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COMPLEX ANALYSIS OF SUBGRADE STRESS-STRAIN STATE WITH COMBINED STRENGTHENING

The paper highlights combined techniques of strengthening that include geotextile laying as well as other related advanced technologies. Subgrade construction analysis and its modification, reinforced with the different types and options of combined strengthening were conducted. To justify strengthening of subgrade a series of numerical calculations were made. Simulation with software package SCAD has confirmed the experimental results. From obtained results one can conclude that minimum horizontal displacements are observed in the version with deepening of geotextile at 1m and vertical ones at 0.4 m. Based on simulation results it is possible to make recommendations concerning modernization of existing subgrade and construction of new one in complex engineering-geological conditions.

***Keywords**: subgrade; combined strengthening; geotextile; stress-strain state*

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КОМПЛЕКСНИЙ АНАЛІЗ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ЗЕМЛЯНОГО ПОЛОТНА З КОМБІНОВАНИМ ПІДСИЛЕННЯМ

Розглянуто комбіновані способи підсилення, які включають в себе не тільки укладання геотекстилю, а й інші супутні прогресивні технології. Проведено аналіз конструкції земляного полотна та його модифікації, укріплені різними типами і варіантами комбінованого підсилення. Для обґрунтування підсилення земляного полотна проведено серію чисельних розрахунків. Моделювання в програмному комплексі SCAD підтвердило результати експериментальних досліджень. З отриманих результатів слідує, що мінімальні горизонтальні переміщення у варіанті з заглибленням геотекстилю на 1 м, а вертикальні – на 0,4 м. На підставі одержаних результатів моделювання можливо надати рекомендації щодо модернізації існуючого та будівництва нового земляного полотна у складних інженерно-геологічних умовах.

***Ключові слова**: земляне полотно, комбіноване підсилення, геотекстиль, напружено-деформований стан.*

Introduction. Nowadays construction volumes of railway tracks are significantly increased as well as the repair and reconstruction of the subgrade, including for the introduction of high-speed traffic. In addition, taking into account the development in the field of construction technologies, it should introduce new technical solutions to reduce the strain of subgrade and, accordingly, increase the period of its operation.

According to state target-oriented programs and programs for high-speed implementation on railways major objectives are crucial improvement the technical level of railway infrastructure, production organization of high-speed rolling stock and other railway equipment as well as development of new materials and technologies [1 – 2].

Placement of artificial substructures in complex engineering-geological conditions let reduce construction costs, prevent possible emergence of strains as a result of uneven subsidences and increase service life.

To justify strengthening of subgrade series of numerical calculations was conducted. Optimal characteristics provide the highest stability, strength and stability that are associated with the general stress-strain state (SSS). Calculation of stress-strain state for constructions was conducted using the finite element method with the help of software package Structure CAD for Windows, v.7.31 R.4 (SCAD).

Analysis of recent sources of research and publications. A great number of studies are devoted to strengthening of subgrade, in particular [2 – 5]. Theoretical questions of subgrade reinforcement with geosynthetics make up the major part of research in this field [6]. However, less attention is focused on determining the optimal option of strengthening in accordance with their impact on the stress-strain state. Prior research have their shortcomings –unsufficient consideration of combined action «soil-reinforcing net» and the use of geosynthetics that are no longer applied [7 – 8].

Highlighting of unsolved before aspects of the common task. Insufficient knowledge about mechanics of the process, lack of specific parameters for usage in various particular engineering-geological conditions, uncertainty of the design methods and so on hinder to widespread introduction of the combined strengthening on the rail transport. Comparison of various technologies integration for strengthening allows making an assumption about possibility of using the different technologies and comprehensive strengthening to enhance the subgrade in different engineering-geological conditions.

Formulation of the objective. Unreinforced subgrade without protective layer is applied in conditions when its construction is structured from noncohesive drainage soil of sufficient bearing capacity, excluding frost-heaving process and having strain modulus at least of 40 MPa (Fig. 1). This type is a major one when overhaul work or modernization at areas where basic platform has no defects and does not require strengthening. When using the machine type RM-80 cross slope of 4 ... 5 ‰ is prepared in one direction.

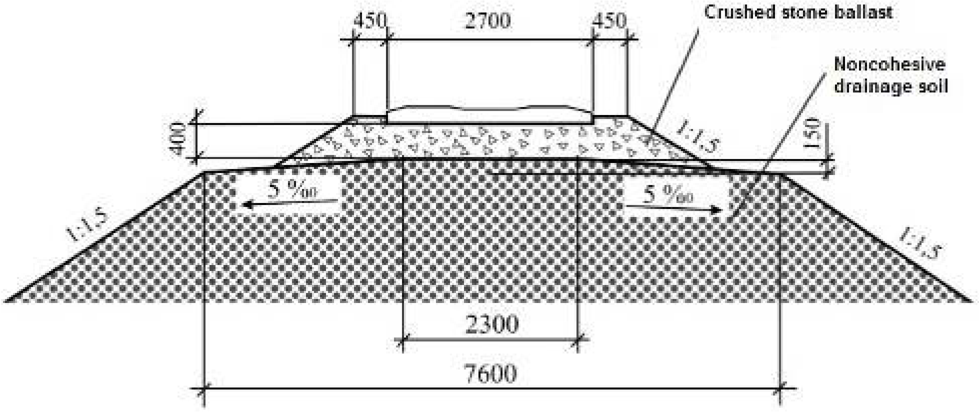

Figure 1 – Subgrade design for single track embankment

When construction repair with the removal of permanent way without the use of ballast cleaning machine, type RM-80 main platform is released from contaminated ballast, leveled by a bulldozer, inequalities are filled up with sand and subgrade is placed.

By modification of formation design (Fig. 1) the option is considered, providing the use of geosynthetics for separation of ballast and subgrade (Fig. 2).

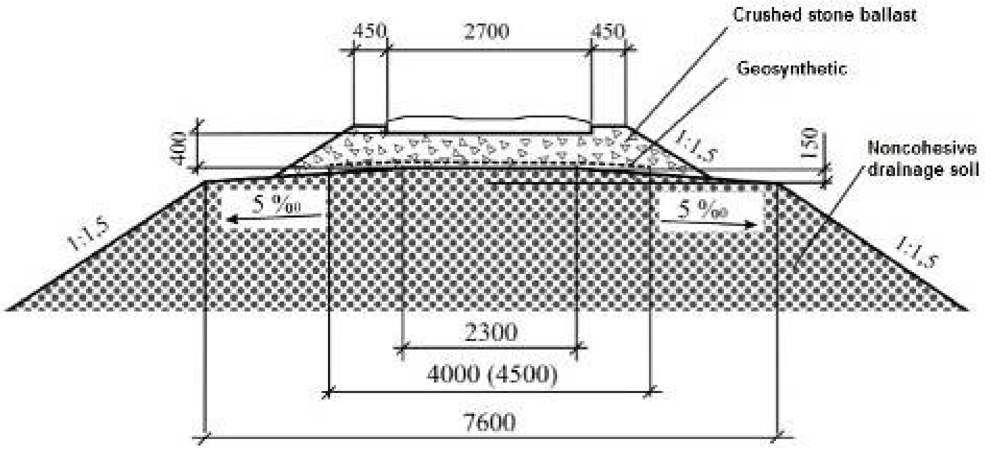

Figure 2 – Subgrade construction with geotextile or geomesh

This design is recommended for subgrade from draining soil, presented with sandy loam or crushed stone mix with elastic modulus E not less than 35 MPa.

Work technology in application of this option is similar to the work technique when using the first option. Geosyntheticsare placed on the prepared basic platform with strain modulus corresponding to project values. Then crushed-stone ballast and rail-sleeper grid are laid over them. The use of geosynthetics with width of 4.2 m is recommended.

When using the machine type RM-80 geosynthetics are placed in mechanized manner by special device. Geosynthetics, used for reinforcement and strengthening of subgrade in order to improve its reliability, have to ensure efficient operation throughout the whole service life (from 50 up to 100 years). This is ensured by correct selection of geosynthetics; pointing (accordingly to the project) of appropriate constructions of strengthening; Regulations for work technology [8, 9].

Constructions for strengthening of subgrade using geosynthetics have to be designed on the basis of engineering-geological and engineering-geodesic surveys. When designing the preset (accordingly to the regulatory requirements) level of reliability of subgrade by strength, stability and deformation capacity throughout the service life of the construction has to be provided. Design solutions must include required calculations justifying structural concept as well as technical-and-economic assessment of their application.

Calculated characteristics of geosynthetics should be accepted in view of their deterioration in design lifetime, including through their aging or damages during laying and operation as well as climatic and biological effects. When designing and calculating constructions with usage of geosynthetics one should take into account the category of the track.

The load on constructions with geosynthetics should be specified taking into account the factor of a possible overload. At this the load from the rolling stock must be taken in view of promising operating conditions of the railway.

The most effective is the construction of strengthening of subgrade using geotextile with bends, inside there are old crashed stone and soil mix (Fig. 3). This design is justified with experimental studies [5, 6] and patented [10].

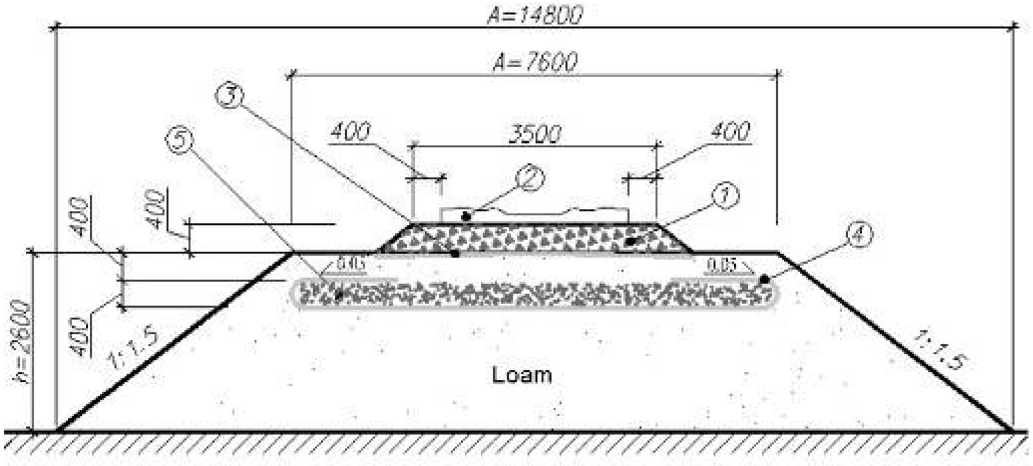

Figure 3 – Combined construction of strengthening of subgrade:
1 – ballast layer; 2 – sleeper; 3 – geotextile under the ballast layer;
4 – strengthening layer of geotextile with bends;
5 – crashed-stone and soil mix

Presented constructions of subgrade can be implemented when conducting overhaul on defective sections of the track and ensure their safe operation. But in the future more attention will be focused on the exactly combined construction of strengthening of subgrade using geotextile and an old layer of crushed stone as the most effective one.

Major material and results. Work technology involves strengthening of deformed embankments by their reinforcing with system of soil-cement piles that are being built accordingly to jet-grouting technology. Such technology of continuous and periodic efforts transmission on stiffest soils excludes unpredictable deformations (subsidences). The theoretical basis for choosing this technology may be the following factors:

– layered character of embankment from soil with various porosity, density and mechanical composition;

– soil layers thickness can vary along the length of the embankment;

– in a base of the embankment there are subsiding soils to be strengthen;

– inability to reuse of soil.

Reinforcement of such embankments is performed in two stages. First, a vertical screen is formed with soil-cement piles of external embankment reinforcement at a composite feeding pressure of 0.1 ... 0.15 MPa. Then soil-cement piles of internal massif are formed at pressure of 0.3 ... 0.3 MPa. This technology eliminates the need of development, transportation and storage for large amounts of material of functioning embankment, exploration and research of soil for the new embankment as well as placing of this soil and layered one, rammer and new embankment compacting.

SSS of reinforcing element is determined on its work as composite, since open-ended shell from geotextile with filler in the form of soil-cement mix (SCM) can be viewed as a three-layer package with significantly different properties of shell and filler.

It should be noted that open-ended shell may be considered as fictitiously closed, it corresponds to the nature of its strain. When increasing the load on the major platform of the model, emerging tensions affect the bends of shell, what is more the topsoil with the additional load leads to restraining effect. Sufficiently long bends allow developing significant friction forces both on outer surface (soil of subgrade is geotextile) and on inner surface (geotextile is SCM). Restraining effect increases proportionally to the load on the main platform of the model and consequently friction increases on pointed surfaces.

In experimental studies [6] in cases of open-ended shell and closed one, it was found that the geotextile surface locking practically did not change SSS of the model, due to the fact that friction at some length of shell ending is enough to develop significant friction and prevent the geotextile from drifting and pulling out. Friction share that in the center of shell, has not so much impact on this effect, therefore open-ended shell with bend is well enough understood as fictitious closed shell (Fig. 4).

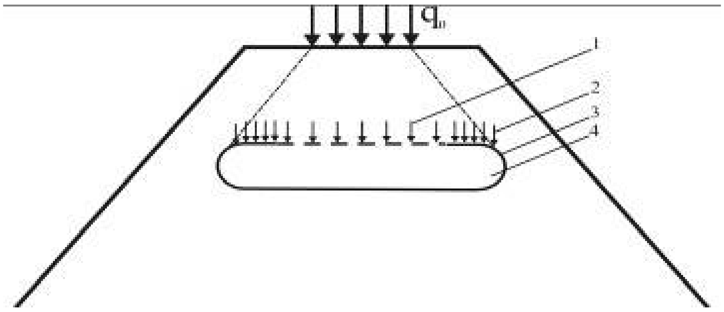

Figure 4 – Diagram of power distribution in view of restraining effect:
1 – load transmitted to the reinforcing element (load portion of the train and net weight);
2 – load transmitted to the bend of shell;
3 – fictitiously closed shell from geotextile; 4 – filler (SCM)

Strain figure of reinforcing element at load impact of the train is changed as follows. Filler as SCM with a high density and is considered substantially incompressible, being separated from the matrix of subgrade with shell is unable to change the volume. Accordingly, the reinforcing element is deformed only with the matrix, and its basis is subgrade with elastic properties (Fig. 5).

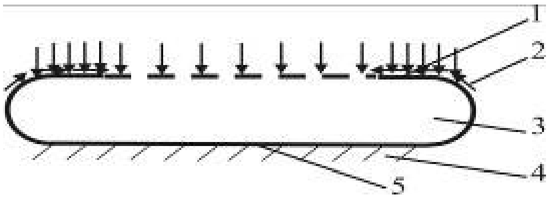

Figure 5 – Diagram of power distribution and friction forces
in the reinforcing element:
1 – clamped bend of geosynthetic shell; 2 – friction forces;
3 – compression zone of filler; 4 – elastic foundation;
5 – tensile fibre of geosynthetic shell

The positive effect from strengthening with the combined method is in the fact that almost all the energy of strain goes for an attempt of strain of the reinforcing element. This element due to its design dissipates or distributes energy on the friction forces and uniform distribution of strain on its basis.

Performed calculation of this strengthening in the software package SCAD (elastic setting [11, 12]) allows comparing the experimental results and mathematical simulation. Stress-strain properties[13, 14] accepted for the calculation are presented in Table 1.

After presentation of all necessary parameters model calculation with multu-frontal method was conducted. On completion it was provided the calculation report (SCAD report [15]) concerning successful performance, then results of the calculation are subject to detailed analysis.

Table 1 – Stress-strain properties of solid component of the model

Model element name	Modulus of elasticity, kN/m^2	Poisson number	Volume weight, kN/m^3
Base	10000…35000	0.3	20
Subgrade	10000…35000	0.3	20
Sand	50000	0.2	20
Crushed stone	100000	0.2	20
Sleeper	$3{,}91 \cdot 10^7$	0.2	24.5
Rail	$2{,}1 \cdot 10^8$	0.3	77.0

Geotextiles is used in three variations: 1) flat; 2) with bend; 3) with bend and placement of soil-cement mix in shell. Geotextile is located at a depth of 0.6 m from the slope point of the main platform (Fig. 6). Height of bend is equal to 0.2 m and the length of upper portion of geotextile bend is equal to 0.4 m (Fig. 7).

Characteristics of these geotextiles are as follows: volume weight – 11 kN/m^3; modulus of elasticity – 0.8 MPa; Poisson number– 0.35; plate thickness – 4 mm.

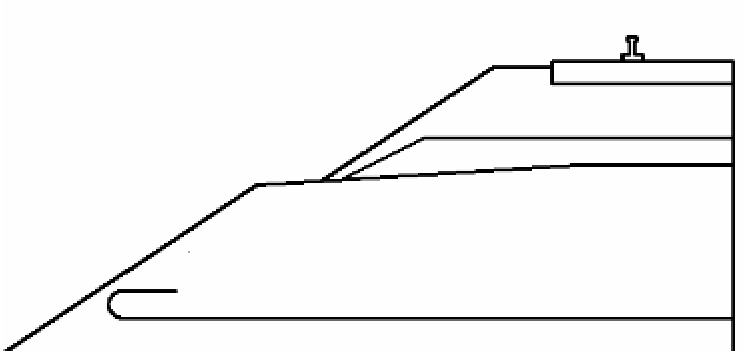

Figure 6 – Placement of geotextile with bend in subgrade

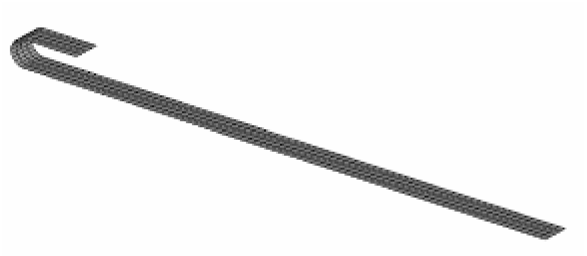

Figure 7 – Model view fragment of geotextile with bend

From obtained results one can conclude that minimum horizontal displacements are observed in the version with deepening of geotextile at 1m and vertical ones at 0.4m. Options of models with geotextile with bend and mineral mix are also under consideration, where position of geotextile changes by edge of the main platform deeper at: 0.4m; 0.6m; 0.8m; 1m.

A typical distribution of stress-strain state when changing the use of geotextile with mineral mix shows that the displacements distribution in all four options is not changed fundamentally, especially as opposed them to options for models with geotextile with crashed stone. The line of added displacements along the location of geotextile was formed in all options (Fig. 8). Distribution of such displacements decreases with the deepening of geotextiles into subgrade.

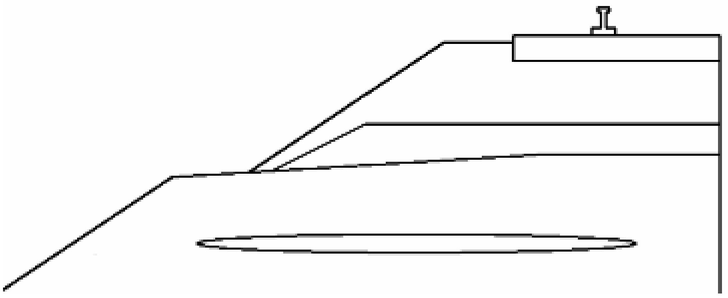

Figure 8 – Typical placement of added horizontal displacements in options of models with geotextile and with mineral mix

All results of maximum horizontal displacements are in Table 2.

Table 2 – Results of strain state by depth of placement

Depth of placement	Maximum horizontal displacements, mm	
	Subtract	Added
0.4	-9.15	3.69
0.6	-8.92	3.76
0.8	-8.65	3.83
1.0	-8.36	3.88

A typical distribution of strain state when changing the use of geotextile with mineral mix also shows that distribution of vertical displacements in four options of models is the same. Isolines distortion is observed in all options of models in the location of geotextiles with mineral mix.

Obtained results when using models with geotextile with bend and mineral mix are follows: the maximum subtract displacements by depth of placement are equal to: 0.4 – 65.98 mm; 0.6 – 66.73 mm; 0.8 – 67.3 mm; 1 – 67.73 mm.

For visual comparison of two options effectiveness for filling of geotextile, graphs of displacements dependency were built in two versions (Fig. 9 – 11).

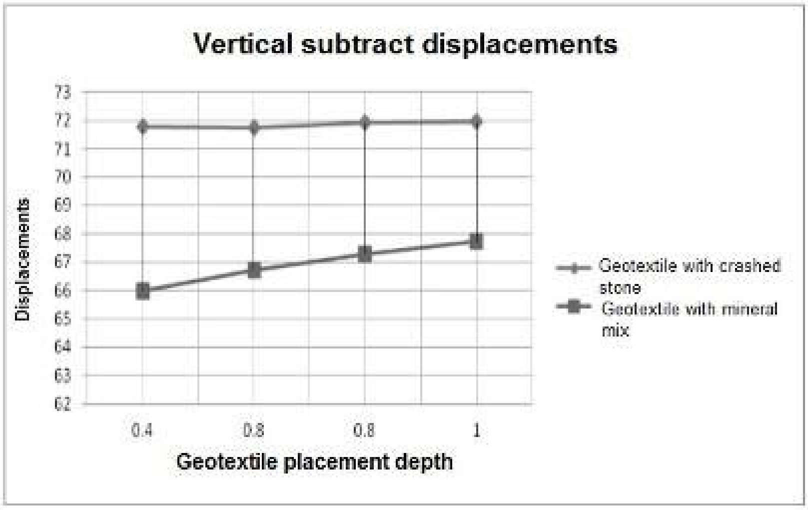

Figure 9 – Dependence of vertical subtract displacements (mm) on geotextile placement depth (m)

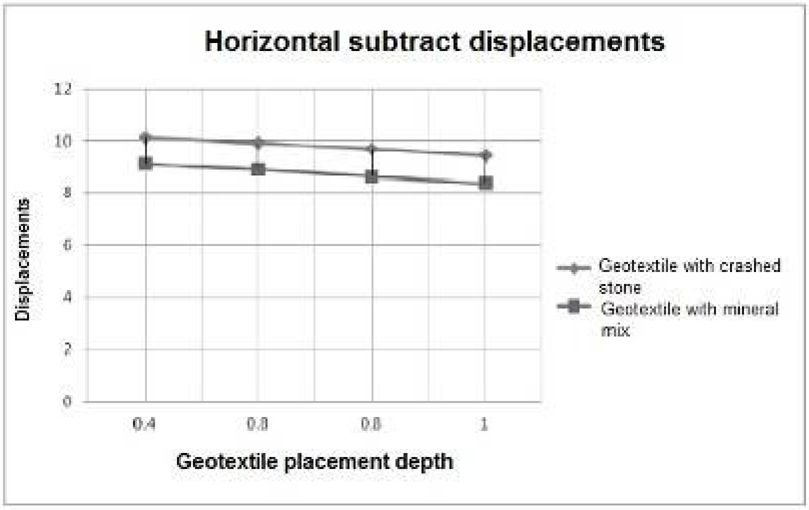

Figure 10 – Dependence of horizontal subtract displacements (mm) on geotextile placement depth (m)

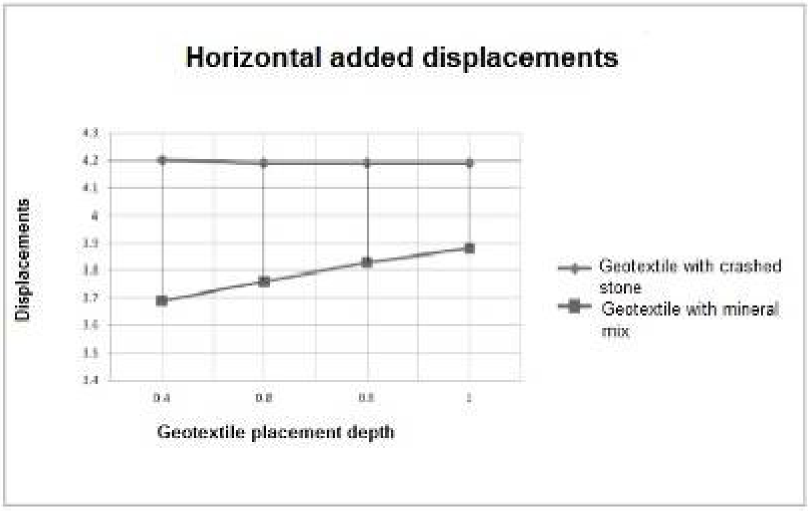

Figure 11 – Dependence of added horizontal displacements (mm) on geotextile placement depth (m)

Conclusions. A few models of strengthening of subgrade differing by depth of cover of geotextile and filler were proposed. Calculations of soil models in the software package SCAD verified themselves properly as actual research.

From obtained results one can conclude that minimum horizontal displacements are observed in models with deepening of geotextile at1 m and vertical ones at 0.4 m. Analysis of grapfs confirms that dependences are linear ones and their nature indicates that the option of geotextile with bends and mineral mix when location at various depths reduces deformation parameters more effectively.

Based on simulation results it is possible to make recommendations concerning modernization of existing subgrade and construction of new one in complex engineering-geological conditions.

One of the promising directions for future research is improvement of strengthening of subgrade based on obtained knowledge at experimental research and simulation. A series of experiments separately with strengthening using soil-cement piles and combined method is planned to perform.

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