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Specific features of accounting of state of the massive of the frozen soil grounds under cyclic loads

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Abstract

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Performance of the forest harvesting operations in the regions of the Russian Extreme North is characterised by the very adverse climatic conditions. Operation of the yarding-and-loading systems on the cryomorphic soil grounds shows that exist the clear need for considering this factor and considering this factor as the complex multicomponent environment. Necessity of minimisation of the man-made burden on the environment is the basis for inclusion of the problem, which is connected with optimisation of quantity of movements of the yarding-and-loading system over one and the same runway, into the category of the most topical problems. The data, which are presented in this article, make it possible to assess (numerically) the effect of application of various systems in the specific climatic and technological conditions. The methodological provisions, which were developed in this article, were the basis of the trial calculations in order to determine adequacy of the mathematical model and technological conditions of exploitation of the yarding-and-loading systems in the case of the cyclic influence of these systems upon the frozen soil ground. It is possible to accept the results of the performed investigations, as well as to accept the performed estimates of influence of parameters of the specific yarding-and-loading system as follows influence of temperature, wetness, ice content, influence of physical and mechanical properties and influence of the state of the frozen soil ground upon the process of deformation of this ground. These results and estimates can be accepted as the initial requirements in the course of simulation and optimisation of the process of cyclic compaction of the soil ground.

Keywords: cryomorphic; tree-felling; yarding-and-loading systems; compaction; deformationof; soil grounds

Introduction

The Russian timber-processing industry has started to develop significantly beginning from the moment of imposition of the protective duties for import of the round timber. More and more woodworking companies and timber-processing enterprises (except for pulp-and-paper plants) are putting into operation every year. At the same time, already existing enterprises are subject to substantial modernisations. These processes make it possible to generate new jobs, as well as to increase payments to the state budget and to budgets of the constituent entities of the Russian Federation due to manufacture of the highly demanded products, which are characterised by the increased added-value cost. First, these goals were set by the Resolution of the Government of the Russian Federation No. 419 dated June 30, 2007, "On the Priority Investment Projects in Forest Development". In accordance with this Resolution, the constituent entities had been given the opportunity to transfer and sell forest resources to the businesses, which wish to establish new enterprises or modernise already existing production facilities in accordance with the following conditions: forest resources may be transferred and sold without holding auctions and they may be transferred and sold at the minimum rate. In return, these businesses must establish power fulstate-of-the-art enterprises, install new production equipment, and increase output of products.

However, increase in the woodworking volumes would always necessitate increase in the volumes of the wood harvesting. At the same time, timber rotation period (especially in respect of the coniferous timber) is a very long period of time in the sufficiently severe climate conditions of the greater part of territory of our country.

Very considerable period of affore station (cultivation of the old growth and quality forests on the felled forest areas) is the great problem of the forest regeneration. Therefore, it is the problem of the forest harvesting enterprises in the future even in the situations, where advanced (and sufficiently expensive) silvicultural methods would be applied (for example, improvement felling operations, as well as application of fertilisers(Martynov et al., 2008; Beliaieva et al., 2011)).

For sufficiently obvious reasons, large wood-processing enterprises have been built within the regions, where large reserves of the standing timber exist – in the Irkutsk region, in the Krasnoyarsk Territory, in the Republic of Buryatia, etc. Another one essential useful contribution for successful conduct of the forest-industry business was as follows: sufficiently low electricity tariffs due to close neighbour ship with powerful hydroelectric power stations within these regions.

However, the reserves of the old growth exploitation forests, which were economically available, decreased with each passing year of the extensive forest exploitation. In the course of time, wood-processing enterprises begin to feel a certain discomfort because of the increasing shortage of timber, amely, the round timber (Kunitskaya, 2014).

The main tree species within the greater territory of the forest fund of the Russian Federation are coniferous species; however, they regenerated rather slowly. Even the model of the intensive forest exploitation, which was put into effect recently, will not change this situation in the next few decades (Grigoreva, 2015). In this connection, the forest-industry companies are forced to bring under cultivation the non-traditional (for them) territories in order to continue wood harvesting: the forests, which are situated within the rugged terrains, as well the forests, which are situated on the cryomorphic soil grounds, for example, in the Republic of Sakha (Yakutia).

Of course, within the southern districts of Yakutia, where good forest vegetation conditions exist and, respectively, quality timber-stands for the timber operators are ensured (as concerns the tree species composition, average volume per tree, and the forest yield per hectare), felling-area works are carried out for a sufficiently long time and on a large scale. However, in the northern direction forest vegetation conditions become more severe, quality of forests decreases. Necessity of development of the forests, which are situated on the cryomorphic soil grounds, is connected not only with the task of satisfaction of the demand for the wood raw materials. It is also connected with the great quantities of the already accumulated over maturity stands, which become weaker, which is the subject to fungal diseases, insects, and other diseases, as well as they begin to burn. There exists the well-known phrase: «if a forest is not cut, this forest will burn».

State of the art technologies and equipment of the sawmill and woodworking enterprises are already fully capable to ensure efficient processing of even small diameter and irregular stems, as well as practically any timber, if only the timber would be available and delivered to the relevant enterprises (Tambi et al., 2017). As it was noted in the article (Abaimov and Matveyev, 1999), «forest ecosystems of the cryomorphic zone are characterised by the following parameters: not so high formation diversity and small biological diversity; low fertility of communities; original structure of the standing timbers; weakened rehabilitation potential; increased sensitivity to the stress influences; specific processes of formation of forests». Consequently, it is necessary to treat the forests of the cryolithozone as the ecosystems, which are particularly sensitive to the external influence.

In principle, the forests in the European portion of Russia, which are situated on the territories with the soil grounds of the third (III) and the fourth (IV) categories(that is, on the water-logged soils and on the marshy land), are especially vulnerable forest ecosystems, which are the most suffering ecosystems from the forest harvesting process.

As a rule, logging operators try to bring such forests under cultivation during the winter seasons in order to decrease environmental damage from destruction of the soil grounds within the cutting areas, as well as from damages of roots of the trees, which are reserved in order to ensure completion of growing in the course of the selective felling operations. In winter time, intensity of influence of propulsion plants of various machines upon the soil horizons is essentially lower (especially in the presence of the stable snow cover(Anisimov et al., 2006)).

Unfortunately, it is not possible to apply such simple method of the substantial increase of the environmental safety of the felling-area works in the forests, which are situated in the cryolithozone. It is possible to state that this fact is connected with the mechanism (as such) of formation of the permanently frozen soil, that is, with the severely continental climate of these regions.

After the summertime, the cold season begins sufficiently quickly. The average air temperature in Yakutia begins to decrease sufficiently intensively. As a rule, it is lower than minus 40ºC by November already. It is prohibited to operate forestry machines at such temperatures of the ambient air. It is connected not only with the hydraulic systems of various machines, but also with the metal of the hydraulic manipulator, frame, suspension mount, etc. In the course of operation at low temperatures, metals, deteriorate quickly, fatigue cracks appear, etc. Strong frosts usually hold off in the regions of the cryolithozone during the entire winter and the greater part of the spring period. The nair temperature begins to increase intensively and it achieves stable positive values. The result of such nature of climate is as follows: very short duration of the winter harvesting period, during which it is not possible to develop the entire designated annual cutting area. Therefore, it appears that timber operators are forced to operate forestry machines on the cryomorphic soil grounds during the warm period of the year as well.

It should be also borne in mind the fact that clear felling of the forest stands on the cryomorphic soil grounds results in quick thawing of the soils, which were in the shade earlier. In addition, such felling operations cause intensive development of the water-logging processes, which, in its turn, have a very negative impact on the subsequent forest restoration processes (Grigoreva et al., 2018). From the above, it is possible to come to the sufficiently well-known conclusion concerning the fact that in the forests, which are situated in the cryolithozone, it would be the most properly to do this business with the help of various systems of the selective felling operations. In the course of this operations, it is necessary to achieve an optimum restriction of stock (denudation of vegetation) not only in respect of the criterion of the subsequent development of the trees, which are reserved in order to ensure completion of growing, but also in respect of the degree of shade of the soil ground within the cutting area (that is, shade from crowns of the reserved trees). This fact, in its turn, means that in the course of the felling-area works, particular attention must be paid to damages of the reserved trees. Prevention of damages of the tree trunks and crowns of the reserved trees does not cause great problems if the qualified and responsible personnel are available (highly experienced operators of the forest machines). However, prevention of damages of the tree roots is the essential problem. The root systems of the trees, which grow on the cryomorphic soil grounds, are subject to deformations and destructions. Even the larch-trees, which grow on the cryomorphic soil grounds and which are commonly available in Yakutia, are characterised by development of the lateral/surface root system (which is similar to the root system of the fir spruce) instead of the tap-root system, which is usual root system of various species of the larch. It connected with the difficulty of root penetration into the frozen horizons of soil (Abaimov et al., 1999).

Even if one would obtain information on location of various root systems (obtaining of such information is theoretically possible operation, this information will not ensure achievement of any essential and useful results in practice. Therefore, the most important criterion of the environmental safety of operation of the forestry machines in the conditions of the cryolithozone will be as follows: minimisation of the track width, as well as minimisation of the degree of the soil ground compaction in order to prevent strong damages of the root systems of the reserved trees in order to ensure completion of their growing. To this end, it is necessary to utilise several methods, list of which we will provide below in accordance with the degrees of their efficiency:

Firstly, it is necessary to ensure adequate selection of the forestry machines, especially the yarding-and-loading machines, which perform multiple movements/runs over the same track (run with the bundle of trees to the upper depot and the reverse run unloaded to the place of the bundle completion). Now, machine technologies of the wood harvesting are predominant ones in Russia already. At the same time, volumes of utilisation of the Scandinavian harvesting technology increase. This technology is based on production of the timber assortments at the stump, as well as on the subsequent yarding of these assortments with the help of the wheeled forwarder (assortment collector) to the point of loading (Grigorev et al., 2016). It is necessary to assess suitability of the soil for such movements/runs, as well as mobility of wheels in proper manner. Suitability of the soil for movement depends on its capability to maintain resistance to the tangential propulsive thrust, which originates from the propulsion plant. Weight of machine provides load on the soil and ensures bearing capacity. The wheel goes down to a certain depth, when load of the wheel and bearing capacity of soil are in equilibrium.

Embedding of the wheel ensures resistance to motion, that is, the force, which prevents forward motion of the wheel. If to decrease embedding of the wheel, it is possible to decrease this resistance and improve movement. Torque moment on the wheel creates the torque moment in respect of the perimeter/circumference of the tyre. This torque moment is transferred to the ground through the tyre or through the caterpillar track. It is possible to utilise the horizontal feed propulsive force in order to overcome resistance to motion and generate proper propulsion. Maximum propulsion, that is, the surface friction force of the specific kind depends on the resistance of layers of the soil shear. Manufacturer of the machine cannot exert influence upon resistance of layers of the soil shear; however, the manufacturing company can exert influence upon dimensions of the area, which carries load from the tyre or from the caterpillar track. The greater this area, the greater forces can be transferred to soil in order to ensure proper propulsion. Total pressure on the soil ground is the sum of the dynamic and static pressures. Pressure of the single tyre is two times greater as compared with the pressure from the framework axis.

As concerns weak soil grounds (for example, as concerns the thawing grounds, which were frozen grounds previously), it is necessary to ensure equipping the wheeled machines with mono caterpillar tracks. In this case, weight and propulsive thrust are distributed over the wide area of the framework, which is equipped with caterpillar tracks. Therefore, total pressure on the soil ground is essentially decreased. In its turn, this fact decreases damages of the soil ground, as well as damages of the root systems of the trees, and ensures convenient movement. It is very desirable to select the forwarder with optimal wheel configuration. For example, it is known that pressure on the soil ground of the eight-wheel forwarder under load is by 50% greater than pressure of the ten-wheel forwarder. This suggests that it is essentially better to operate the 10-wheel forwarders on the cryomorphic soil grounds that are subject to thawing, despite of the fact that their manoeuvrability is slightly worse as compared with the eight-wheel forwarders.

What is more, it is possible to change the wheel configuration of the state-of-the-art forwarders depending on conditions of exploitation in accordance with the relevant commands of operator. For example, the ten-wheel forwarder (model: Ponsse Buffalo 10W) has the design possibility to lift its rear axle (operator presses special button on the cabin). When rear axle is lifted, manoeuvrability of this machine is the same as manoeuvrability of the 8-wheel forwarders. In the course of operation on the soft soil ground, rear axle is pressed down. Area of the contact patch under load is equal to 6.05 m^2; therefore, it is possible to ensure very low pressure on the bearing surface area. In its turn, low pressure on the ground helps to save roots of the trees in the course of the selective felling operations.

In addition, it is necessary to utilise the caterpillar tracks of the special structure on the weak-bearing soil grounds (that is, the caterpillar tracks, which are equipped with the rounded plates). The rounded plate of the caterpillar track does not cut upper layers of soil. If one would utilise the caterpillar track of unsuitable structure (there exist sufficiently many structures for various conditions of exploitation), then the sharp end of plate of the caterpillar track would cut the upper layer of the thawed soil. At the same time, bearing capacity of the soil ground is essentially decreased and roots of the reserved trees are subject to damages. However, in this case it is necessary to clarify that cost of each mono caterpillar track is equal to several dozens of thousands Roubles (depending on the length and type of the caterpillar track. It is possible to state that this cost depends on the specific consumption of metal in the caterpillar track. In addition, mono caterpillar track is not included to the standard configuration of the wheeled forestry machines, which are now sold in Russia. It is necessary to have 4-caterpillar tracks for any wheeled machine (both for 8-wheeled and for 10-wheeled machines). Therefore, for the reasons of economy many timber operators try to do their business without mono caterpillar tracks. In addition, it is necessary to spend certain time for assembly and subsequent disassembly of such caterpillar track. There is no necessity to mention the increase of fuel consumption by the wheeled machine in the case of its operation on the caterpillar tracks.

Secondly, in the course of operation on the weak soil grounds, it is possible to decrease the load for a single run of the forwarder (that is, to decrease volume of the bundle of the timber assortments which is to be trailed), while this fact will respectively decrease pressure of the propulsion plant on the surface of movement. However, this method will not always be the optimal method; because of in this case the specific fuel consumption per cubic metre of the harvested wood will increased due to the essential tare-load ratio of the forwarder. In addition, such method will only increase quantity of runs, which the forwarder must go on over the same runway. Thirdly, it is possible to strengthen surface of runways with the help of the felling residues (slashes). This practice is widely used among the forest harvesting enterprises of Russia. It is considered that the over pressed felling residues, which were introduced into the soil, will be quickly transformed into the earth humus, which will subsequently nourish the forest soil. However, in the conditions, which are analysed in this article, this alternative cannot be optimal one, because of there is the extremely small quantity of microorganisms, which decompose wood biomass in the frozen soils. Forests in Yakutia are very fire-hazardous zones because the dead soil cover in the hemlock forests (or acerous leaf) is not decomposed. This dead soil cover is only accumulated from year to year. Later on, this dead soil cover dries. I n summer, it transforms into the inflammable material (like the gunpowder). It appears that the felling residues, which were embedded into the cryomorphic soil, can be decomposed during very prolonged period. Therefore, there will be no forest reproduction processes on the surface, which is occupied by the felling residues, because of the tree-seeds cannot achieve the soil (Grigoreva, 2014).

In principle, the assigned task is reduced to the following: degree of damage of the runway on the soil ground must be within the limits of the permissible degree. Degree of damage must not cause excessive over compaction, and depth of the track must not achieve the main mass of roots of the reserved trees. It means that it is necessary to have the adequate mathematical model, which makes it possible to obtain (in a timely manner) the forward-looking information in respect of development of the compaction processes and the processes of the wheel track rutting (depending on the characteristics of the soil ground, as well as depending on the parameters of the forestry machines) (Gabitov et al., 2018). Such information will make it possible to arrive at the optimal technological decisions, which will ensure environmental safety of the felling-area works from the point of view of their influence upon the soil grounds of the cutting areas, as well as upon the root systems of the reserved trees.

Such forward-looking models have been already developed, and it is possible to give sufficiently many examples of such models. As of today, the results, which were obtained in the article (Grigorev, 2006), are regarded as the classics of such models for the wheeled forestry machines. From the point of view of applicability of the results, which were obtained in the article (Grigorev, 2006), there exists another problem, which is connected with the practice of the forest harvesting operations. It would be necessary to have results of the laboratory tests of soil grounds over the potential yarding routes. Such tests are quite prolonged and complicated tests even if the field-testing laboratory is available. Even the largest forest harvesting enterprises have no such laboratories. On the other hand, method of the rapid assessment of physical and mechanical properties of the soil ground with the help of the down-the-hole penetrometers (Dmitrieva et al., 2017; Khitrov et al., 2017) was already adapted and improved.

However, all these achievements can be only used as the starting point in the course of solving the assigned task, because of the cryomorphic soil grounds were not subjects of the above-listed investigations. Moreover (as concerns the forest harvesting enterprises), we have not practically found any articles (neither in Russia, nor in foreign countries), which were devoted to investigations of the following processes: interaction of the stump-to-roadside equipment and technological processes with ecosystems of forests of the cryolithozone (including investigations upon the cryomorphic soil grounds). However, these soil grounds have their own patterns and specifics. For example, in the course of thawing of the frozen soil ground, it becomes super saturated with water. Therefore, natural connections between solid particles will become substantially weaker, while physical and mechanical properties will lose their original values (Rudov et al., 2019). At the same time, forces of adhesion of the soil ground will decrease at the boundary of thawing. Intensity of this decrease depends on the original wetness of the soil ground. Presence of ice within the frozen soil ground imposes restrictions upon the nature of destruction of the frozen soil ground in the case of achievement of ultimate loads. The ice (as compared with other crystalline solids)exerts its plastic properties in the obvious manner. Under the influence of the vertical compressive load, ice can change its form without changing its volume, that is, ice «flows as water». This state of ice corresponds to the mode of flow of viscous fluid. Yarding-and-loading system exerts influence upon the soil ground through tyres and creates certain pressure, which results information of the stress-strain state of the soil body within the «tyre-soil ground» contact zone, which is subject to destruction in the case of achievement of ultimate loads.

In accordance with the data of the article (Sparchez et al., 2009), it is possible to separate and classify four states of the soil body due to destruction of the fertile layer of soil in the course of movements of the yarding-and-loading system: weak damage of the soil layer, moderate damage (up to 50%), strong damage (from 50 up to 100%) and very strong damage, when the productive layer is being destructed and removed completely.

These circumstances (in combination with the necessity of minimisation of the man-made burden on the environment) move the problem of optimisation of quantity of movements of the yarding-and-loading system over one and the same runway into the category of the most topical problems (Shapiro and Grigorev, 2006; Shapiro et al., 2008; Ticu & Alexandru, 2012). At the same time, in accordance with the data of the article (Kotliarenko, 2008), the single movement/run of the yarding-and-loading system (even at the low average pressure on the ground (at the level of no more than 47 kPa)) results in certain failures of the solid soil body. The two-foldrun destroys up to 30% of volume of the contact layer, while three-foldrun destroys up to 80% of this volume.

In principle, these conclusions were made in respect of the cohesive grounds of various kind sat positive values of the environmental temperature (T). As concerns conditions of influence upon the frozen grounds, process of their deformation and destruction will be additionally characterised by influence of the factor of negative temperatures (and, as a consequence, by influence of ice)upon the physical and mechanical properties of the ground, first of all, upon its elastic, plastic, and strength characteristics.

The yarding-and-loading system exerts the main destructive influence upon the frozen ground with weak surface layer, which contains ice (up to 60 per cent and more per unit volume). It is the ice, which exerts drastic influence upon the nature of behaviour of the ground at static loads.

In this context, in the course of exploitation of the state-of-the-art yarding-and-loading systems (particularly, in the course of exploitation of the forwarders of various modifications),one of the methods of management of the process of influence upon the ground is as follows: selection of the optimal quantity of wheel pairs in order o decrease value of pressure.

Materials and Methods

Table 1 presents characteristics of certain yarding-and-loading systems, as well as values (q) of the pressure, which these systems develop on the ground under wheels due to their dynamic and static influence (Hahina et al., 2018). The first stamp (stamp 1) means the propulsion plant; the second stamp (stamp 2) means the transportation trolley (Table 1).

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

Yarding-and-loading system	Weight, tons	q, kPa	
		stamp 1/ quantity of the wheel pairs	stamp 2/ quantity of the wheel pairs
4-wheeled	15	68 / 1	0 /1
6-wheeled	16	72 / 1	0/ 2
8-wheeled	19	35 / 2	58 / 2
10-wheeled	20	35 / 2	37 / 3

Therefore, utilisation of the 8-wheeled and 10-wheeled yarding-and-loading systems at the loads P = 19-20 tons develops pressure on the soil ground (particularly, under propulsion plant), which is equal to q = 35kPa. This value is practically 2 times lesser than the value of the relevant pressure in the case of utilisation of the 4-wheeled and 6-wheeled systems. In the case of exploitation of forestry machines on the weak-bearing grounds, application of the caterpillar tracks makes it possible to decrease value of q down to 27 kPa, however, utilisation of such arrangements results in the additional material expenses and labour costs.

Pressure on the ground causes formation of the zone of compression of the frozen soil ground. The greater dimensions of this zone, the greater effort can be transferred to the soil ground in order to ensure proper draught of the propulsion plant.

Total value of compression (total deformation) ε is the sum of permanent deformations $\varepsilon_{permanent}$ (deformations of structural compaction, plastic deformations) and elastic deformations $\varepsilon_{elastic}$ (Ageykin, 1972). In this case, elastic deformations can achieve the level of 60% and more in respect of the value of ε. As concerns the thawed grounds, temperature of which is approximately equal to 0°C ($T \approx 0$°C) in the case of the prolonged influence of the pressure, value of $\varepsilon_{elastic}$ tends toward zero ($\varepsilon_{elastic} \rightarrow 0$). In the case of quick loading, (it can be treated as interaction of a wheel with the ground), elastic deformations always occur. In order to estimate the relationship between $\varepsilon_{permanent}$ and $\varepsilon_{elastic}$, let us introduce the dimensionless parameter $\psi = \varepsilon_{permanent} / \varepsilon_{elastic}$.

Ratio of value q to ε is characterised by the module of the total deformation E, provided that (in accordance with the data of the article [28]) value of E (in the case of changing T from -2°C up to -6°C within the range of changing q from 100 kPa up to 300 kPa) depends essentially on the value of q for the frozen sandy loams, while this same ratio does not depend on the value of q for the argilloarenaceous ground. Figure 1 presents dependence of the total deformation module from the pressure on the soil ground or the sandy loams and argilloarenaceous ground.

In the range of values of q < 100 kPa (it is the range of pressures for the yarding-and-loading systems in accordance with the data of Table 1) dependence of the value E from the value q was not revealed.

Along with further decrease in the values of T, value of E is in the linear progression practically for all kinds of the frozen grounds.

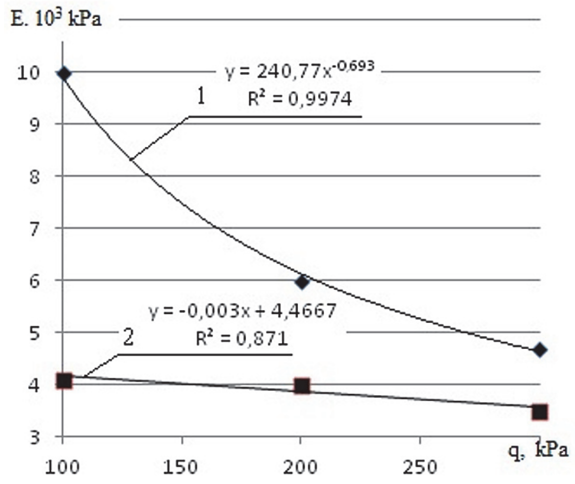

Fig. 1. Dependence of the total deformation module from the pressure on the soil ground: *1* –sandy loams; *2* – loamy soil

Therefore (particularly, as concerns the sandy loams within the range of values 0.1°C > T > -3.6°C), E are to be determined in accordance with the following dependence (R^2 = 0.9625):

$$E(T) = -1/2793T + 0.6835, \text{ MPa} \quad (1)$$

It is necessary to reveal relevant relationship (1) for each kind of the frozen grounds, as well as for other specific conditions.

As the result, in the course of utilisation of equation (1) for the frozen sandy loams we will use the following equation for calculation of ε taking into account values T and q:

$$\varepsilon(q,T) = q/(-1.2793T; -0.6835) \quad (2)$$

That is, value ε is two-dimensional function of parameters q and T and this value increases in proportion to q.

It follows from this conclusion that increase of pressure of the relevant stamp on the soil ground ensures development of substantial deformations in this soil ground, which cause compaction of this ground, while in the case of exceedance of the bearing capability these deformations cause destruction of this ground. Value of the relative compaction is calculated according to the following formula:

$$\bar{\rho} = \rho/\rho_{original} = 1 + \varepsilon,$$

where $\rho_{original}$ is the original density of the ground, ρ is the density after compression of the soil ground due to influence of the wheel.

Figure 2 presents graph of the two-dimensional function of the relative compaction of the frozen ground as depen-

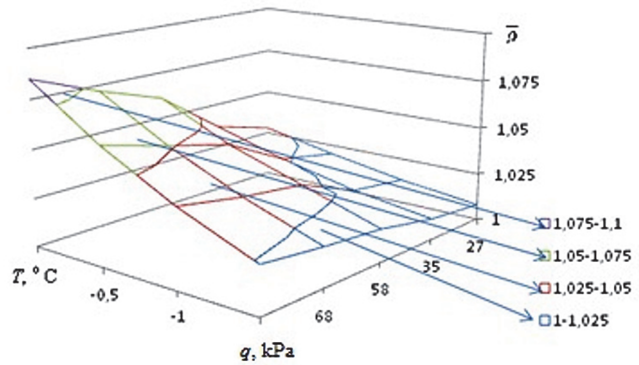

Fig. 2. Dependence of the relative compaction of the frozen ground from its temperature and from the external pressure of the stamp

dence from its temperature and from external pressure of the stamp in accordance with the relationship (2).

As you can see from the Figure 2, utilisation of the 10–wheeled transportation systems on the thawed ground causes certain compaction ($\bar{\rho} \approx 1.04$) already following the first cycle of influence of the relevant stamp, while possible application of the caterpillar tracks decreases level of compaction by 32%. Under these circumstances, exploitation of the 4-wheeled systems causes substantial compaction of the ground ($\bar{\rho} \approx 1.09$).

As concerns the table frozen ground, all systems, which are listed in Table 1, do not move parameter $\bar{\rho}$ beyond the limits of 1.025 on the first cycle of influence of the relevant stamp.

It is very interesting to study process of increase of the total deformation and compaction of the frozen ground in the course of movement of the transportation system, as well as in the course of implementation of the cyclic influence of stamps. Therefore, it is necessary to take into account plastic and elastic properties of the soil ground in the context of accumulation of permanent deformations. It is obvious that these specific features depend on wetness of the frozen ground, on the ground temperature and, respectively, on the content of ice in this ground.

As concerns frozen grounds, no stable correlation relationships between E and W were revealed (Velli et al., 1963; Tsytovich, 1983; Vialov, 2000), while spread in values of E achieves dozens per cent.

As concerns thawed grounds, value of E depends on the wetness W and it can be changed from 0.1 up to 1.0 MPa for the water-logged grounds, parameter W of which exceeds the liquid limit of these grounds up to 35-50 MPa (for the grounds, parameter W of which does not exceed plastic limit of these grounds (Ageykin, 1972)). It is noted that there exists increase in values of the Poisson's ratio ν along with increase of parameter *W*.

Taking into account the fact that value ν (all other conditions being equal) characterises plasticity of the ground, it is possible to take into consideration (at the expert level) the following grounds:

a) Dry grounds (W = 0.1-0.2) (with the Poisson's ratio ν no more than 0.15-0.2) in the course of deformation exert (in principle) properties of brittleness, and parameter $\psi = 0.25/0.75 = 0.3$;

b) Grounds of moderate wetness (W = 0.2-0.3) (with the Poisson's ratio ν up to 0.2-0.3) in the course of deformation exert both brittleness and plasticity, and parameter $\psi = 0.5/0.5 = 1$;

c) Grounds of high wetness (W = 0.35-0.55 and more) (with the Poisson's ratio ν = 0.3 – 0.5) in the course of deformation exert (in principle) properties of plasticity, and parameter $\psi = 0.75/0.25 = 3$.

Compaction and destruction of the ground cause embedding of the wheel at certain depth h_{original} and worsens conditions of exploitation of the yarding-and-loading systems. Maximum force of the propulsive thrust, which is ensured by the force of the surface friction, depends on the value of ultimate shear strength of the ground σ_{shear}.

Vertical pressure q in the models of the soil mechanics with internal friction (Shapiro & Grigorev, 2006) is connected with horizontal pressure τ with the help of the following relationship:

$$\tau = \mu q, \tag{4}$$

where $\mu = \nu/(1 - \nu)$ is the side thrust coefficient, which is determined by the Poisson's ratio ν.

Analysis of the relationship (4) shows that for the waterlogged soil grounds $\mu \to 1$ and $\tau \approx q$ in the cases, where $\nu \to 0.5$. The soil ground is in the conditions of the volumetric compression and the models of the incompressible fluid describe its behaviour.

In the cases, where $\nu \to 0.2$, that is, in the cases, where dry soil ground exerts properties of brittleness (to a large extent) in the course of deformation, value τ is equal to $0.25q$. In a number of situations, this fact results in the situation, where efforts with the purpose of soil shear of the frozen soil ground would be insufficient. Therefore, forces of vertical compression, which cause formation of relevant zones of compaction, will dominate.

In order to investigate processes of possible destruction of the frozen soil ground under the influence of relevant stamps, it is necessary to make estimates of the strength characteristics, as well as estimates of their dependence on the actual state of the soil body.

Factor of temperature of the frozen soil ground T exerts substantial influence upon parameters of strength of this ground, namely, values of the ultimate compression strength $\sigma_{compression}$, ultimate shear strength σ_{shear}, and ultimate tensile strength $\sigma_{tensile}$. The closer these values to each other are (first of all, characteristics $\sigma_{compression}$ and σ_{shear}), the greater plasticity the soil body exerts. For the most part, the following inequalities are valid for the above-listed strength characteristics:

$$\sigma_{compression} > \sigma_{shear} > \sigma_{tensile} \tag{3}$$

Table 2 presents data concerning strength of compression of samples of the frozen sandy loams and ice $\sigma_{compression}$ (numerator) and shear strength σ_{shear}(demoninator).

Table 2. Values of the ultimate compression strength and ultimate shear strength (kPa) taking into account T

T, °C	Sandy loams	χ	Ice	χ
-0.1	900/120	7.50	100/80	1.25
-1	1,500/1,000	1.50	500/400	1.25
-2	2,100/1,400	1.50	1,300/1,500	0.90
-3	3,100/2,100	1.48	2,100/1,900	1.11
-4	4,100/2,600	1.58	2,800/1,900	1.47

As concerns value of σ_{shear}, there are only certain sampling data grounds. Particularly, for the frozen sandy loams $\sigma_{shear} \approx 700 - 800$ kPa at $T < -1$°C and $\sigma_{shear} \approx 2000$ kPa at $T \approx -4$°C. These parameters are commensurable quantities with the value of the bearing capability of the dry cohesive grounds (Ageykin, 1972) at positive values of *T*. As concerns wet soils and waterlogged grounds, their bearing capacity is decreased down to 10-80 kPa. Therefore, value of $\tau \approx q = 35/80$ kPa (Table 1) can exceed the ultimate values of strength of the soil ground, and this process will cause destruction of this soil ground.

It is interesting to analyse value of χ, which is equal to ratio of strength characteristics $\sigma_{compression}$ to σ_{shear}. This fact is presented by Figure 3, where graph illustrates dependence of value of the ratio $\chi = \sigma_{compression} / \sigma_{shear}$ from *T*°C) for the sandy loams and ice.

As you can see from the Figure 3, as concerns the state of the stable frozen soil ground (*T* does not exceed -1°C), differences between values of χ for the sandy loams and for ice are inessential.

It is known that the closer χ to 1, to the greater extent the frozen soil ground would exert its plastic properties. In this connection, it is emphasised in the article (Velli et al., 1963) that sandy loams at $T \approx -3$–4°C behave like ice from the point of view of plastic properties. This conclusion is confirmed by the data, which are presented by Table 2 and Figure 2.

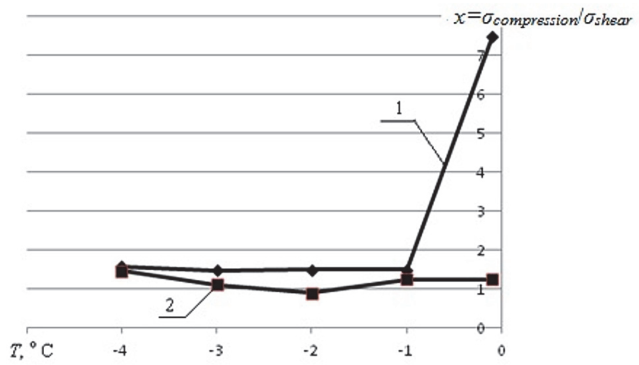

Fig. 3. Dependence of value χ from *T*:
***1* – sandy loams; *2* – ice**

If one would accept parameters of strength of the thawed soil ground at T = -0.1°C as the scale unit, then it is interesting to reveal dependences of the dimensionless coefficients $K_{compression}$ and K_{shear} from T.

Results

Figure 4 presents results of the relevant calculations (curve 1 for the relative parameter of the ultimate shear strength; curve 2 for the relative parameter of the ultimate compression strength).

It is well established that dependence $K_{compression}$ (*T*) is properly described by the linear function, while K_{shear} (*T*) is properly described by the polynome of the second degree. As concerns slope of these curves in respect of the axis of *T*

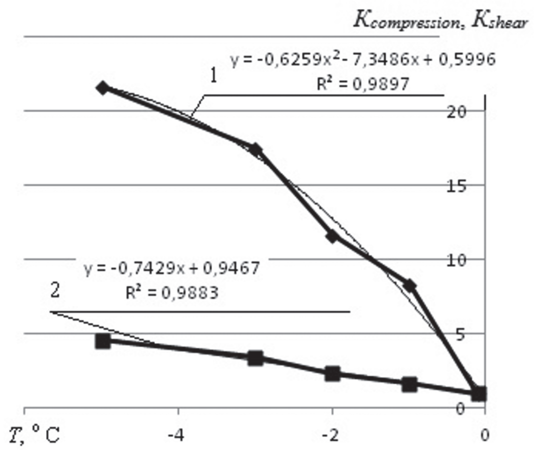

Fig. 4. Increase of the relative parameters of the ultimate compression strength and the ultimate shear strength in the case of decrease in temperature of the frozen ground: *1* –ultimate shear strength; *2* –ultimate compression strength

(that is, as concerns the first-order derivatives of the relevant functions), it is possible to draw the following conclusion: intensity of increase of the ultimate shear strength is the multiple value (up to 5 and more times) in respect of the intensity of increase of the ultimate compression strength. This result is becoming particularly important taking into consideration the fact that dimensions of the destructible layer exert influence upon the force of thrust of the propulsion plant. That is, value of the bearing capability of the soil ground, which (depending on the nature of destruction) is equal to the ultimate shear strength or to the ultimate tensile strength.

Value of the ultimate tensile strength of the ground $\sigma_{tensile}$ is determined by the same factors, which determine value of the ultimate compression strength.

Contrastive analysis of values $\sigma_{tensile}$ and $\sigma_{compression}$ shows that (all other conditions being equal) value $\sigma_{tensile}$ is equal to $(0.2/0.4)\sigma_{compression}$ upon the average. If one would turn to the quantitative estimate of influence of wetness upon the strength properties of the frozen grounds, then dependence $\sigma_{compression}(W)$ for the frozen sandy loams within the range of changing *W* from 10-15% (dry sandy loams) up to 35-40% (very moist sandy loams) is governed by the law of quadratic hyperbola.

As concerns sands in the case of changing *W* from 5 up to 20% of value, $\sigma_{compression}$ increases by more than 2 times. As concerns clay at *T* = -3-4°C, decrease of $\sigma_{compression}$ from 5,000 down to 3,500 kPa is revealed in the case of increase of *W* from 15 up to 35%.

Our attempts to reveal influence of the parameter of wetness upon value of $\sigma_{compression}$ (if such influence would be uniform and unique one for all frozen grounds) have not been successful. Therefore, it is necessary to determine relevant dependence $\sigma_{compression}(W)$ for the specific technological conditions.

It is emphasised in the articles (Vialov, 2000; Iospa, 2014) that practically all frozen grounds have rheological properties, as well as that presence of ice is the main connecting factor. Due to influence of rheology, tests of the strength properties and deformation characteristics of the frozen grounds (both laboratory investigations, and in situ soil tests) are very labour-consuming investigations. It is necessary to spend essential time for these tests (duration of each test: from 1 week up to 4 weeks). In addition, there are great differences (many times over) in the volumes of information on physical and mechanical properties even of the same group of the frozen grounds. Therefore, it is very difficult to ensure practical utilisation of this information in the course of calculations of original parameters of the contact destruction within the zone of interaction of the wheel and the frozen soil ground.

It is noted that the higher *W,* the more substantial influence of the parameter *T* upon the nature of implementation of the process of destruction will be especially, at the moment of transfer of *T* through the freezing point of water, transformation of water into ice, and, as a consequence, at the moment of increase of adhesion of the soil body. As compared with other crystalline solids, ice exerts its plastic properties in the obvious manner. Under prolonged influence of load, ice can change its form without changing its volume, that is, "ice can flow". This state of ice corresponds to the mode of flow of viscous fluid. At the same time, in the case of influence of the static force *P* upon ice, ice undergoes deformation and can behave like elastic body, plastic body or behave like a brittle solid now of destruction (Bychkovskiy & Gurianov, 2005). Nature of ice behaviour depends on the duration of application of load.

It is possible to state that action of the propulsion plant (that is, action of the first stamp) is immediate and instantaneous action. At the speed of movement of the transportation system at the level of 2.5 kilometres per hour and at the distance between the stamps at the level of 2 metres, interval of time of the beginning of influence of the second stamp will not exceed 3 seconds. However, ice behaves like elastic body during not less than 100-1,000 seconds. That is, under the influence of the yarding-and-loading system it is possible to state that elastic deformations in the course of destruction of ice will dominate.

Investigations of processes of water freezing in the frozen ground have made it possible to separate four main stages of these processes running: 1) decrease of *T* in the course of subcooling of the pore water; 2) increase of *T* due to crystallisation of the certain part of water; 3) quick transformation of the greater part of water into ice; 4) stage-by-stage decrease in temperature *T* of the already frozen ground upon completion of final freezing of the entire water.

It is not possible to perform quantitative estimates in respect of various stages and to take into account influence of the above-listed factors upon the physical and mechanical properties of the frozen ground in the course of changing temperature *T.* This fact is the reason why "temperature" term is meant as the value of *T* of the last stage of freezing. At the same time, temperature of the beginning of freezing of each frozen ground $T_{freezing}$ depends on: the initial temperature $T_{initial}$; level of salinity (C, %); wetness (*W*,%).

If one would neglect the percentage of water, which is in the form of vapour (this percentage is equal to thousandth of one percent from the total volume of water), then it is possible to state (schematically) that water in the liquid phase is contained in the soil ground in two main states: in the localised state and in the free state of water.

Under the influence of static loads, the localised high-density water (up to 1,200-1,400 kg/m^3) does not become compact practically. This water occupies up to 40 per cent and more from the total volume of water. Gradient of movement of this water: in the direction of influence of the relevant load, as well as in the direction of decrease in temperature *T*. Such water transforms into ice at sufficiently low temperatures of water freezing T_{water}-4-6°C.

Free water is the sum of gravitational component and capillary component. Capillary water freezes at the values of *T*, which are close to the values of temperature of freezing of the localised water. Process of transformation of the gravitational water into ice begins already at any negative temperatures *T* 0°C.

Therefore, from the point of view of the mechanics of deformation of the frozen soil ground of the certain wetness, it is possible to separate three main states of the water in the liquid form and in the solid form in this frozen soil ground:

1 – Localised high-density water with density up to 1,400 kg/m^3, which is characterised by low temperature (down to -6°C) of the water freezing and which includes both localised and free capillary water;

2 – Free gravitational water (with density at the level of 1,000 kg/m^3), which transforms into ice in the case of achievement of any negative temperatures;

3 – Ice.

It is emphasised in the article (Roman et al., 2016) that all frozen grounds are divided into solidly frozen grounds and plastic frozen grounds.

The first group includes the grounds, which are practically incompressible and coefficient of compressibility of which is as follows: $m_f < 0.01$ MPa^{-1}. The second group includes the grounds with $m_f > 0.01$ MPa^{-1} . In this case, solidly frozen grounds must be only calculated in respect of the bearing capability, while the plastic frozen grounds must be calculated both in respect of the bearing capability, and in respect of deformations.

In addition to the parameter of compressibility, as concerns the solidly frozen grounds, it is also accepted the state, when $T < T_{freezing}$. As concerns the plastic frozen grounds, temperature of the ground *T* is within the range of $T_{freezing} < T < T_{water}$, where T_{water} is the temperature of water freezing, which is close to 0 °C.

In accordance with the data of the article (Roman et al., 2016), Table 3 presents values of $T_{freezing}$ for several frozen grounds.

As it was already mentioned above, parameter $T_{freezing}$ depends on the wetness and salinity of the frozen ground.

Processing of the experimental data, which are presented in the article (Roman et al., 2016) for the salinified argilloar-

Table 3. Temperature of freezing of the frozen grounds

Name of the frozen ground	Temperature of freezing, °C
Fine sands and dust sands	-0.3
Sandy loams	-0.6
Argilloarenaceous ground	-1.0
Clay	-1.5

enaceous ground (salinified in various degree: parameter *C* changes from 0.2 up to 1.1%) within the range of changing the wetness *W* from 20% up to 50%, has made it possible to construct graphs of function $T_{freezing} = f(C)$. These graphs are presented in Figure 5, where values of C, %, are shown along the axis of abscissas and negative values of $T_{freezing}$, °C, are shown along the axis of ordinates (depending on the values of *W*,%). As we can see at this Figure, in the case of high salinity and low wetness, parameter $T_{freezing}$ is in the range of values -2.5-3, while in the case of low salinity and high wetness of the frozen ground, temperature of freezing does not fall below the values of $T_{freezing}$= -0.5. Therefore, for the soil ground with the prescribed degree of salinity, temperature of this soil ground *T* is the dominating factor of state of this soil ground, and this factor will be changed along with the depth of occurrence of the soil ground layer.

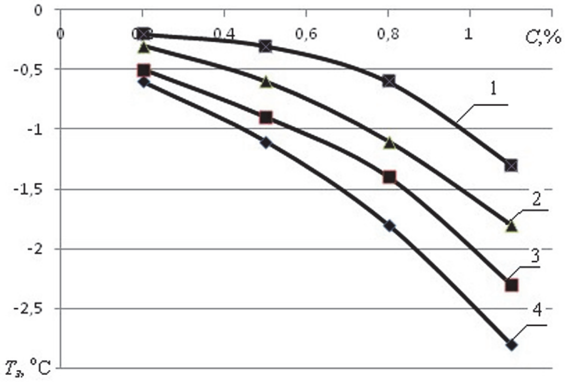

Fig. 5. Dependence of the freezing temperature from salinity of the frozen ground at the following values of wetness of this frozen ground:
***1* – 20%; *2* – 30%; *3* – 40%; *4* – 50%**

Movement/run of the yarding-and-loading system over the frozen soil ground causes cyclic static influence of stamps upon the frozen soil ground (Grigorev et al., 2018; Ivanov et al., 2018).

Following the first movement of the yarding-and-loading system(two cycles of the static influence of stamps), the wheel will go down to a certain depth, which depends on parameters of the yarding-and-loading system, on physical and mechanical properties and on the state of the frozen soil ground (Manukovsky et al., 2018; Zhuk et al., 2018).

At the same time, under action of the vertical static load P, certain part of the free water, which has achieved new depth (where temperature of the soil ground is substantially lower as compared with the temperature T on the surface), will be transformed into the solid phase, that is into ice. The localised water is almost not subject to migration and its freezing temperature is substantially below 0°C. With the certain degree of probability, the above-described process will be, in all appearances, repeated many times for the same contact patch.

The probabilistic processes of any nature (physical and mechanical, financial and economical, social and psychological, as well as other processes, which are cyclically reproducible) are properly described with the help of the apparatus of the Markov chains.

Let us assume that initial distribution of the free water, localised water, and ice in the unit volume of the frozen ground is determined by the relevant components of the vector $\vec{v}_o = (\omega_{1.}\omega_{2.}\omega_3)$, provided that $\omega_1 + \omega_2 + \omega_3 = 1$. The Markov matrix of transitional states in respect of the assigned task (to determine pressure on the ground) is the square probability matrix P_c (dimensionality of the matrix: 3×3), main diagonal of which includes probabilities $p_{11}p_{22}p_{33}$, which reflect the fact of the quantitative maintenance (expressed as percentage) of the initial state of water in all three forms of water.

Other matrix elements (namely, probabilities p_{ij}) describe probability of transformation of water from i^{-th} state to j^{-th} state and vice versa. Then, in accordance with the Markov theory, multiplication of the vector $\vec{v}_o$ by matrix P_c determines vector$_1$ that is, distribution of forms of water following the first cycle of action (movement of the first wheel pair of the yarding-and-loading system).

Let us assume that initial state is characterised by the vector $\vec{v}_o$, which is equal to:

$$\vec{v}_o = (0.3; 0.4; 0.3) \tag{5}$$

It is conceivable that in the case of utilisation of the 10-wheeled system and in the case, where pressure on the ground is equal q = 35 kPa at T = -0.2°C, matrix of transitional states P_c has the following form:

$$P_c = \begin{pmatrix} 0.80 & 015 & 0.05 \\ 0.05 & 0.90 & 0.05 \\ 0 & 0 & 1 \end{pmatrix} \tag{6}$$

Particularly, the last row of this matrix P_c means that in the course of embedding of the stamp into the frozen soil ground, ice cannot transform into the liquid phase. At the same time, we will consider probability of implementation of the reverse process (which is described by the first two rows of the matrix) as small quantity, which differs from zero and which is equal to 5% ($p_{13} = p_{23} = 0.05$; it is permissible value).

Then, multiplication of the vector (5) bymatrix (6) will give the vector of the state of water and ice following the first cycle movement, which is equal to $\vec{v}_1 = (0.26; 0.4; 0.34)$.

Multiplication of $\vec{v}_1$ by P_c will give the vector $\vec{v}_2$ of states of the following cycle of movements, etc.

Figure 6 presents graphs of changes of the component ω_i in the course of increase in quantity of cycles N.

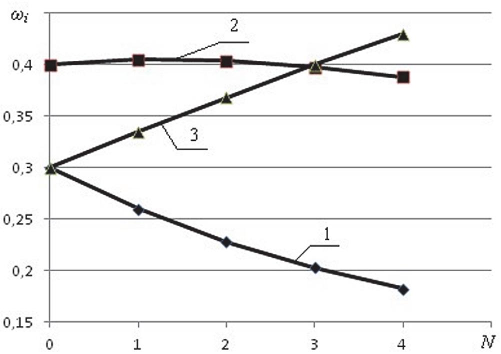

Fig .6. Change of states of water and ice along with increase in cycles of movements of the 10-wheeled yarding-and-loading system: *1* – ω_1; *2* – ω_2; *3* – ω_3

As you can see from the Figure 6, quantity of the localised water in the unit volume of the frozen soil ground even upon completion of the fourth cycle (two movements of the yarding-and-loading system) did not change practically. In this situation, very essential volume of the free water at T <0°C can be transformed into ice. This fact (taking into account substantially different deformation characteristics of water and ice) will influence upon the process of deformation and destruction of the soil ground.

Deformation properties of water and ice are substantially different. Therefore, value of E for the free water is equal to 2,030 MPa, for the high-density localised water value of $E \approx 2{,}840$ MPa, while for ice value of $E = 9{,}000$ MPa. This fact makes it possible (at the initial value of the vector of the moisture state $\vec{v}_o$) to estimate value of E as the weighted-average value, which is equal to $E_o = 4{,}445$ MPa.

Following implementation of the first cycle (due to increase of the volumetric share of ice), module of the total deformation has increased by 5.6% and it was equal to $E_o = 4{,}694$MPa.

Figure 7 presents graphs of changing coefficient of increase in the module for E both for water and for the soil ground depending on quantity of cycles N.

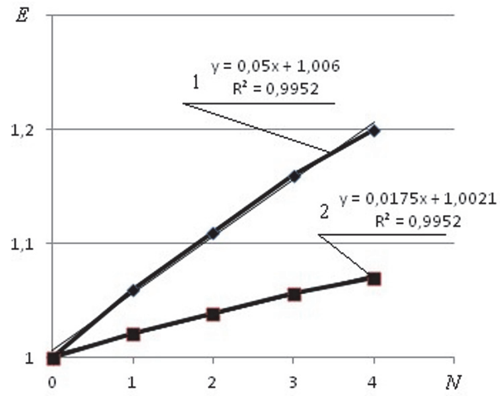

Fig. 7. Increase in the modulus of elasticity of water and modulus of elasticity of the soil ground in the course of increase in quantity of movements of the 10-wheeled yarding-and-loading system: *1* – water; *2* – soil ground

Following the fourth cycle (two movements of the system at $N = 4$), this module has achieved value of $E_o = 5{,}341$ MPa, that is, it has increased by more than 20%. If we assume that wetness W of the frozen soil ground is at the moderate level and that it is equal to 35%, then increase of the total module of deformation of the soil ground E due to increase in the volumetric content of ice will be equal to 7%. Because of parameter, ε is inversely proportional to parameter E, it is natural to conclude that total relative deformation of the frozen soil ground will be decreased by 7%.

Now let us make similar estimates in the case of utilisation of the 4-wheeled system at the pressure on the ground $q = 68$ kPa.

Assuming that there is intensification of the process of transformation of water from the liquid form into ice at such loads and that this intensification is in proportion to increase in pressure, as well as assuming that $p_{13} = p_{23} = 0.1$ in the matrix of transitional states, then results of calculations show that increase in the total module E due to increase in the volumetric content of ice will be equal to 13%.That is, the total module will be increased by 1.85 times, and this fact causes relevant decrease in value of the total deformation ε.

However, on the other hand (taking into account dependence (2)), in the case of increase of q from 35 kPa up to 68 kPa, total relative deformation ε will be increased by 1.94 times and summary increase of ε will not exceed 5% in the end.

This conclusion additionally underlines appropriateness of optimisation of parameters of influence of stamps of the yarding-and-loading system upon the frozen soil ground with the purpose of increase of quantity of movements, as well as with the purpose of assurance that environmental requirements are complied with. The methodological provisions, which were developed in this article, were the basis of the trial calculations in order to determine adequacy between the mathematical model and technological conditions of exploitation of the yarding-and-loading systems in the case of their cyclic influence upon the frozen soil ground. At this stage of investigations, certain factors were out of the framework of the performed calculations: processes of destruction of the soil ground, processes of formation of the primary nucleus of compaction, as well as processes of additional compaction within the limits of the compressible layer. These

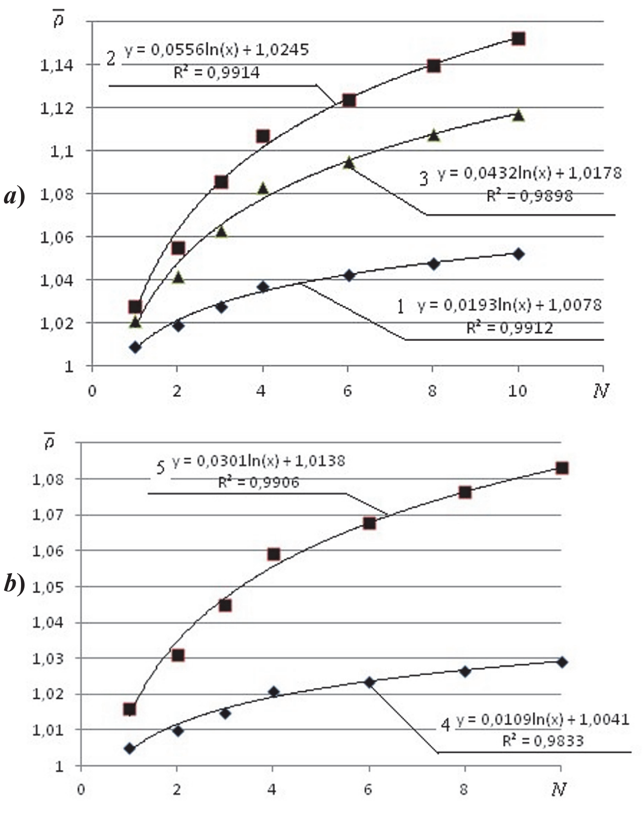

Fig. 8. Dependence of value of the relative compaction from quantity of cycles of influence of the relevant stampson the ground: *a*) thawed loamy soil; *b*) frozen loamy soil: *1* – dry soil ground, *W* = 0.15, *q* = 35 kPa; *2* –moist soil ground, *W* = 0.5, *q* = 35 kPa; *3* – moist soil ground, *W* = 0.5 and *q* = 27 kPa (utilisation of the caterpillar tracks); *4* – dry soil ground, *W* = 0.15; *5* – moist soil ground, *W* = 0.5

factors will determine increase in value $\bar{\rho}$ in the course of deepening the track and embedding the wheel into the soil ground (especially at high values of wetness and at high values of pressure of relevant stamps). In the course of increasing the depth of the track, it is also necessary to take into account the decrease in temperature T of the soil ground, increase in module E and relevant decrease in total deformations. Increase in the ice content along with depth will facilitate increase in plasticity of the deformable soil ground. Therefore, the calculations, which we have performed, must be accepted as the low boundary of the range of possible values of compaction of the cryomorphic soil grounds.

Figure 8 presents graphical dependence of $\bar{\rho}$ from N for the thawed (a) and frozen (b) argilloarenaceous ground in the case of movements of the 10-wheeled and 4-wheeled forwarders, respectively.

Figure 8a: curve 1 corresponds to the dry soil ground with $W = 0.15$ and $q = 35$ kPa; curve 2 corresponds to the moist soil ground with $W = 0.5$ and $q = 35$ kPa, curve 3–$W = 0.5$ and $q = 27$ kPa (utilisation of the caterpillar tracks).

Figure 8b at $q = 68$ kPa: curve 4 corresponds to the dry soil ground with $W = 0.15$, curve 5 corresponds to the moist soil ground with $W = 0.5$.

The presented data make it possible to assess numerically the effect of application of various systems in the specific climatic conditions and technological conditions.

Conclusion

To sum up, it is possible to accept results of the performed investigations as well as to accept certain estimates (estimates of influence of parameters of the yarding-and-loading system, estimates of temperature, wetness, ice content, physical and mechanical properties and estimates of the state of the frozen soil ground in the course of its deformation) as the initial requirements in the course of simulation and optimisation of the process of cyclic compaction of the soil ground.

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