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DETERMINING PATTERNS IN THE STRESSED-DEFORMED STATE OF THE RAILROAD TRACK SUBGRADE REINFORCED WITH TUBULAR DRAINS

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The technical condition of the railroad track subgrade has been analyzed, as well as the issues related to ensuring its strength and stability when exposed to floodwaters and when the track's sections are overmoistened during operation. As a result, it has been established that it is necessary to develop methods aimed at improving the subgrade's carrying capacity.

The georadar research has explored the problematic areas of the railroad track subgrade, based on which the distribution of subgrade heterogeneity in the vertical plane, as well as the boundaries of its location, were established. Therefore, georadar research makes it possible to detect hidden defective sites in the subgrade without disrupting its strength characteristics.

A technique has been proposed to improve the carrying capacity of the failed subgrade of a railroad track using the combined arrangement of drainage pipes in the vertical and horizontal directions in the railroad embankment. The special feature of this technique is the possibility to drain water at the different levels of surface water, which provides for an increase in the carrying capacity of the failed subgrade.

The strained-deformed state of the subgrade reinforced with tubular drainage has been investigated. The result has proven the effectiveness of the use of tubular drainages to improve the carrying capacity of the railroad track overmoistened subgrade exposed to constant and temporary loads.

This study findings have established that the deformity of the subgrade increases when using tubular drainage, though this occurs only in the initial period of its arrangement, in further operation, when it removes water from the subgrade body, the carrying capacity of the subgrade, on the contrary, will improve due to the enhanced physical and mechanical properties of soils

Keywords: subgrade, stresses, deformations, carrying capacity, drainage pipes, finite-element method

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1. Introduction

The main task in maintaining the subgrade is to ensure the serviceable condition of all its elements, prevent malfunctions, timely eliminate them, as well as eliminate the causes of malfunctions. All this is regulated by Instruction [1]. According to the normative document [2], all elements of the railroad track should, in terms of strength, stability, and condition, ensure safe and smooth movement of trains at set speeds. Consequently, all defects and damage to the subgrade and its structures should be detected in time by various diagnosing tools. Their elimination should be carried out during the current track maintenance, in the course of the planned and precautionary repairs of the upper structure of the track, as well as in the repairs and reinforcement of the subgrade.

Subgrade is the base of transportation lines, which perceives constant and temporary loads from vehicles. In addition to these loads, the subgrade is exposed to natural and climatic influences (floods, precipitation), which cause a decrease or loss of its carrying capacity.

The total length of subgrade on the railroads is 21,872.2 km while the length of the subgrade, prone to deformations, is up to 870.8 km [3].

One of the most common defects that lead to the emergence of deformations of the subgrade are defects of the main site, manifested in the form of ballast recesses and ingestions. These defects are dangerous because they indicate that the subgrade is undergoing soil overmoistening. This leads to disruption of the geometry of the rail track, reduced strength, and the loss of subgrade stability, which adversely affects the safety of movement. It should also be noted that during the floods in 2020 in the Western regions of Ukraine there was destruction and washing away of embankments of 150 m long (Fig. 1, *a*). As a result, the movement of trains for international freight transportation with the EU countries was suspended. In addition, landslides were recorded due to the movement of deep groundwater as a result of unspecified changes in the geology of rocks (Fig. 1, *b*). Due to a natural disaster at the specified location, which is located on a sloping hill, 30 m of the track was deformed.

Such destruction is inherent in the transport infrastructure around the world and is often the subject of discussion by civil engineers at scientific conferences, round tables, etc. [4].

a

b

Fig. 1. Destruction and washing out of the railroad embankment during floods: *a* – kilometer 224 along the line Zabolotiv-Vydyniv [5]; *b* – kilometer 124 along the line Lviv-Sambir-Uzhgorod [6]

To eliminate the consequences of erosion of the rail roadbed, significant financial resources are allocated. In addition, stopping the movement of trains and vehicles causes significant economic losses for the state, especially at cross-border areas.

The overmoistening of subgrade causes accelerated deterioration of the technical condition of the railroad track, loss of carrying capacity of the subgrade, which leads to an increase in the cost of maintenance of the track, including cleaning and ballast forking. Taking into consideration the negative consequences due to climate change (increasing rainfall), the need for drainage structures that provide the designed carrying capacity of the subgrade is relevant and timely for railroads.

The specified tasks require the development of new and progressive methods of rapid restoration of the capacity of the railroad track. It is likely that a more rational technique to improve the carrying capacity of the overmoistened subgrade is to eliminate the factor causing its deformations and defects, namely water drainage. Therefore, we have considered, as one of the options, the possibility of using tubular drains and estimated the carrying capacity of the subgrade when they are used in different combinations of arrangement in the body of the railroad embankment.

2. Literature review and problem statement

To date, there are many scientific works that address increasing the strength and stability of the subgrade. However, they are all aimed at the use of geotextile [7], geosynthetics [8], injection solutions [9]. It should be noted that the issue of effective withdrawal of water from the body of the subgrade remained unresolved. The practice shows that the long operation of geotextile in the structure of a railroad track adversely affects its technical condition due to the accumulation of water.

More rational methods to divert water from subgrade is the use of tubular drains, which is confirmed by research conducted on Finnish railroads [10]. It was established that the areas where drainage is arranged experience fewer disorders of track geometry and the carrying capacity of the subgrade is higher than similar areas without drains.

Paper [11] experimentally proved that drainage arrangements are effective to divert water from a contaminated railroad track ballast. However, the cited study focused only on the hydraulic behavior of drainage structures.

The authors of work [12] investigated operating conditions of atypical road structures with tubular drains under the influence of loads from rolling stock and carried out numerical studies of the strained-deformed state of the subgrade. The most effective structural-technological solution for the use of tubular drains in the road structure was determined. In addition, the authors point out that in practice drainage structures are assigned based on the experience of designers and recommendations of customers.

A study into the impact of vibration load on the drainage structure is reported in [13]. The authors conducted a series of tests using the experimental installation of a road structure, which simulated vibrations from traffic. They implied examining the operation of two types of drainage structures of shallow laying with tubular drains, showered with coarse sand and gravel filling. The experiments were conducted both with and without vibration impacts from vehicles. An analysis of the study results showed that the intensity of water drainage using a structure with tubular drains is almost not affected by vibration.

Works [14–16] assessed the carrying capacity of the reinforced sections of the railroad track using the metallic corrugated structures Multiplate MP 150 and SuperCor. The studies found that metallic corrugated structures are an alternative to restoring the capacity of problematic sections of the railroad track. However, such structures are effective in the elimination of the consequences of floods for the subgrade of the railroad track or a motor road and in restoring the carrying capacity of damaged structures [17]. However, they are economically impractical to increase the carrying capacity of the subgrade defective sites, which extend over small sections of the track.

Papers [18, 19] proved that the increase in the dynamic action of moving transport units on the subgrade occurs due to the uneven subsidence of the ballast of the railroad track. It was also proved [20] that in order to ensure the smooth operation of the track, control over the condition of its lower structure, namely the subgrade under the action of dynamic loads from the rolling stock of railroads, is required.

In studies [4, 21], numerical methods were applied to establish that the overmoistening of the subgrade leads to a decrease in its strength characteristics. Therefore, one should expect a decrease in carrying capacity and loss of stability under the action of temporary loads from vehicles.

Experimental research in work [22] found that the intensive subsidence of the lower structure of the track occurs during the initial period of its operation. It was also noted that the total subsidence of the track consists of the amount of plastic and viscosity components of the subsidence of aggregate ballast. The plastic subsidence of the ballast depends on the initial load during the operation of the track, and the viscous-plastic subsidence – on the number of load cycles encountered in the history of track operation.

Papers [4, 18–22] examine the processes of the subsidence of the ballast of the railroad track under the action of static and dynamic loads without taking into consideration the technical condition of the subgrade. In addition, none of these papers resolved the issue of increasing the carrying capacity of a heterogeneous subgrade, which is of great importance in the operation of the railroad track.

The basic document regulating the design standards of railroad subgrade is DBN V 2.3-19:2018 [23]. However, it lacks a methodology for calculating the strength and stability of subgrade reinforced with tubular drains.

Analytical methods for assessing the strength and stability of the subgrade, developed in work [24], are almost impossible to use due to the complexity of the configuration of such a structure. To date, such problems can be solved by applying the method of finite elements. This method removes all the difficulties in building a geometric model that is closest to a real object. It also makes it possible to take into consideration the physical and mechanical characteristics of the material of the railroad track elements.

Our analysis of research into increasing the carrying capacity of the railroad track subgrade reveals that all studies are mainly aimed at investigating the hydraulic behavior of drainage systems and geotextile materials. We should note that there are no studies on the assessment of the carrying capacity of the subgrade when using drainage systems.

To protect the subgrade from the destructive effects of natural factors and increase the operational reliability of the flood and defective subgrade during floods that cause the destruction of the subgrade, one option suggested is the use of tubular drains, and it is proposed to apply a georadar method to search for defective places in subgrade.

Reinforcement of the failed subgrade with tubular drains is the most technically-economically feasible technique compared to existing methods, namely board clipping, replacement of the soil layer, the arrangement of clamped berms. It should also be noted that existing methods are expensive and require a long-term stop of trains [25]. In addition, the maintenance of the subgrade reinforced with tubular drains should be performed by available crews that service the subgrade, responsible for catchment trays, wells, water pipes. Therefore, maintaining drainage structures does not require the creation or additional staffing of these crews, and, as a result, is not expensive.

3. The aim and objectives of the study

The aim of this study is to determine the stressed-strained state of the railroad track subgrade reinforced with tubular drains.

To accomplish the aim, the following tasks have been set:

– to assess the technical condition of the railroad track subgrade using a georadar method;

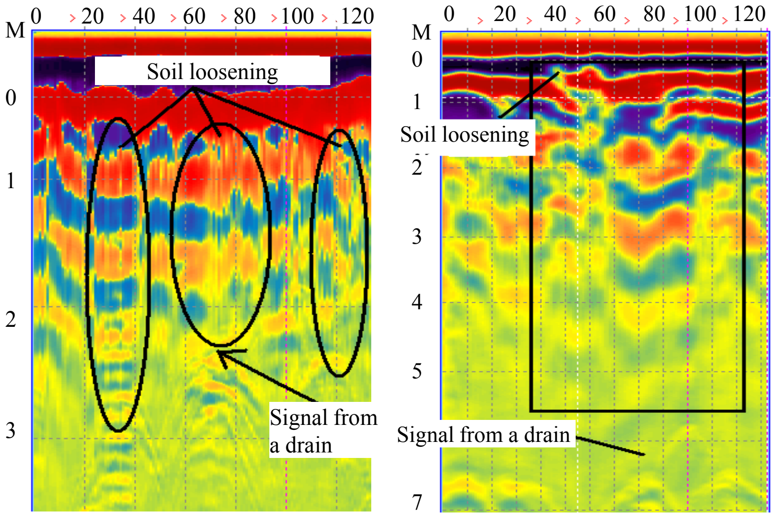
– to devise a technique to improve the carrying capacity of overmoistened subgrade and a procedure of assessing its strain-deformed state;

– to perform multivariant calculations of the stressed-deformed state of the reinforced subgrade with a different combination of the arrangement of tubular drains.

4. Assessment of the technical condition of the railroad track subgrade using a georadar method

Georadar method was used to establish the technical condition of the subgrade at the railroad line Chernivtsi Vadul Siret [26]. Transverse electromagnetic profiling of the subgrade was carried out on the left sole of the embankment (TP 1) and on the left side of the embankment (TP 2).

Our study has found that at TP 1, at a depth of 0.3 m to 3 m, there are areas of loosening the soil (Fig. 2, *a*). Also, at a depth of 2.3 m, there is a signal from the reinforced concrete pipe and, in addition, in the same place, at a depth of 0.3 m to 2.3 m, there is an area of loosening the soil over the reinforced concrete pipe. At TP 2, at the depth of the subgrade from 0.3 m to 5.6 m, there are areas of loosening the soil over the reinforced concrete pipe, there are also visible characteristic signals at a depth of 6.0 m from the reinforced concrete pipe (Fig. 2, *b*).



a *b*

Fig. 2. Radargram of transverse electromagnetic profiling: *a* – TP 1 – on the left sole of the embankment; *b* – TP 2 – on the left side of the embankment

Based on our georadar research, the areas of the heterogeneous and overmoistened subgrade were detected. Therefore, the use of the georadar method is effective in determining the technical condition of the subgrade and taking reasonable design measures to restore and enhance its carrying capacity and choose an effective place for arranging drainage pipes.

5. Results of determining the stressed-strained state of the subgrade

5. 1. Algorithm for assessing the stressed-strained state of subgrade with tubular drains

Overmoistened plots of the railroad track subgrade lead to the loss of its strength and stability. Therefore, this work proposes using tubular drains, which are embedded in the body of the subgrade in its transverse direction.

The proposed estimation scheme of the railroad track subgrade reinforced with tubular drains exposed to a transportation loading is shown in Fig. 3.

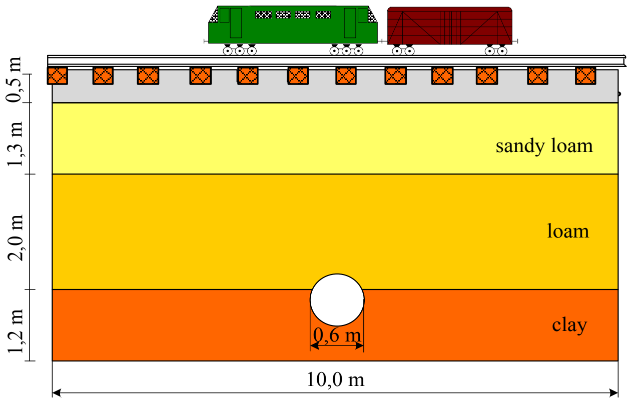


Fig. 3. Schematic of the geometric cross-section of reinforced subgrade

A fragment of the subgrade railroad track consists of three layers of soil. The thickness of the first layer, sandy loam, is 1.3 m, the second layer, loam, is 2.0 m, and the third layer, clay, is 1.2 m. The subgrade layers to a height of 4.3 m are water-saturated, with specific water weight of 10 kN/m^3. The physical and mechanical characteristics of each subgrade layer are given in Table 1.

Table 1

The physical-mechanical characteristics of soil sealing infill

Title of soil mechanical characteristic	Gravel ballast	Sandy loam	Loam	Clay
Specific weight, γ, kN/m^3	13.8	21.7	22.6	27.4
Poisson coefficient, ν	0.27	0.27	0.27	0.27
Adhesion factor c, kPa	0.1	5	13	30
Angle of internal friction, φ°	43	37	25	17
Dilatation angle, ψ°	0	1	1	2
E, MPa	150	110	28	16.4

The uniformly distributed temporary load is set by the quantity q=249.5 kN/m from the equivalent load SK 14 [27] at the load length of the influence line λ=5.0 m, and the relative position of the top of the influence line at α=0.5.

To compare the stresses arising from the action of loads from railroad transport, we calculate the strained-deformed state of the subgrade using a method of the finite-element analysis. The calculation is carried out at different quantities and combinations of the arrangement of tubular reinforced-concrete drains in the body of the subgrade. In total, four estimation schemes were created for different techniques of arranging the drainage pipes and without them. In the first version, we calculated the subgrade, which is flooded with groundwater without the arrangement of tubular drains. In the second version, one drainage pipe is installed in the body of the subgrade. The third and fourth variants imply the arrangement of two and three drainage pipes, respectively.

The subgrade is reinforced with tubular drains by the method of forcing without stopping the traffic of trains. The maximum diameter of the pipes that can be arranged by a puncture method is 600 mm [28]. In addition, these pipes are among the most industrial ones and used in the drainage of streets, roads from groundwater [29].

The depth of arranging drainage pipes depends on the level of the water-saturated layers of subgrade, which are found from the results of georadar research.

The depth of drainage pipes' arrangement is determined from the following formula

$$H_{T}=\mathrm{SE}-\mathrm{LA}-0.5, \qquad (1)$$

where SE is the subgrade embankment edge; LA is the level of the aquifer, determined from the results of georadar research; 0.5 is the distance to the top of the drainage pipe from LA.

In the fourth version, one of the drainage pipes is arranged below (Fig. 4, *d*), compared to the two adjacent ones, which is due to the accumulation of the water-saturated heterogeneous subgrade soil, which is evident from the results of the georadar research (Fig. 2).

It should be noted that the number of drainage pipes in the body of the subgrade is calculated depending on the flow rate of water that should be passed during spring floods. The layout of their arrangement in the body of the subgrade depends on the peculiarities of water-saturated layers of subgrade.

In order to choose the optimal scheme for the arrangement of tubular drains in the subgrade, a multivariant assessment of the strained-deformed state of the subgrade was carried out depending on the number of drainage pipes and the scheme of their arrangement.

We calculated the strained-deformed state of the reinforced subgrade in a nonlinear statement using an elastic-plastic Mohr-Coulomb model [30, 31].

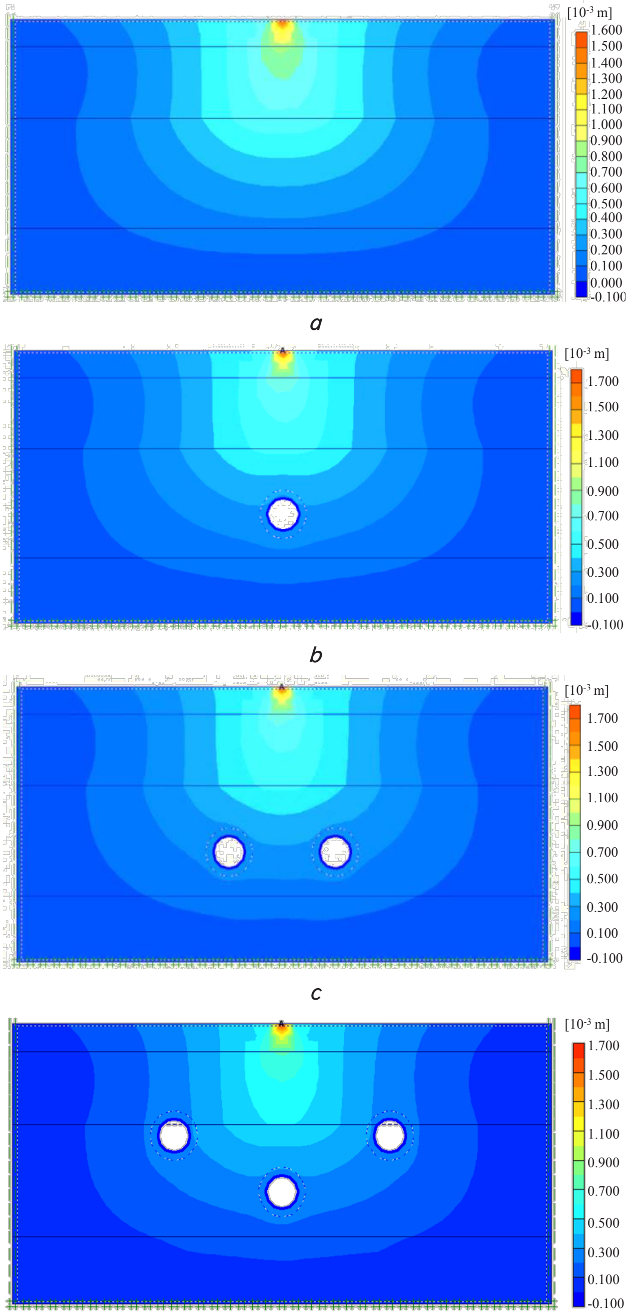
The soil array was simulated by fifteen-node finite elements [32] with the predefined physical and mechanical characteristics of each layer of soil, given in Table 1.

Drainage pipes were assigned the following physical and mechanical parameters: the Young modulus, $3.6\cdot10^4$ MPa; Poisson coefficient, 0.3. In all variants, the diameter of drainage pipes is 600 mm.

When calculating the stressed-deformed state of reinforced subgrade, the following boundary conditions were set: on the sides of the estimated model, the movements in the horizontal direction are restricted; at the bottom – the vertical and horizontal movements are restricted.

5. 2. Results from the multivariant calculations of the stressed-strained state of the reinforced subgrade with a different combination of the arrangement of tubular drains

The results of calculating the subgrade's deformed state for different variants of the arrangement of tubular drains in the railroad track subgrade are shown in Fig. 5.



a

b

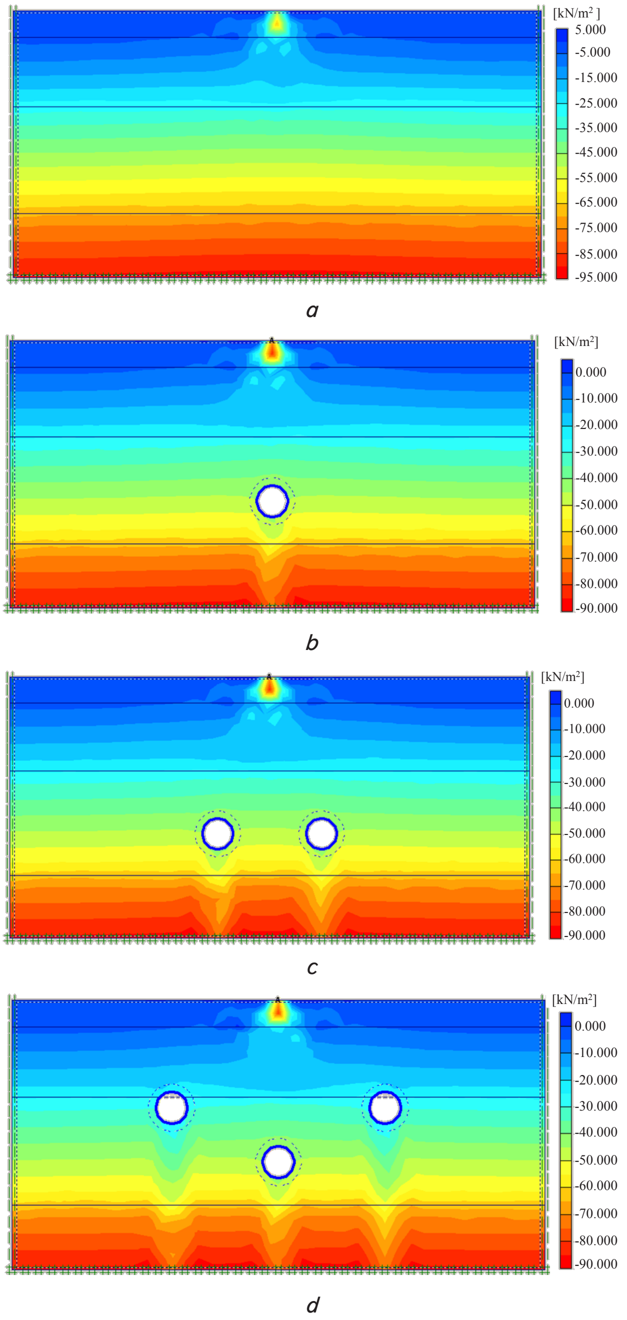
c

d

Fig. 4. The distribution of deformations in the subgrade for the following variants: *a* – without drainage; *b* – one drainage pipe; *c* – two drainage pipes; *d* – three drainage pipes

Fig. 4 shows that the maximum vertical deformations that occur in the subgrade without tubular drains are 1.54 mm. When arranging tubular drains in the subgrade body, the maximum deformations are: 1.77 mm – for a single drainage pipe; 1.75 mm – for two drainage pipes; 1.66 mm – for three drainage pipes.

The results of calculating the stresses that occur in the subgrade are shown in Fig. 5.



a

b

c

d

Fig. 5. The distribution of stresses in the subgrade for the following variants: *a* – without drainage; *b* – for a single drainage pipe; *c* – for two drainage pipes; *d* – for three drainage pipes

Fig. 5 shows that the maximum stresses that occur in the subgrade without the arrangement of tubular drains are 92.28 kPa. When arranging tubular drains, there are stresses of 88.97 kPa – for a single tubular drain, 89.40 kPa – for two tubular drains, and 89.58 kPa – for three tubular drains.

The results of multivariant calculations of the strained-deformed state of the reinforced subgrade are given in Table 2.

Table 2

The strained-deformed state of the railroad track subgrade

Reinforcement variant	Number of drainage pipes	Strains in subgrade, kPa	Vertical deformations in subgrade, mm	Difference in percentage	
				Strains	Deformations
1	–	92.28	1.54	–	–
2	One	88.97	1.77	–3.65 %	14.93 %
3	Two	89.40	1.75	–3.12 %	13.63 %
4	Three	89.58	1.66	–2.92 %	7.79 %

The results of calculating the strained-deformed state of the subgrade (Fig. 4, 5, Table 2) demonstrate that the use of tubular drains leads to the increased deformity of the railroad track subgrade. Namely, by 14.93 % when arranging one pipe, by 13.63 % – two, and by 7.79 % when arranging three drainage pipes. However, the stresses in the subgrade on the contrary decrease. In the case of arranging a single drainage pipe, relative to the stresses without drainage pipes, they decreased by 3.65 %; when arranging two pipes, by 3.12 %; in the case of arranging three drainage pipes, the stresses decreased by 2.92 %.

The results of comparing the deformations and stresses of the subgrade depending on the variant of reinforcement with tubular drains are shown in Fig. 6.

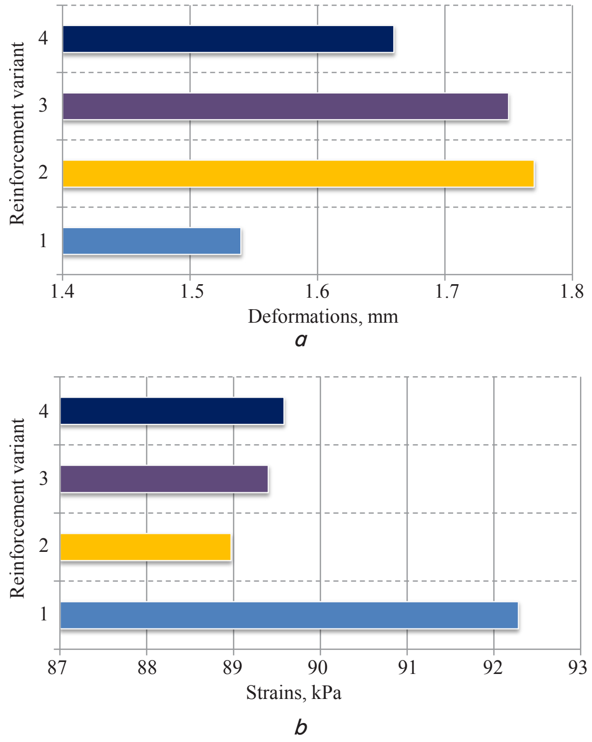


Fig. 6. Comparing the results of the stressed-strained state of the subgrade: *a* – deformations; *b* – stresses

The results of determining the deformations (Fig. 6, *a*) demonstrate that the smallest deformations occur when reinforcing the subgrade with three drainage pipes, and they are 1.66 mm. And the largest ones occur when reinforced with a single pipe, and are 1.77 mm.

The maximum stresses in the subgrade occur when it is reinforced with three drainage pipes, and the smallest ones – when reinforced with one pipe, and are 89.58 kPa and 88.97 kPa, respectively.

6. Discussion of results of assessing the stressed-strained state of the subgrade with tubular drains

Our study shows that the amount of the concentration of the deformation distribution zone in the subgrade depends on the estimation scheme of arranging the drainage pipes. In the case of calculating the deformations of subgrade without drainage pipes, the distribution zone of larger deformations occupies a larger area. Further, when using tubular drains, the distribution zone of such deformations extends to a smaller area of the subgrade. This effect is due that a significant share of loads is perceived by a reinforced-concrete pipe.

The use of tubular drains increases the deformity of the subgrade as opposed to subgrade without drainage, by 14.93 % (Fig. 4). However, analyzing the distribution of stresses, shown in Fig. 5, we note some differences. That is, it can be stated that the amount of stresses that occur in the body of the subgrade are higher than the stresses that arise in the body of the subgrade, which houses a drainage pipe. The stress difference is up to 3.65 %.

Thus, as we can see it, the compromise result is as follows: on the one hand, the deformity of the subgrade increases (Fig. 6, *a*) when using tubular drains, but this is true only in the initial period of their arrangement. However, during operation, tubular drains remove water from the subgrade, which leads to its increased strength and stability. In addition, as shown by the calculation of the distribution of stress in the subgrade when using tubular drains, they decrease up to 4 % compared to the option without the use of tubular drains (Fig. 6, *a*). It also has a positive effect on increasing the carrying capacity of the subgrade.

The results of our study into the stressed-strained state of the subgrade (Table 2, Fig. 6) prove the effectiveness of the use of tubular drains. Therefore, it is recommended to apply them in order to improve the strength of the railroad track subgrade, which could reduce the disorder in the track geometry and improve the safety of trains.

This research has established that the scheme of drainage arrangement does not significantly affect the strained-deformed state of the railroad track subgrade (Table 2, Fig. 6). Therefore, the effective choice of the option for arranging a drainage reinforced-concrete pipe in the railroad track subgrade should be an economically justified solution because technically the number of pipes depends only on the maximum flow rate of water, which must be passed by a drainage pipe. The results of calculating the strained-deformed state of the subgrade reinforced with tubular drains are confirmed by the convergence with the results of calculating the stresses and deformations obtained by the method of finite elements and an iterative method in works [12, 27, 31].

7. Conclusions

1. The technical condition of the subgrade can be assessed by a georadar method, which makes it possible to carry out its effective diagnosing with the detection of hidden defects and, accordingly, to prevent the occurrence of emergencies. A given method makes it possible to perform research without

stopping the movement of transport units and perform operations in a short time.

2. To increase the carrying capacity of the problematic plots in the subgrade, a structural scheme of its reinforcement with tubular drains in its transverse direction has been proposed. The number of drainage pipes and the technique of arranging them in the body of the subgrade depends on the hydraulic parameters of the road section. The maximum diameter of drainage pipes should equal 600 mm when arranged by a puncturing method.

When assessing the stressed-deformed state of the reinforced subgrade, the most correct method is a finite-element simulation.

3. Our multivariant calculations of the strained-deformed state of the reinforced subgrade have established that tubular drains increase the deformity of the subgrade by 14.93 % when arranging one pipe, by 13.63 % – two pipes, and by 7.79 % – three drainage pipes, relative to the results of calculating the subgrade without arranging tubular drains.

The stresses that occur in the body of the subgrade without tubular drains are higher than the stresses that occur in the body of the subgrade that hosts drainage pipes. The stress difference is up to 3.65 % when arranging one pipe, 3.12 % – two, and 2.92 % – three drainage pipes, which proves the effectiveness of the use of tubular drains with a diameter of 600 mm to reinforce the overmoistened railroad track subgrade.

It was established that the scheme of arranging drainage pipes in the transverse direction of the subgrade does not significantly affect its strained-deformed state. Therefore, when selecting the variant of arranging drainage pipes, one must be guided by the technical-economic feasibility of using the drainage pipes whose number depends on the flow rate of water passing through the drainage pipe.

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