thawing of the frozen soil ground, this soil ground will be oversaturated with water. Therefore, the natural connections between hard particles weaken. At the same time, physical-and-mechanical properties of the soil ground will lose their initial values. In this case, concentration of moisture at the boundary with the zone of the permafrost causes certain decrease in the values of the angle of internal friction φ. At the same time, this fact also causes essential (in many cases -in multiple times) decrease in the value of the soil ground friction C (Roman et al., 2018), thus decreasing its carrying capacity (in the first turn, its capacity in respect of the shear strength) and causing formation of the deeper tracing rut. From our point of view, this fact is connected with the fundamental distinction of the thawing soil ground from the thawed soil ground.

Requirements in respect of limitation of the load-carrying capacity of the forwarding machine, as well as in respect of decrease in the resistance of its motion determine that maximum allowable depth of the tracing rut (h_{tr}) following the first runway must be within the limits $h_{tr} \leq 0.10$ metre.

On the frozen soil grounds, this limitation is observed in the most cases. However, this requirement is not complied with on the soil grounds, which are at the stage of thawing. As a rule, we observe essential growth of this parameter up to the values of $h_{tr} = 0.25$-0.3 metre (while in certain cases up to 0.4-0.5 metre and more), up to achievement of the value of the forwarder clearance.

The yarding-and-loading system creates the tracing rut directly in the zone of contact of the wheel with the soil ground. The greater dimensions of this zone, the greater efforts are transferred to the soil ground in order to ensure the required thrust.

It is possible to utilise horizontal feed propulsive force in order to overcome effort of the resistance of motion and to ensure the required thrust.

Therefore, it is possible to utilise (all other conditions being equal) the value of h_{tr} as the operational criterion in order to estimate the carrying capacity of the soil ground and efficiency of the forwarder

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motion over this soil ground. It is obvious that this value is the function of many variables and parameters and it can be calculated in the course of determination of patterns and specifics of destruction of the soil ground massive under the action of static loads.

Maximum thrust and force of the surface friction (which is associated with this maximum thrust) exert influence upon the value of resistance of the soil ground shear τ, which depends on the acting normal (vertical) stress q, as well as on the values C and φ and which is equal to in accordance with the Coulomb-Mohr generalised equation:

$$\tau = C + q \cdot \mathrm{tg}\varphi. \quad (1)$$

Let us consider that the depth of the thawing zone is equal to - H (metre). Beyond the limits of this zone, the frozen soil ground has the form of the very hard impervious foundation. Depending on the natural and climatic conditions of the forests growing, value H does not exceed 1 metre within the regions of high latitudes (64-67 $^{\circ}$ north latitude), while this value can rise (in the course of decrease in the latitude up to 2 metres and more. In the course of investigation of the process of formation of the tracing rut, it is possible to assume that this value is limited at the level of $H \leq 1$ metre.

It is obvious that physical-and-mechanical properties of the soil ground within the limits and beyond the limits of the depth H have essential differences from one another. The value of the Young's modulus (E, MPa) can be used as the integral characteristics of these differences.

Article (Khitrov et al., 2014) presents correlation ratios between parameters C, φ, H, and E for three categories of the grounds within the quite wide range of changes in their physical and mechanical properties:

$$C = 10.774E^{0.7737}; \quad \varphi = 13.669E^{0.1818}; \quad H = 0.4714E^{-0.479}. \quad (2)$$

In these cases, it is assumed that value of the modulus E for the weak grounds (the first category) is equal to E = 0.4 MPa; for the average grounds (the second category) E = 1 MPa; for the strong grounds of the third category E = 3 MPa.

Values of E for the frozen grounds have essential differences from these values; they exceed the above presented values by many times (Velli et al., 1963).

As it follows from the equation (1), value of the ultimate shear resistance of the soil ground depends on the normal pressure, that is, on the external load, which is exerted by the yarding-and-loading system on the soil ground.

Table 1 presents characteristics of several forwarders along with the achievable initial values of *qinitial* under the wheel pairs. Hereinafter we will assume these values as the corresponding stamps.

As we can see, utilisation of the yarding-and-loading systems on the basis of the 8-10-wheeled forwarders in the case of application of the caterpillar tracks at the load P = 19-20 tonnes ensures pressure *qinitial* = 35-37 kPa. This value is more than 2 times lesser than the acting pressures *qinitial* = 68-80 kPa in the case of utilisation of the yarding-and-loading systems on the basis of the 4-6–wheeled forwarders without application of the caterpillar tracks. At the same time, application of the caterpillar tracks in the 6-wheeled system ensures decrease in the pressure practically by 33% (from 40 down to 27 kPa).

Table 1. Characteristics of the yarding-and-loading systems and values of the pressure, which these systems develop on the ground

Categories of the yarding-and-loading system	Weight P, tons	*qinitial*, kPa	
		stamp 1/ quantity of the wheel pairs	stamp 2/ quantity of the wheel pairs
I. 4-wheeled	15	68 / 1	80 / 1
II. 6-wheeled	16	72 / 1	40+40; 27 / 3
III. 8-wheeled	19	35 / 2	58 / 2
IV. 10-wheeled	20	35 / 2	37 / 3

Let us estimate value of the soil shear strength τ depending on the initial pressure $q_{initial}$ taking into consideration the moisture content W.
Because of value τ is one of the criteria of the massive destruction (while in consequence of the equation (1) and due to the data of investigations (Roman et al., 2018) value τ is the variable), then (in the course of increase in the tracing rut depth and subsequent motion of the tracing rut in the direction of the boundary of the frozen ground), it is interesting to give the generalised quantitative assessment of influence of W upon the value of τ.
Towards this end in view, we have developed the experimental data (Roman et al., 2018) in order to reveal influence of W upon the parameters C and φ for two kinds of the frozen grounds (sandy loam and argilloarenaceous ground). Then these data were transformed into the dimensionless form, while the data at the minimal moisture content (W = 15 %) were assumed as the reference of measurement (scale multiplier unit).
Figure 1 presents results of these calculations, where: axis of abscisses presents values of the relative moisture content $\bar{W}$, axis of ordinates presents values of the relative friction $\bar{C}$ (curve 1) and relative angle $\bar{\varphi}$ (curve 2) in the totality of the data both inside of the thawing massive and at the boundary of this massive with the frozen ground.
As we can see, behaviour of the graphs of the dimensionless values $\bar{C}(\bar{W})$ and $\bar{\varphi}(\bar{W})$ is similar, therefore, it is possible to make adequate calculations in absolute units.

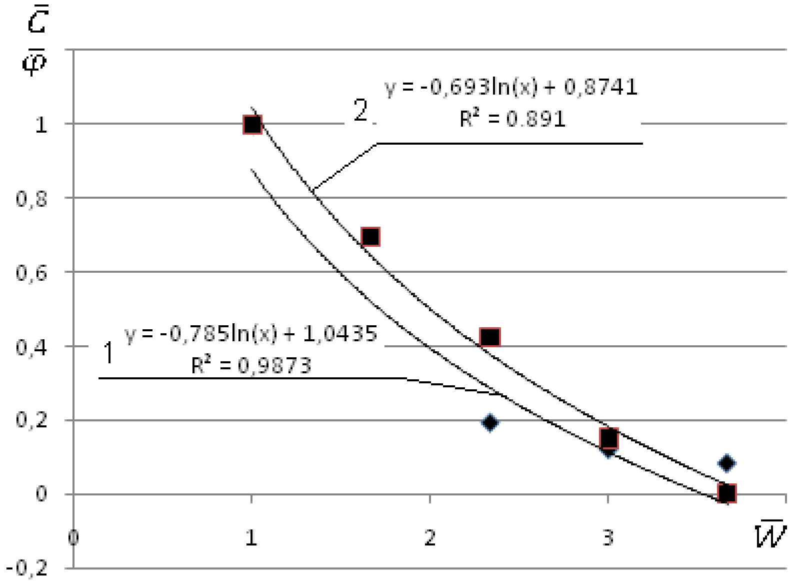

Figure 1. Changes in the relative values of the adhesion and the angle of internal friction depending on the relative moisture content of the ground: 1 - $\bar{C}(\bar{W})$; 2 - $\bar{\varphi}(\bar{W})$

Transfer to the absolute values of W, C and φ (taking into consideration the initial pressures of $q_{initial}$) has made it possible to obtain graphical dependences of the decrease in the ultimate stress limit τ from the increase in the moisture content W (Figure 2). It is possible to describe these graphical dependences with a high degree of confidence with the help of the following exponential relationships:

$$\tau = k_1 e^{(-\kappa_2 W)}. \quad (3)$$

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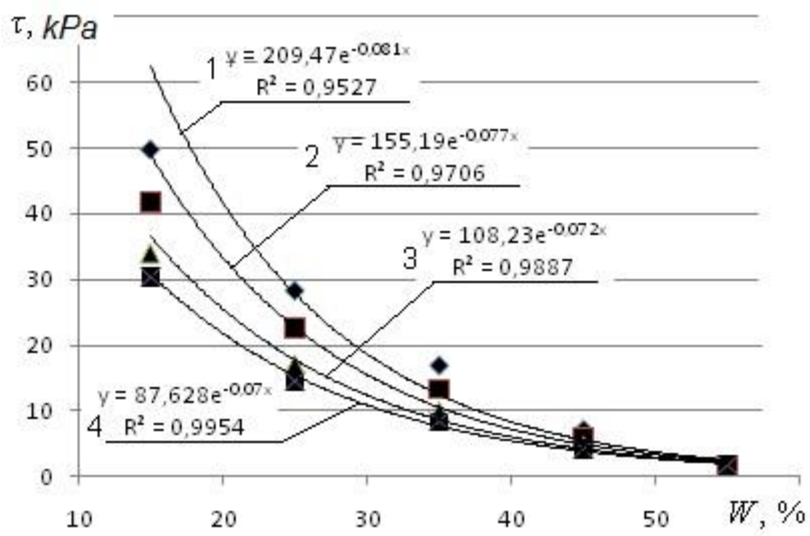

Figure 2. Dependence τ from W at: 1 - $q_{initial}$=80 kPa; 2 - $q_{initial}$=58 kPa; 3 - $q_{initial}$=37 kPa; 4 - $q_{initial}$=27 kPa

The following interrelations were found for the coefficients k_i, which are present in the relationships (3), with a high degree of confidence (R^2 exceeds 0.95):

$\kappa_1 = 2.2q_o+30.64$, $k_2 \approx 0.075$. (4)

Therefore, it is possible to make calculation of the value τ as the function of two variables: $q_{initial}$ and W:

$\tau = (2.2q_o+30.64)e^{-0.075W}$. (5)

Under the action of the load P (т), the contact area (radius – a (metre); area of the contact – $s = \pi a^2$; depth of the contact approach – h_o) is formed on the surface of the soil ground

On the basis of statements of the article (Morozov & Zernin, 2010), we will determine parameters "a" and "h_o" in the following manner:

$$a = \sqrt[3]{\frac{3P(1-\nu^2)R}{4E}}; \quad h_o = a^2/R, \tag{6}$$

where: R - radius of the wheel (metre); ν - Poisson’s ratio.

Process of deformation of the soil ground due to the action of the external pressure *qinitial* under the load P occurs in the spatial Cartesian coordinate system *Oxyz*, where the stress tensor acts on the arbitrary elementary area of the massive. Components of this tensor we will determine as follows: $\sigma_z = -q_0\psi_z(r,z) = -q_0 (\frac{z}{\sqrt{u}})^3 \frac{a^2u}{u^2+a^2z^2}$; $\sigma_x = \alpha\sigma_z = \frac{\nu}{1-\nu}\sigma_z$; $\sigma_y = q_0\psi_y(r,z)$, where α is the side thrust coefficient, while functions of two variables $\psi_z(r,z)$, $\psi_y(r,z)$, and $\psi_{yz}(r,z)$ are usually called as the coordinate functions, which are equal to:

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

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

The parameter u, which is presented in the (7), is the positive root of the quadratic equation (equation of the second degree) $\frac{r^2}{a^2+u} + \frac{z^2}{u} = 1$.

The stresses (the main stresses) in the main axes are assumed in accordance with the following condition:

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

In this case, there are no any shear stresses.
Let us make calculations on the basis of relationships (7) within the zone of the soil ground immediately under the first stamp in order to determine components of the stress tensor σ_x, σ_y, σ_z at the following initial data: P = 19 tonnes, $q_{initial}$ = 58 kPa, E = 1 MPa, W = 35 %, ν = 0.35.
In respect of the above-listed data, we calculate the following parameters with the help of the relationships (2) - (6): a = 0.175 metre, h_o = 0.068 metre, H = 0.47 metre, C = 10.774 kPa, φ = 13.67°, τ = 24.88 kPa, $\sigma_p \approx \tau/2$=12.44 kPa.
Calculations of the stress tensor components have demonstrated that the main stress σ_1 is the alternating stress. Therefore, positive stresses (tensile stresses) are developed within the zone of the soil ground massive near the contact surface with the stamp ($z = h_p \leq 0.128$ metre). In this case, positive stresses significantly exceed the value of the tensile strength rupture limit σ_p. If the destruction criterion will be achieved in this zone, this fact will result in formation of tensile cracks.
Beyond the boundaries of the rupture zone, level of the tensile stresses is insufficient for destruction of the soil ground, however, negative stresses (compactive stresses) σ_2 and σ_3 result in occurrence of the maximum shear stresses (tangential stresses):

$$\tau_c = 0.5(\sigma_2\text{-}\sigma_3). \qquad (9)$$

These shear stresses can exceed the value of the ultimate shear stress τ, thus determining the zone depth h_s, which can be considered as the most probable depth of the tracing rut h_{tr} due to action of the first stamp.
The differentiated approach in the course of revealing the mechanism of destruction of the continuous medium (particularly, in the course of decortication of the pulpwood bolts) was developed in the article (Gazizov et al., 2010).
In the course of the forwarder manoeuvrings, when forwarder moves away from the prescribed direction of motion by the certain angle θ, deformation of the soil ground occurs under the action of the stress tensor with the following components:

$$\sigma_y = \sigma_1; \quad \sigma_z = 0.5(\sigma_2+\sigma_3) + 0.5(\sigma_2\text{-}\sigma_3)\cos 2\,\theta; \ \sigma_x=0.5(\sigma_2+\sigma_3)\text{-}0.5(\sigma_2\text{-}\sigma_3)\cos 2\theta; \ \tau_{zx}=0.5(\sigma_2\text{-}\sigma_3)\sin 2\theta. \qquad (10)$$

It follows from the relationships (10), particularly, that at $\theta = 0$ components of the stress tensor are the main components, that is, we have the following relationships:

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

Therefore, criterion of destruction of the soil ground massive will be achieved in the case, if the following conditions will be complied with:
the rupture within the zone of destruction: $\sigma_y > \sigma_r$;
the shear within the zone of destruction: $\tau_\Sigma = \tau_s + \tau_{zx} > \tau$, (12)
where τ_Σ - total shear stresses.
The elasto-plastic properties of the soil grounds are characterised not only by the modulus of the general deformation E, but by the Poisson's ratio ν, as well. In this case, in accordance with the data of the article (Tsytovich, 1983), moisture content W exerts influence upon ν. For example, as concerns the frozen grounds, as well as the grounds, which are at the stage of thawing (sands, sandy loams, argilloarenaceous grounds, and clay) this relationship is properly described by the exponential dependence. Therefore, within the range of change in the values of W from 15 up to 35% (R^2=0.9729):

$$\nu=0.0887e^{0.0442W}. \qquad (13)$$

At the values of $W > 35\%$, Poisson's ratio is bounded from above by the value of the limit ν=0.5, while dependence $\nu(W)$ will take the following form:

$$\nu=0.2234\ln W\text{-}0.4463. \qquad (14)$$

Therefore, at high moisture content $\nu \rightarrow 0.5$, that is, the side thrust coefficient $\alpha = \nu/(1\text{-}\nu)$ (which combines components of the vertical σ_z and horizontal σ_x compactive stresses) tends to 1. It means that relevant massive of the soil ground is in the state of the quasi-incompressible liquid, as well as that this

massive is under the influence of the maximum tensile stresses (which result in rupture) in the surface zone only.
As it was shown with the help of calculations, maximum possible values of h_p do not exceed 0.12 metre, and they depend essentially on the value of the Young's modulus *E*. In this case, moisture content *W* and initial load *P* exert weak influence upon h_p (relative changes do not exceed 8-10% in the case of change of *P* from 12 up to 19 tonnes and change of *W* from 15 up to 35%).
Results of calculations, which were made in order to determine the zone of the shear destruction, as well as to estimate possible depth of the tracing rut, confirm that there exists a certain dependence of h_{tr} from the following parameters: weight of the yarding-and-loading system; initial pressure on the soil ground; angle of the frame rotation; moisture content; Young's modulus.
Particularly, Figure 3 presents graphs of functions h_{tr} (axis of ordinates, metres) from the angle θ (axis of abscisses, degrees) at W = 35 % and three kinds of the load *P*. These graphs let us to make the conclusion on the negative influence of manoeuvres of the forwarder upon the process of formation of the tracing rut. For example, even at the small mass of the yarding-and-loading system (P = 12 tonnes) rotation of the frame by the certain angle (15 degrees) causes increase in the tracing rut depth almost by 2 times from 0.09 up to 0.18 metre.
In the course of motion of the forwarder in accordance with the prescribed direction, manoeuvres with angle of rotation θ up to 10° are quite natural. However, in many cases angles of rotation achieve 15-20° and more. Maximum technically possible value of the angle of rotation of the frame θ achieves 42-44°. As results of investigations demonstrate, it is necessary to take into consideration influence of the angle of the frame rotation in the course of determination of routes of the forwarder movements (it is especially important in respect of the waterlogged soil grounds).
The data, which are presented in Figure 3, demonstrate that at high moisture content absence of manoeuvring of the forwarder makes it possible to comply with the limitation $h_{tr} \leq 0.1$ metres only at small loads (up to 12-15 tonnes). At any load *P* manoeuvres on the moisture soil grounds even with small angles of the frame rotation (angle θ = 10-15 degrees) result in the essential increase in the tracing rut depth.

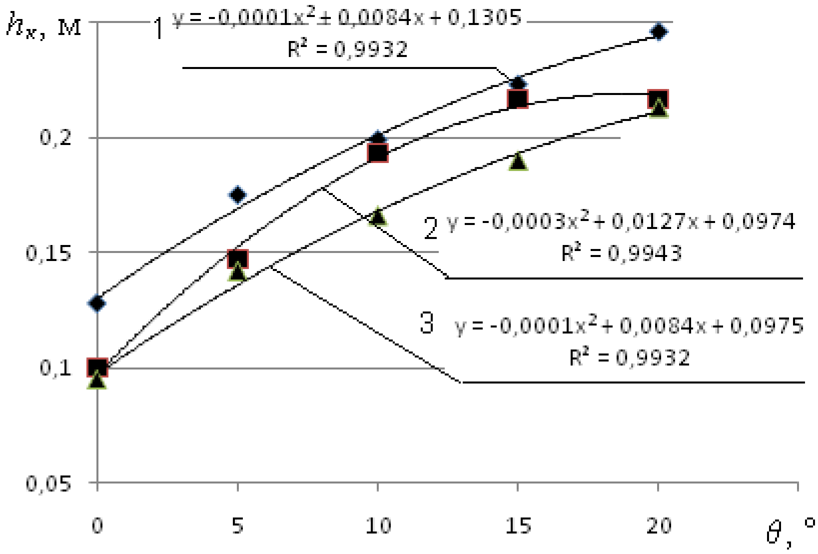

Figure 3. Dependence of zone of the shear destruction from the angle of rotation at the following loads: 1 – *P* = 19 t; 2 – *P* = 15 t; 3 – *P* = 12 t.

Investigations of influence of the moisture content upon the process of formation of the tracing rut have demonstrated the following trends.

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In the course of motion of the forwarder over the relatively moisture soil grounds (W = 25-30%), it is possible to comply with the established limitation ($h_{tr} \leq 0.1$ metres) even at the load P = 19 t.
In the course of increase in values of W up to 40-45%, the tracing rut depth achieves the values at the level of 0.25 metres at low loads (P = 12 t) and at small angles of the frame rotation (θ = 5-10°).
In the final analysis, on the basis of the previously obtained relationships (5)–(10), derived the formula for calculation of the tracing rut depth following action of the first stamp:

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

where ultimate shear stress τ is calculated in accordance with (5), while radius of the contact area *'a'* is calculated in accordance with (6).
Formula (15) demonstrates that the tracing rut depth is the function of many variables and other parameters, which determine physical-and-mechanical properties of the thawing soil ground taking into consideration its moisture content, as well as technical characteristics of the yarding-and-loading system.
Calculations in accordance with the formula (15) demonstrate that value of h_{tr} changes from 0 up to 0.5 metres and more (as concerns the allowable range of changes in the technological parameters and in the natural-and-climatic parameters of interaction of various forwarders with the frozen soil grounds, as well as with the soil grounds, which are at the stage of thawing).
In this connection, there is a certain interest in analysing necessity of solving problem of classification of the soil grounds within the boundaries of the route of motion of various forwarders in respect of the value of h_{tr} as the criterion of resistance to the massive destructive action of static loads.
At the first stage, let us determine confidence intervals in respect of change in the value of h_{tr}, at which it is possible to make the conclusion (on the basis of the Student's t-test) concerning difference between average values of two various samples (test of the null hypothesis).
In accordance with the article (Gazizov et al., 2009), scheme of statistical tests is as follows: it is necessary to determine (with the help of the random numbers transducer) $n = n_1 \cdot n_2$ random sampling numbers ξ_i, which have to be distributed within the range from -1 up to 1 in accordance with the normal law with the zero mathematical expectation.
Now it is necessary to determine mathematical expectation of the certain tracing rut depth $M_1(htr)$ and it is necessary to determine n_1 values of $M_i = M_1(1+\xi_i)$. It is necessary to repeat this experiment n_1 times, to process the obtained sample, as well as to determine the root-mean-square deviation $\sigma_1(htr)$ and coefficient of variation $\eta_1 = \sigma_1(htr)/M_1(htr)$.
It is necessary to determine step of change in the tracing rut depth ΔM, to repeat this experiment $n_2 = n_1$ times for the obtained mathematical expectation $M_2(htr) = M_1(htr)+\Delta M$, and then it is necessary to determine corresponding values of $\sigma_2(htr)$ and η_2.
Now it is necessary to calculate the empirical criterion $t_{\text{empirical}}$, which is based on two samples and which is to be compared with the theoretical criterion t_m. In this case, It is necessary to determine minimal value of ΔM, which (at the prescribed number of degrees of freedom $k = n_1+n_2-2 = 18$, as well as at the prescribed significance level β = 0.05) makes it possible to make the conclusion on the essential differences between two average values: $M_1(htr)$ and $M_2(htr)$.
In the final analysis, it is necessary to determine dependence of the average coefficient of variation ($\eta_{\text{average}} = (\eta_1+\eta_2)/2$) from the original value of $M_1(htr)$.
Table 2 presents a certain part of the results of these calculations, which makes it possible to compare previously obtained values of $t_э$ with the tabular criterion $t_m = 2.1$.

Table 2. Results of calculations with the purpose of testing the null hypothesis

M_1, 10^{-2} m	M_2, 10^{-2} m	σ_1, 10^{-2} m	σ_2, 10^{-2} m	η_1, %	η_2, %	$\eta_{average}$, %	t_{exp}

8.5	9.7	1.35	1.16	16	12	14	2.13
11.5	13.4	1.84	2.07	16	15	15.5	2.17
15.3	16.9	1.89	1.45	12	9	10.5	2.12
22.1	23.9	1.66	2.13	8	9	8.5	2.11

On the basis of the data that are presented in the Table 2, Figure 4 presents the decreasing statistical dependence of η_{cp} (axis of ordinates, %) from the increase in M_1 (axis of abscisses, 10^{-2} m).
The result, which is to be obtained, makes it possible to make the conclusion on the following fact: in the course of deepening of the tracing rut, variation of the values of *htr* decreases.
It means that range of variations of the value of h_{tr} is limited even in the complex natural-and-climatic and technological conditions. Therefore, it is possible to classify conditions of the ground yarding with the purpose of stabilisation of their design parameters.
Let us assume (at the expert level) that stable conditions of the ground yarding (the first category – I category) correspond to the coefficient of variation $\eta \leq$ 10 % of the most changeable parameter.
As concerns the second category (II category; category of transition from the stable conditions to unstable conditions), value of η can achieve 20%.
Unstable conditions of operation (III category) are observed in the cases of their variation within the range of 20% $< \eta \leq$ 30%.
Beyond the boundaries of the III category, the statistical data are not representative ones. Therefore, this model describes the ongoing processes in the inadequate manner.

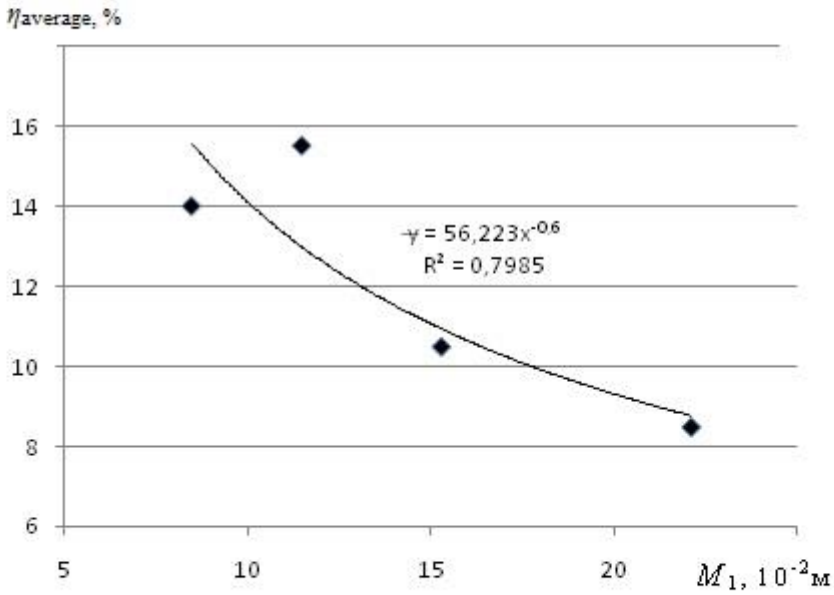

Figure 4. Dependence of the variation coefficient of the tracing rut depth from the mathematical expectation of this depth value

Let us formulate the variational problem in order to determine influence of the changeability of the physical and mechanical properties of the thawing soil ground at the boundary with the permafrost ground. In the first turn, let us determine influence of parameters E and W upon variation of values of h_{tr}, as well as influence of the relative compaction of the ground $\bar{\rho}$ due to the action of the load from the transportation system.
Towards this end in view, random normal numbers ξ_i are inserted into the relationships of the following form:

$$E_i = M(E)\cdot(1+\xi_i\,\eta); \quad W_i = M(W)\cdot(1+\xi_i\,\eta), \qquad (16)$$

where $M(E)$ and $M(W)$ are mathematical expectations of values of the relevant parameters E and W.
Now, it is necessary to determine random values of h_{tri} at the fixed values of other parameters: weight P, initial pressure $q_{initial}$, the Poisson's ratio ν, angle of the frame rotation θ, as well as other parameters (with the help of relationships (5)-(10)).
If we will assume value of $z = htr_i$ for the certain prescribed depth, we can determine values of the vertical stresses σ_{zi} with the help of equation (7). Then we can connect them with the random values of moduluses of deformation E_i and determine the sample of values of the relative total deformation ε_i and relative compaction of the ground $\bar{\rho}_i=1+\varepsilon_i$.
Therefore, we can form statistical samples of four random parameters (E, W, htr, and $\bar{\rho}$), processing of which makes it possible to determine dependence of their variation coefficients (%; see axis of ordinates in Figure 5 – $\eta(E)$, $\eta(W)$, $\eta(htr)$ and $\eta(\bar{\rho})$б respectively) from the coefficient of variation of the initial conditions η (axis of abscisses, %).
The data, which are presented in Figure 5, were obtained at the following initial data:

P = 15 t, $q_{initial}$ = 80 kPa, ν = 0.35, θ = 10º, $M(W)$ = 35%, $M(E)$ = 1000 kPa (17)

The results, which we have obtained, make it possible to make certain conclusions:

1. Because of $\eta(h_{tr}) \approx \eta$ (error of calculations does not exceed 10-13%), we can reasonably accept indicators of variation of the tracing rut depth as the indicator of changeability of the operating conditions. Obviousness of this indicator and operational efficiency of its determination/calculation under natural conditions speak out in support of this criterion as well.
2. Because of we have previously accepted three categories of changeability of conditions, it is reasonable to replace strict limitation of the normative tracing rut depth ($h_{tr} \leq 0.1$ metre) with more significant allowable intervals: for the I category – 0.09 metre $\leq h_{tr} \leq$ 0.11 metre; for the II category – 0.08 metre $\leq h_{tr} \leq$ 0.12 metre; for the III category – 0.07 metre $\leq h_{tr} \leq$ 0.13 metre.
3. Value of the relative compaction of the soil ground is the most stable indicator of the result of interaction between the yarding-and-loading system and the soil ground massive. Coefficient of variation of this relative compaction following influence of the first stamp for all three categories of changeability of conditions does not exceed 5%.

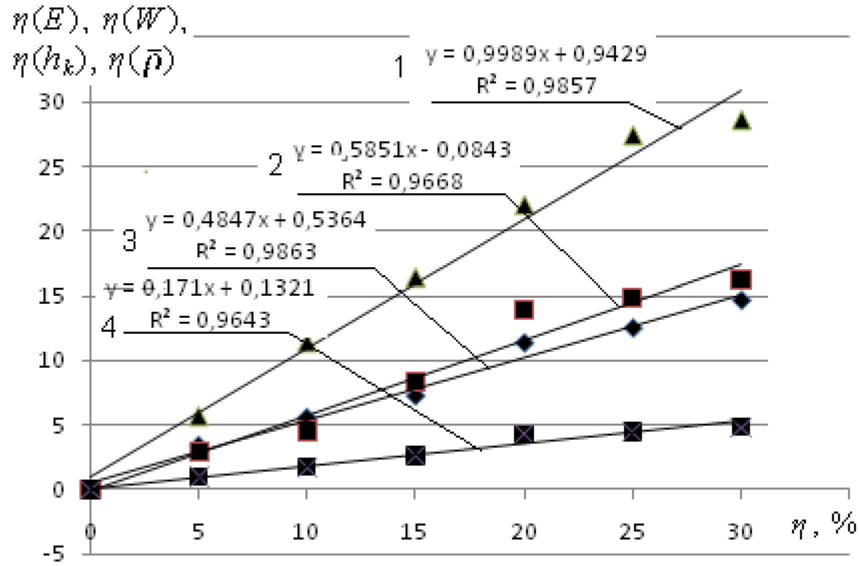

Figure 5. Influence of variations of the operating conditions upon variations of: modulus of deformation; moisture content; tracing rut depth; relative compaction of the ground

Analysis of the data, which are presented in Figure 5, demonstrates that graphs 1 and 2 of the dependencies $\eta(E)$ and $\eta(W)$ from η are the same from the statistical point of view. That is, E and W are equisignificant factors of influence. However, it is essentially simpler to ensure operational control of and supervision over variation of *W* as compared with variation of *E*.

Figure 6 presents dependences (axis of ordinates, %) of the value $\eta(htr)$ from η (axis of abscisses, %) for three states of the expected moisture content of the soil ground: 1 - $M(W)$ = 15%, 2 - $M(W)$ = 25%, 3 - $M(W)$ = 35%. It is assumed that all other parameters are constant values and that these parameters comply with the conditions (17).

As we can see, in the stable conditions (η up to 10%) factor *W* has only limited influence.

For example, as concerns dry (W = 15%), relatively moistured (W = 25%) and moistured (W = 35%) soil grounds, variations of the tracing rut depth differ from one another by no more than 9%.

As concerns the more changeable conditions, in the cases of changes in the value of η up to 20%, then the above-listed differences exceed 20%. Therefore, it is necessary to take into consideration the factor of moisture content *W*.

As concerns the unstable operating conditions (where value of η achieves 30 % and more), then differences in the changeability of the tracing rut depth achieve 40 % and more. Factor of the moisture content is the dominating factor.

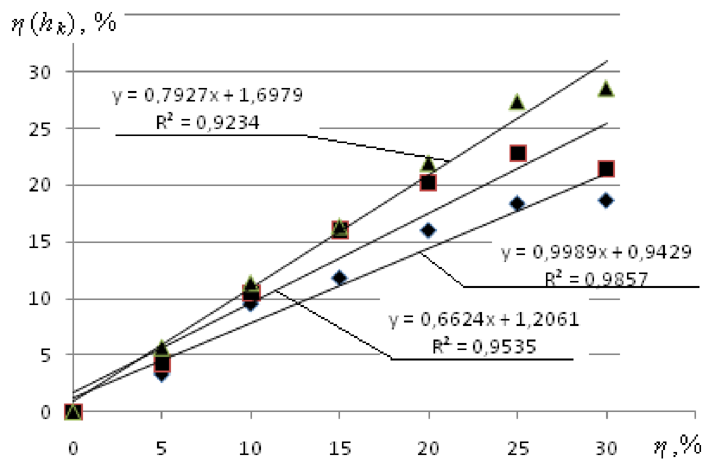

Figure 6. Dependence of variation of the tracing rut depth from the variation of working conditions for three states of the expected moisture content of the ground: 1 - $M(W)$ = 15%; 2 - $M(W)$ = 25%; 3 - $M(W)$ = 35%

As concerns actual operating conditions, it is necessary to take into account that in the course of one and the same production cycle a forwarder often moves over three or four various kinds of the soil grounds, physical-and-mechanical properties of which can be essentially different.

There is another problem of topical interest. This problem is connected with classification and determination of relevant categories of the soil grounds in accordance with the criterion of their capacity to overcome the destructive action of the load of the yarding-and-loading system. Hereinafter we will refer this capacity of the thawing soil ground as the technological property of the resistance against static loads.

In order to find the answer to the above-described issue, let us formulate the following problem and then find relevant solution of this problem.

Let us assume that variations of the technological and natural-and-climatic conditions (within the limits of each category of the soil grounds) are quite stable, as well as that indicator η does not exceed 10%.

We will begin to develop classification of the soil grounds in respect of the conditions of exploitation of the yarding-and-loading systems of the first (I) and second (II) categories (see Table 1). These systems include the wheeled pairs with high static pressures: 68 kPa and 72 kPa under the first stamp and 80 kPa under the second stamp.

ISSN: 2005-4238 IJAST

Let us determine the following parameters: weight of system P = 15 tonnes and angle of the frame rotation $\theta = 10^{o}$.
Table 3 presents results of statistical simulation of the process of formation of the tracing rut, as well as results of calculation of the relative compaction following the single runway of these systems. These results are presented in accordance with the condition that value of E changes from 400 kPa up to 3,000 kPa, while value of W changes from 15% up to 35% (numerators of fractions include indicators due to action of the first stamp, while common denominators of fractions include indicators due to action of the second stamp).

Table 3. Results of statistical simulation of formation of the tracing rut, as well as results of calculation of the relative compaction of the ground in the case of utilisation of the yarding-and-loading system of the I category

$M(W)$, %	$M(E)$, kPa	$M(htr)10^{-2}$, m	$\sigma(htr)10^{-2}$, m	$\eta(htr)$, %	$M(\bar{\rho})$
15	3,000	3.95/4.0	0.4/0.4	10.6/11.3	1.021/1.023
20	2,000	6.4/6.75	0.64/0.76	10.93/11.28	1.028/1.032
25	1,000	12.07/12.9	1.46/1.68	12.1/13.0	1.045/1.06
30	700	17.7/17.9	2.3/2.52	13.12/14.0	1.053/1.06
35	400	28.7/31.0	4.0/4.5	13.99/14.64	1.064/1.072

On the basis of the data that are presented in the Table 3, Figure 7 presents dependence of the averaged (following one runway of the forwarder) coefficient of variation $\eta(htr)$ of the tracing rut depth (axis of ordinates, 10^{-2} metres) from the mathematical expectation $M(htr)$ of the tracing rut depth (axis of abscisses, 10^{-2} metres).

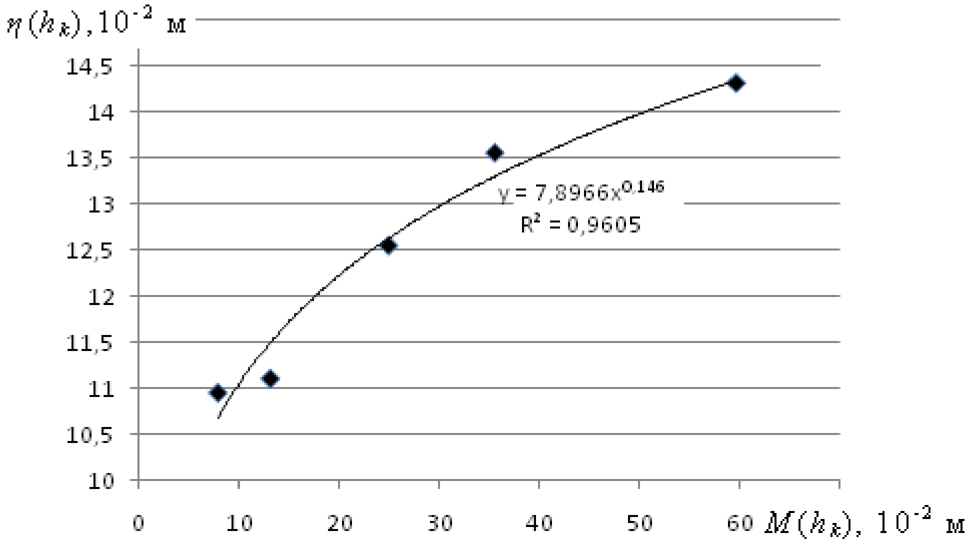

Figure 7. Dependence of the coefficient of variation of the tracing rut depth from its mathematical expectation following one runway of the yarding-and-loading system of the I category

This correlation dependence $\eta(htr)$ from $M(htr)$, which was obtained with sufficiently high accuracy (R^2 has exceed 0.96), has made it possible to determine boundaries of the strength categories of the soil grounds along the route of the yarding-and-loading / skidding track. Within these boundaries, relevant technological properties can be considered as the stable properties, which do not need any adjustments of the following parameters: weight of the bundle of trees; pressure on the soil ground; road speed of the forwarder; quantity of the forwarder runways over one and the same section of the route.

These strength categories of the soil grounds form the characterful scale (Table 4), which was constructed in accordance with the following requirement: range of variation of the relevant criterion must be one and the same (constant) within the boundaries of each category.

The data, which are presented in the Table 4, uniquely demonstrate that efficient exploitation of the yarding-and-loading systems under investigation is only reasonable within the areas of the soil grounds of the first and second categories (I and II categories) without any essential adjustments of the load and pressures with rounding downward.

In the case of movements of the forwarder over the areas of the soil grounds with the lower carrying capacity, it is necessary to ensure performance of the above-listed adjustments.

Table 4. Classification of the soil grounds in accordance with the criterion of their carrying capacity

No.	Carrying capacity	Limits of changes in the value of h_{tr}, 10^{-2} metre	Range, 10^{-2} metre
I	Extremely high	No more than 10	
IIa IIb	Very high High	From 10 up to 12 From 12 up to 14	2 2
III	Very average	From 14 up to 18	4
Iva IVb	Moderately average Average	From 18 up to 24 From 24 up to 30	6 6
V	Low	From 30 up to 40	10
VI	Very low	From 40 up to 52	12
VII	Extremely low	More than 52	

As it was shown with the help of calculations (see Figure 8), relative increase of the weight P (curve 1) and initial pressure $q_{initial}$ (curve 2) by ψ times (axis of abscisses) result in the nonlinear relative increase in the tracing rut depth by ψ_h times (axis of ordinates).

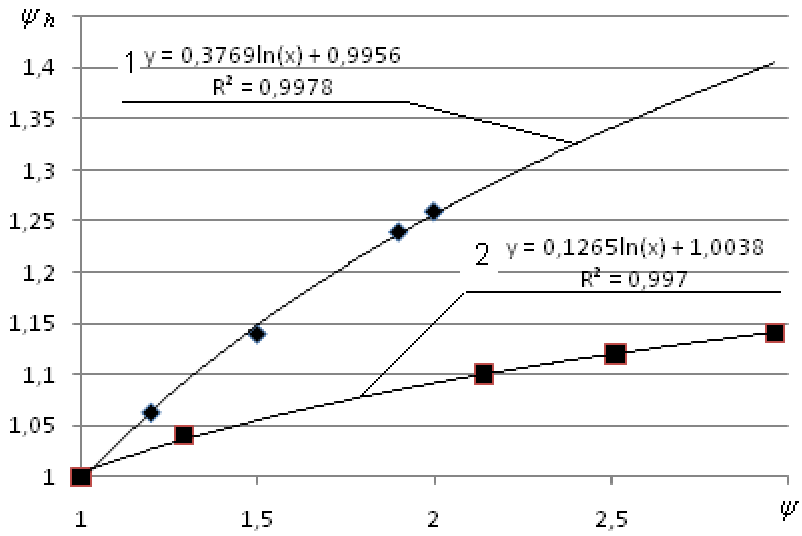

Figure 8. Influence of the relative increase in the weight and initial pressure of the yarding system upon the relative increase in the tracing rut depth

The logarithmic dependences, which we have obtained, demonstrate that decrease in the weight of the yarding-and-loading system, as well as (especially!) decrease in the pressure on the soil ground are only limited factors in the processes, which increase efficiency of the ground yarding.

Secondly, decrease in the value of P (as concerns its factor significance) essentially exceeds factor significance of the decrease in the value of pressure.

The combined influence of these factors (simultaneous decrease in the system weight and decrease in the pressure on the soil) ensures increase of efficiency of exploitation of the forwarder up to 40-50%. Such practices are considered as the activities of especial importance on the soil grounds of the fifth, sixth, and seventh categories of strength (V-VII categories).

The data, which are presented in Figure 9, clearly and graphically demonstrate this result. Indicators of the relative change in the tracing rut depth Δh (applicate axis) are presented as dependences on the values of P (axis of abscisses, tonnes) and $q_{initial}$ (axis of ordinates, kPa).

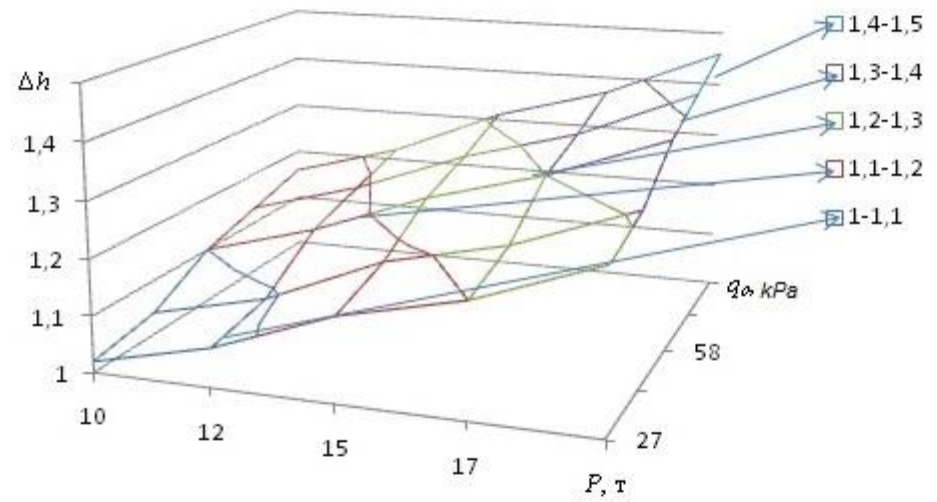

Figure 9. Dependence of the relative change in the tracing rut depth on the weight of the bundle of trees and on the pressure on the soil ground

In the case of application of the caterpillar tracks, such yarding-and-logging systems can be efficiently utilised on the soil grounds of the first, second, third, and fourth categories of strength (I-IV categories) at the loads up to 20 tonnes. However, in the course of movement over the areas of the soil grounds with low carrying capacity (soil grounds of V-VII categories), it is necessary to decrease the above-listed values of the load down to 12-13 tonnes.

It would be logically to complete analysis of the above-described investigations with the help of presentation (see Figure 10) of the relevant graphs of dependences of the mathematical expectation $M(\bar{\rho})$ (axis of ordinates) of the relative compaction of the soil ground within the boundaries of the tracing rut (following the single runway of the forwarder I (curve 1) and IV (curve 2)) upon the value $M(h_{tr})$ (axis of abscisses, 10^{-2} metre).

In the course of calculation of the values of deformations ε_i due to action of the first and second stamps, we have taken into consideration total deformations, but we did not take into account the possible elastic recovery of the soil ground massive (Shapiro et al., 2008).

High confidence of the logarithmic approximation confirms the following conclusions. Firstly, the previously obtained dependencies are dependencies of the asymptotic behaviour (and this fact is in correspondence with the results of investigations of the article [30]). Secondly, as concerns the strong soil grounds of the first and second categories, degree of their compaction is by 2 times lower (upon the average) as compared with compaction of the weak soil grounds massives (III–V categories).

Therefore, the proposed variational approach to the calculation of parameters of the process of formation of the tracing rut in the case of utilisation of different yarding-and-loading systems makes it possible to classify the thawing soil grounds on the certain sections of various routes in accordance with the criterion of their carrying capacity, as well as in accordance with the capacity to overcome the destructive action of static loads.

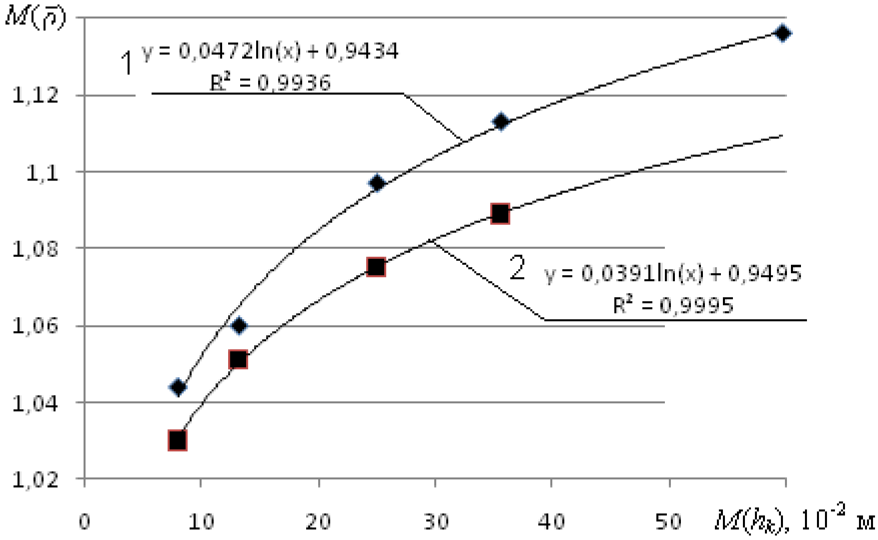

Figure 10. Dependence of $M(\bar{p})$ from $M(h_{tr})$: 1 – soil ground of the first category (I category); 2 – soil ground of the fourth category (IV category).

Conclusion

The results obtained ensure development of the prerequisites in order to increase reliability of forecasting the design parameters and conditions of the efficient exploitation of the state-of-the-art forwarders in the course of their utilisation within the forests of the cryolithozone.

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ISSN: 2005-4238 IJAST