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## FINITE-ELEMENT ANALYSIS OF STRENGTHENING THE SUBGRADE ON THE BASIS OF BORING AND MIXING TECHNOLOGY

**Summary.** One of the effective techniques to strengthen the subgrade is boring and mixing technology, which is based on the immersion of vertical elements – piles into the subgrade. This method of strengthening significantly affects the stress state of the track superstructure. Two options of the placement of strengthening elements are examined in this paper. To determine the influence of position of strengthening elements on the stress state of the track superstructure, appropriate finite-element models were created. The models fully reflect the geometric and deformation characteristics of a real subgrade, which is strengthened by piles. The calculated stress state of the track superstructure is shown and analyzed in this paper. The main contribution of the paper lies in optimization of the geometric parameters of the technology to reduce the stress state of the "track superstructure–subgrade–soil basement" system. The results show that the location of piles near the rails is more effective than the location of piles near the ballast section.

### 1. INTRODUCTION

The railway, as the most important part of the transport infrastructure, must meet the highest criteria of strength, stability, reliability and durability. There is no doubt that the general parameters of the "track superstructure–subgrade–soil basement" system consist of the values of the subsystems. Therefore, this system, which ensures the normal operation of the railway and is characterized by a high level of carrying capacity, should be considered in parts, analyzing each of them as a subsystem.

The determining impact in this system is the trainload, which, with varying intensity, affects the subsystems of this system, considered in this article. The greatest impact is observed in the zone of the track superstructure, smaller values of stresses from the action of a train in the subgrade and damping in the soil basement [1]. However, the basement should not be excluded as the least loaded subsystem – there are cases of such deformation values of the sub-soil, which contribute the largest proportion of the stress state of the system than the subgrade or the track superstructure.

In the general case, the analysis of the system should begin with the determination of trainload, which is characterized by dynamic effects caused by the design of the locomotive and cars [2-3]. Different types of modeling, in particular, physical and simulative, allow us to ascertain the impact from train load [4-6], which, in our particular case, is considered quasi-static and stable.

It should also be noted that the analysis of the stress state of the subgrade depends (in addition to the train load impact) on a range of factors. The main factors are the impact of the track irregularities [7] and the wheel profile [8-9], clogging of ballast during the operation [10], the impact of a climatic zone,

temperature, humidity, [11-12], various initial defects of parts in the "track superstructure–subgrade–soil basement" system, etc. [13].

Various methods of a subgrade strengthening are used to increase the resistance of the subsoil to adverse effects. Among them, boring and mixing technology has recently become widespread [14-16]. This method is in principle similar to the jet-grouting technology. Both technologies are based on the injection of cement mortar under pressure into the subgrade, where it is mixed with soil. The main difference between boring and mixing technology from jet grouting [15] is in the pressure values. The first uses a pressure of about 0.1 MPa; the second technology uses pressure from ten to one hundred times higher. Both technologies allow to create piles with a length from 2 to 15 m and a diameter of 300 up to 1000 mm. On railway transport, the implementation of boring and mixing technology is performed by placing a working body on the railway flat wagons [17]. The subgrade strengthening works could be carried out from several positions. Drilling can be performed near the rail, near the sleeper end or on the slope of the subgrade.

## 2. ANALYSIS OF THE PROBLEM AND THE METHOD TO SOLVE IT

Due to many reasons (wetting of the fill by atmospheric precipitation, insufficient measures to remove moisture in the subgrade, etc.), defects and deformations occur in the subgrade under the action of train load [1, 17, 18]. This is manifested in the wash-out of fill, development of cracks on the shoulder/roadside and along the track, depression of the track superstructure, etc. (Fig. 1).

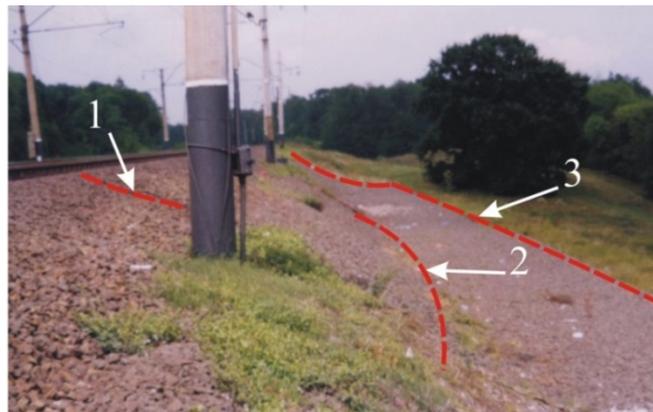


Fig. 1. Deformations of the subgrade: 1 – crack on the shoulder/roadside, 2 – crack along the track, and 3 – wash-out of fill

Typical defects for the main site of the subgrade are ballast lanks, sacks, holes and beds. The most characteristic deformations occur due to overwetting of subsoils, poor condition of the ballast section, insufficient ballast thickness, the presence of weak soil on the main site, incorrect location of subsoils in the body of the fill and unsatisfactory current track maintenance on weak areas for a long time [1]. They lead to distortion of the cross-section in the subgrade, bending of electricity poles, speed limits on the section and emergency situations (Fig. 2).

The subgrade gradually loses strength when interacting with the track superstructure and train load. There may be cases when the maintenance of the track is insufficient and impractical, and it is difficult to create a new subgrade. Then, measures should be taken to strengthen the subgrade.

Physical modeling is an important part of the research that provides possibilities to correct theoretical foundations. A number of methods exist for solving the problem of strengthening of the subgrade in transport [17-21], one of which is strengthening the subgrade by various methods, which significantly affects the stress state of the track superstructure.

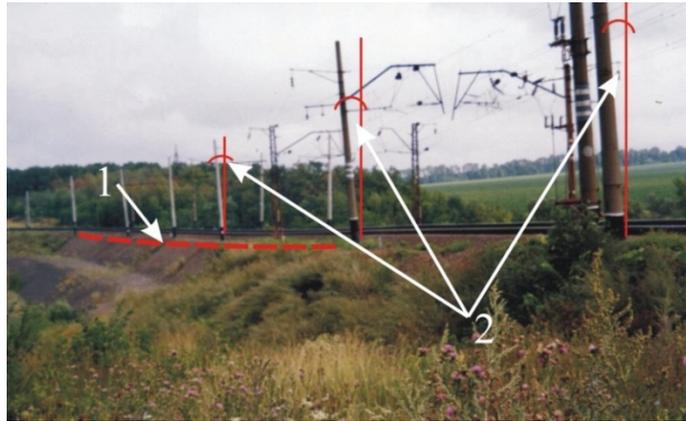


Fig. 2. Depression of the subgrade: 1 – curvature of the cross-section of the subgrade and 2 – the bending of electricity supply poles

One of the effective techniques to strengthen the subgrade [14-18] is boring and mixing technology [15, 16], which is based on the immersion of vertical elements into the subgrade. They are created using specialized equipment (monitor or chisel) attached to the drilling rod – a mechanical–hydraulic device that rotates and destroys the subsoil of the subgrade. This method involves the use of energy from water or emanating from the monitor nozzle or chisel in the form of a jet of pressure water. After the hardening of a mortar soil-cement is formed.

The works begin with the supply of the monitor to the surface of the subgrade (Fig. 3, stage 1).

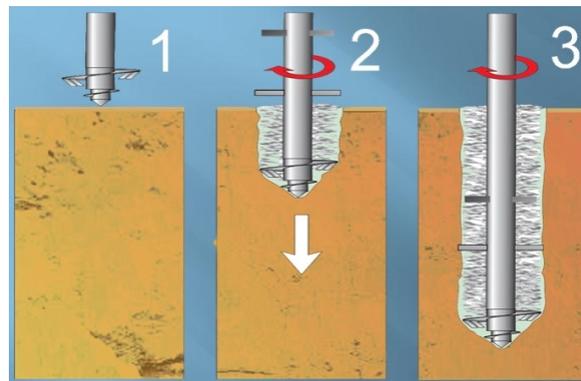


Fig. 3. Stages of boring and mixing technology

After that, the monitor is vertically immersed in the soil of the subgrade with its simultaneous destruction (Fig. 3, stage 2). Air, water and cement mortar are pumped into the soil through the nozzles in the monitor or chisels from the sides under pressure; also, the monitor rotates (Fig. 3, stage 3). When lifting the drilling rod, which is mounted on the chassis and on which the monitor is placed, a horizontally directed jet is turned on, which washes away the subsoil around the well. After removing the device, in the subgrade from the soil-cement mortar, a pile is formed – a vertical cylindrical body filled with a hardening material. It has greater deformation and strength properties than the subsoil of the subgrade. The presence of such piles in the subgrade increases its strength and reduces the deformation property.

This technology is suitable for strengthening the subsoil basement on railways. Due to the connection with the existing railway track elements, it needs a detailed technical analysis that consists of determining the geometric parameters that provide the most effective reduction of the stress state "track superstructure–subgrade–soil basement" system.

### 3. FINITE-ELEMENT ANALYSIS OF STRENGTHENING THE SUBGRADE

To properly operate the subgrade, increase the load capacity of subsoils, protect them from low temperatures and moisture, ensure the stability of the "track superstructure–subgrade–soil basement" system in general, authors have developed the basic subgrade designs. They do not require strengthening during construction, but during operation, already noted defects and deformations arise in them.

Based on the need to ensure the reliability of the construction of the subgrade for a single-track section, several main types in the installation of the main site of the subgrade are provided. These types envisage a constructive solution based on specific conditions: the type of subsoil of a base, the type of subsoil of the subgrade, climatic conditions of the railway operation, load intensity and so on.

The geometry of the finite-element model is based on the cross-section of the single-track section, which is the most common (Fig. 4). For research, the authors propose two options for strengthening the single-track section: Option 1 – piles are placed near a rail (Fig. 4a) and Option 2 – piles are placed near the ballast section (Fig. 4b).

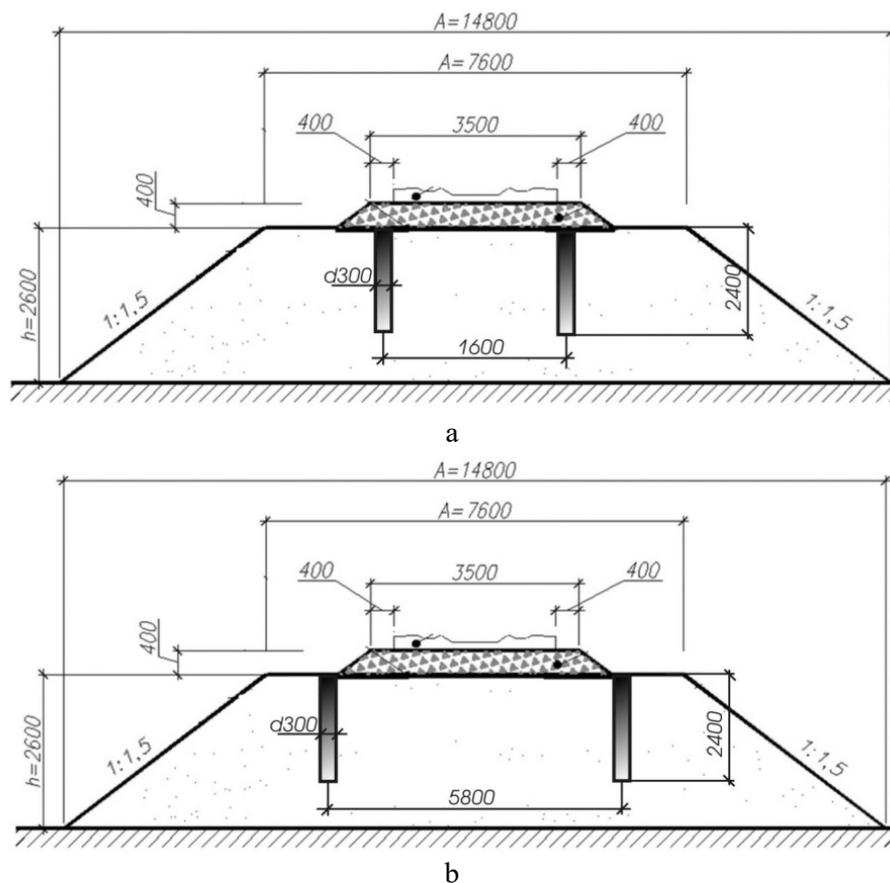


Fig. 4. Cross-section of the subgrade and the track structure for a single-track section: a) Option 1 and b) Option 2

The distance between centers of piles in the longitudinal direction is 0.75 m. This distance is determined by the distance of the sleepers. It allows the placement of a drilling rod between sleepers and application of boring and mixing technology directly from the track without the necessity of removal of rails and sleepers. Various longitudinal distances of piles could be used, but in this case, the subgrade reinforcement process will require removal of a sleeper lattice. Therefore, the distance of 0.75 m is used in this study and recommended by authors.

To determine the influence of the subgrade strengthening on the stress state of the track superstructure, two finite-element models were constructed using a professional complex SCAD. They correspond to the strengthening of the subgrade by soil-cement piles: Option 1 (Fig. 5a) and Option 2 (Fig. 5b).

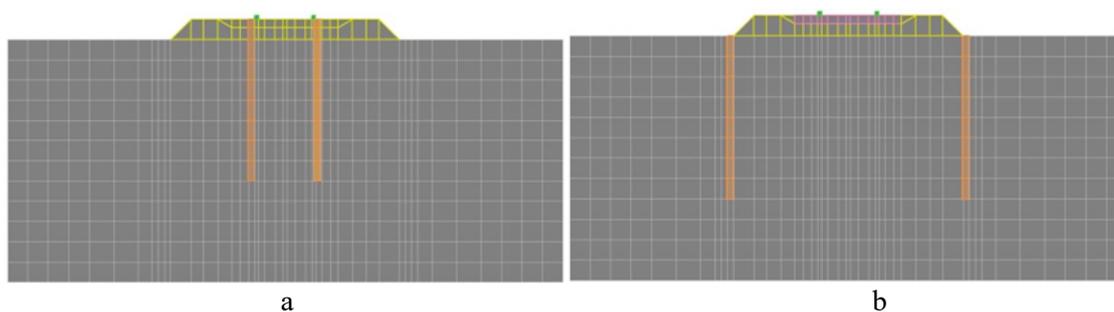


Fig. 5. Finite-element models of the subgrade: a) Option 1 and b) Option 2

The models fully reflect the geometric and deformation characteristics of a real subgrade that is strengthened by piles. The deformation characteristics of steel rails, reinforced concrete of sleepers, soil of the subgrade, crushed stone of ballast and soil-cement material of piles are represented by finite elements with corresponding properties.

The total number of model nodes is 28 203 pcs. (about 85 thousand degrees of freedom; the task is considered to be large-sized), the number of finite elements is 31 572 pcs. The finite elements in the model are accepted as compatible ones, that is, all nodes of neighboring elements coincide, which positively affects the accuracy of the solution. The final elements of the “prism” and “tetrahedron” types were taken from the SCAD complex library. These are isoparametric elements with a maximum size of  $0.2 \times 0.2 \times 0.2$  m (there are elements with a size of  $0.25 \times 0.25 \times 0.25$  m, not more than 5... 7% of the total number of finite elements in the model). Model dimensions: the length (base) is 40.6 m, the width is 1.64 m and the height is 11.1 m (2.6 m of which is the height of the subgrade). The finite elements of the model were conferred the corresponding stress–strain properties (Table 1).

Boundary conditions are imposed on the model: below is the ban in displacement along all three axes  $x$ ,  $y$  and  $z$ , on the sides of the base is the ban on  $x$  and  $y$  axes and on the transverse sides of the model is the ban on the  $y$  axis (flat deformation condition). The top and slopes of the model are free from boundary conditions. The train was considered as an isolated static vertical load; the axle load was assumed to be equal to the normative load of a train  $P=230.5$  kN per axle. The static load was applied as a point contact to the finite-element node that simulates the rail.

For the two finite-element models, the stress state of the track superstructure was calculated along the  $x$  (horizontal) and  $z$  (vertical) axes in the place of a sleeper and in the place between sleepers. The results of the calculations are presented in Figs. 6-9.

Table 1

Stress–strain properties of finite elements of the model

Model element name	Modulus of elasticity $E$ , kPa	Poisson's ratio	Specific gravity $\gamma$ , kN/m <sup>3</sup>
Loam (basis of the subgrade)	$25 \cdot 10^3$	0.3	19.0
Ballast (crushed stone)	$15 \cdot 10^4$	0.2	22.0
Rail (steel)	$2.1 \cdot 10^8$	0.3	77.0
Pile (soil-cement material)	$2 \cdot 10^5$	0.2	23.0
Sleeper (reinforced concrete)	$4 \cdot 10^7$	0.2	25.0

The distribution patterns of vertical normal stresses (Fig. 6–7) in the rail reach  $-21795 \dots -7979$  kPa and  $-26262 \dots -5842$  kPa (load in the place of a sleeper) and  $-26728 \dots -7650$  kPa and  $-35946 \dots -7676$  kPa (load in the place between sleepers) according to Options 1 and 2. The distribution patterns of vertical normal stresses (Fig. 6–7) in the ballast section reach  $-3411 \dots -4031$  kPa and  $-1549 \dots -3289$  kPa according to Options 1 and 2, which is significantly less than the strength of the ballast material.

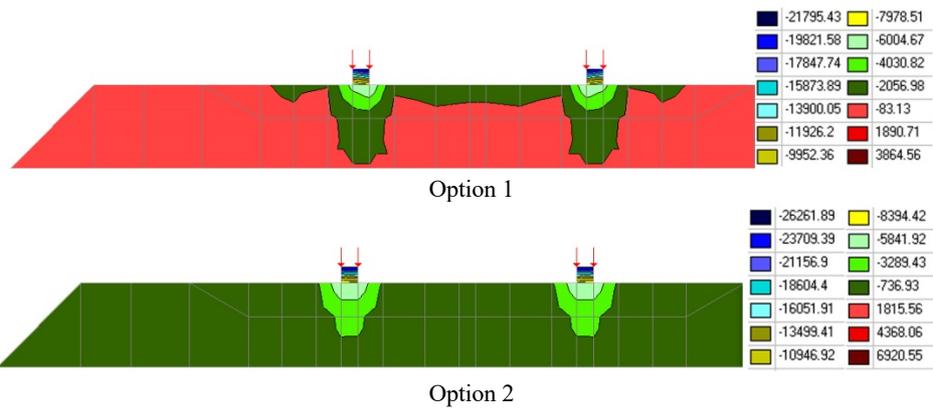


Fig. 6. Isolines and isofields of vertical normal stresses in the fragment of models (ballast, load in the place of a sleeper)

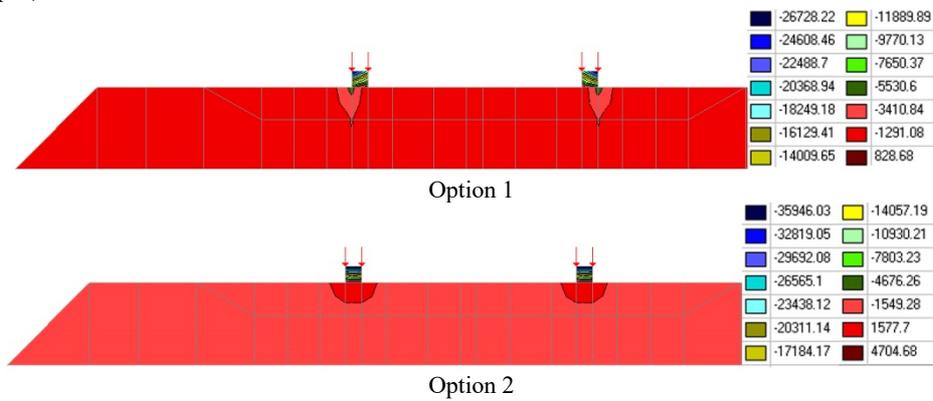


Fig. 7. Isolines and isofields of vertical normal stresses in the fragment of models (ballast, load in the place between sleepers)

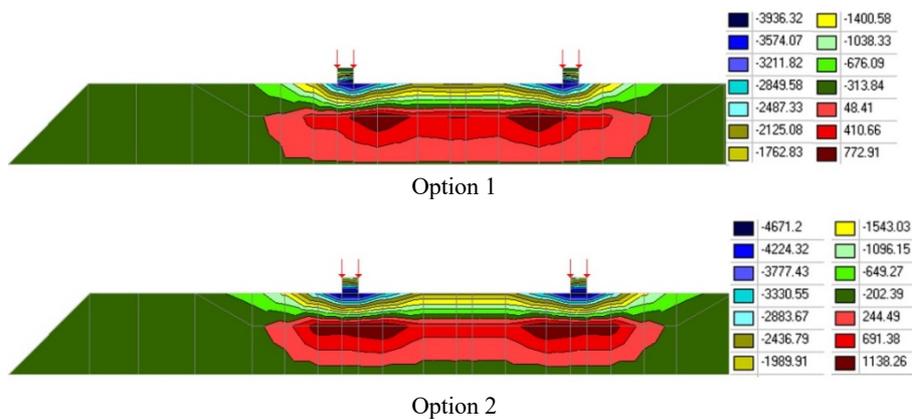


Fig. 8. Isolines and isofields of horizontal normal stresses in the fragment of models (ballast, load in the place of a sleeper)

The distribution of normal horizontal stresses for the two options is radically different both qualitatively and quantitatively (Fig. 10-11).

The value of the maximum horizontal stresses for Option 1 is -65.3 kPa at the sleeper point and -21.4 kPa at the point between sleepers. For Option 2 is the value of the maximum horizontal stresses -68.8 kPa at the sleeper point and -27.7 kPa at the point between sleepers. That is, options differ slightly in the efficiency of reducing horizontal stresses. The maximum horizontal stress values in both options, which are in the range of -65.3 ... -68.8 kPa, are in the vertical elements and the minimum values (-21.4 ... -27.7 kPa) are in the area of the ballast under the sleeper.

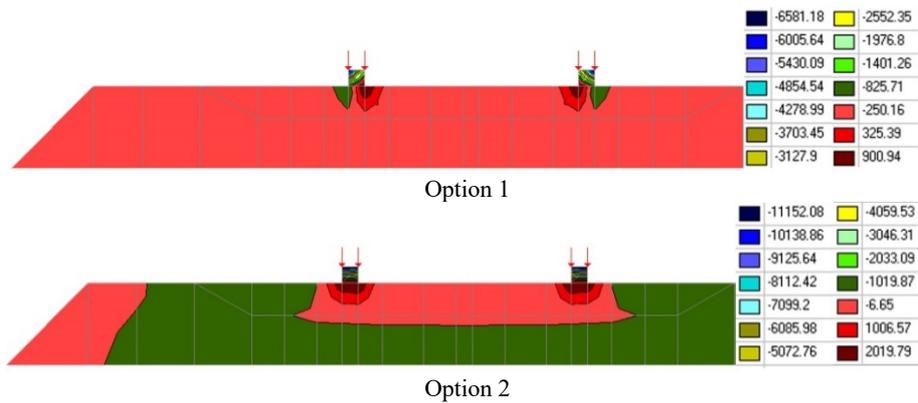


Fig. 9. Isolines and isofields of horizontal normal stresses in the fragment of models (ballast, load in the place between sleepers)

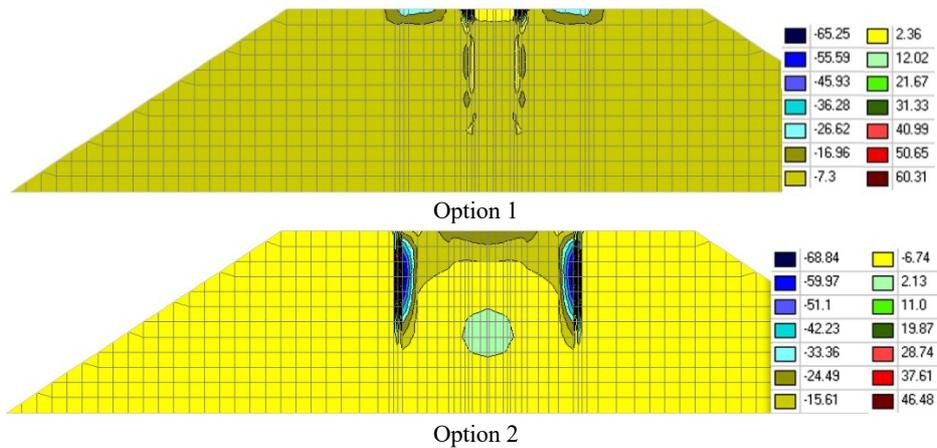


Fig. 10. Isolines and isofields of horizontal normal stresses in the fragment of models (track superstructure, load in the place of a sleeper)

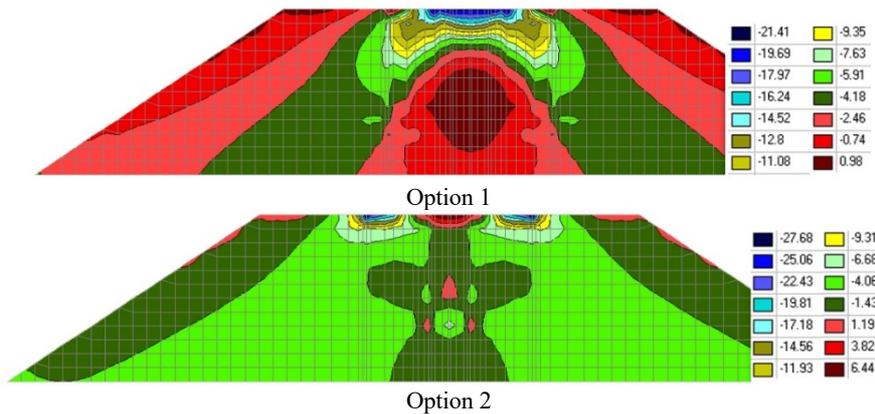


Fig. 11. Isolines and isofields of horizontal normal stresses in the fragment of models (track superstructure, load in the place between sleepers)

#### 4. CONCLUSIONS

The finite-element analysis of the strengthening the subgrade on the basis of boring and mixing technology made it possible to draw the following conclusions:

1. The relationship between the deformation properties in the subsoil of the subgrade and soil-cement varies within two orders of magnitude. Thus, there is a kind of reinforcement of the subgrade that is less deformed than the subsoil from which it is built.
2. The system of soil-cement piles, which is analyzed in the finite-element analysis, introduces a significant positive fluctuation in the "track superstructure–the subgrade" system. This is expressed in the significant heterogeneity of the stress state around the piles, which has a significant impact on the train load.
3. After analyzing the obtained results, a more effective (from the stress state viewpoint) location of the subgrade strengthening piles was chosen. This is Option 1 (piles are located near the rail). As the next step in future work, the influence of such subgrade strengthening on the characteristics of the train load will be investigated.
4. Having determined the most effective option of strengthening, its technological development should be carried out in the future, taking into account the peculiarities of construction and reconstruction of railway lines. Boring and mixing technology is generally developed in great detail, but its application to strengthen the subgrade requires new design solutions. It can be noted that the options of strengthening considered in the paper require the development of a railway platform that would allow the placement of the desired device and contribute toward strengthening of the subgrade.

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