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FORECASTING A MOISTURE MODE OF THE DRAINAGE LAYER IN A ROAD STRUCTURE UNDER THE ACTION OF LOADING

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The processes forming the humidity mode of the drainage layer of a road structure under the action of excess load have been investigated. The stressed-strained state was determined based on a numerical experiment using the software-calculation suite SCAD Office. The numerical modeling of the examined structure involved the static load of the A_2 group for a road of category II. A series of numerical experiments were performed, which included an increase in the rated load by 10–50 % when overwetting the drainage layer and the earth bed. The distribution of the isofields and isolines of normal stresses and deformations in the volumetric elements was derived, which made it possible to determine the thickness of the soil layer of the earth bed, 0.67 m, from which water is squeezed out under the influence of excess loading.

Based on the approach for determining the parameters of soil subsidence at its drying or freezing, the dependences were established for the relative subsidence of soil, the coefficients of linear subsidence and compaction of soil under the influence of excess load. The proposed dependences integrate such indicators as the deformation below a drainage layer, the depth of stress spread, at which water is not squeezed out from soil, the optimum humidity, and the full moisture content of the soil.

Based on the results of numerical experiments and soil subsidence parameters, the amount of water squeezed out from a layer of soil under the influence of excess load has been determined, which is 5.4 liters per m^2. The results obtained make it possible to adjust the value of the total specific excess water flowing into a drainage structure. Taking into consideration the squeezing out of water from an earth bed from a soil layer under the influence of excess load from a wheel of 86.25 kN, the general specific excess could vary in the range from 35.4 to 22.4 liters per 1 m^2. Increasing it by 18–32 % would change the humidity mode of the road bed and reduce the overall elasticity module

Keywords: stressed-strained state, road structure, drainage layer, water squeezing, excess load

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1. Introduction

Increasing the traffic intensity of heavy-weight automobiles predetermines the continuous growth of loads, motion speeds, and, accordingly, the stricter requirements for the strength and stability of road structure. Note that the adverse situation arises when a large weight of the cargo leads to irreversible deformations in both the asphalt-concrete coating and the layers of a road bed's base. Significant changes in the humidity regime in the spring, especially during the first month, are observed in the draining or frost-protective layers of the road base and in a working layer (in the upper part under a road base) of the earth bed (EB).

The greatest value of moisture content is reached through atmospheric precipitation, penetrating the cracks in a coating, a curb, the EB slopes, and squeezing water into the draining layer when the lower layers of soil that melted subside.

The drainage layers are typically made of immovable sands across the EB entire width and are designed for the operational conditions of absorption or drainage. The thickness of such a layer without special additional draining structures should be large enough to provide for the accommodation of all the incoming water in it over a long time. It is required that the level of free gravitational water in the sand should not exceed a certain mark, which ensures the durability of a road base.

Based on the experimental and field studies [1], at the territory of the USSR, for the overwetted road sections, it was established that the drainage layers, which are designed on the principle of drainage, actually operate on the principle of absorption. As a rule, these are the sections in low embankments, at zero marks, in recesses. The influence of heavy vehicles, especially those with over-rated weight, also leads to the additional moisture migration in a road structure, due to squeezing out moisture from the lower layers of an EB soil to the upper drainage layer.

The application of numerical modeling of the SSS of a road structure based on modern software-calculation complex SCAD Office (PRK SCAD Office) could make it possible to accurately determine the thickness of the soil layer located under the draining layer, from which water would be squeezed out under the action of transport load. This approach is relevant and would allow a reasonable design solution to be chosen regarding the drainage layers of a road base for the new construction objects, as well as after repairs.

2. Literature review and problem statement

The influence of water on road structure over an annual cycle is always substantial and is multivariate in nature. Paper [2] proposed an analytical solution to determine the amount of water removed by the drainage layer of a road base. The authors gave recommendations on the use of materials in drainage layers depending on their filtration properties. The results of a field study into the deformation module of a road structure taking into consideration the seasonal changes in the soil moisture content of an earth bed are reported in work [3]. This allowed the authors to suggest a method for evaluating the SSS of a road structure during the annual cycle for different climatic conditions. However, the cited studies [2, 3] do not consider a change in the humidity of the road base layers under the influence of a load, which can significantly affect the transportation-operational state of the road in general.

The importance of the strength and integrity of a road base that characterize the SSS of a road structure as indexes of the qualitative condition of a road section is addressed in works [4, 5].

The impact of the condition of a road base with an improved coating on road safety taking into consideration the water-thermal balance of an EB massif is considered in paper [6]. The mathematical models are given reflecting the processes of the temperature and filtration fluid distribution in soil. The paper focuses on that the intensity of changing the amount of moisture in an EB soil depends on the type of soil, the amount of precipitation, the duration of moistening by surface or groundwater, the temperature regime. In addition, the authors noted the dangerous effect of loads from vehicles on a road base during the period of strong moisturizing and overwetting; they, however, did not offer appropriate methods taking into consideration this problematic issue.

A study of moisture distribution depending on a temperature mode in a road structure is reported in [7]. Based on experimental measurements, the authors built the charts of humidity change in the autumn, spring, and summer periods of the year. The distribution and fluctuations in moisture for depth over time has a complex nature. It is also noted that at a depth of more than 2 m the maximum humidity value is reached in the spring period after complete defrosting.

In [8], mathematical modeling was applied as a method to investigate the processes of crack formation in a concrete coating, based on the dependences of the effect exerted by rolling stock and weather conditions. A numerical experiment involved three stages of modeling: meteorological parameters; annual change in water-thermal regime (WTR), the SSS of a road structure. The SSS simulation approach was based on the results of testing the bending of concrete beams for deflection. However, this calculation scheme is significantly different from the one proposed in this work and does not make it possible to take into consideration the impact of a soil base's resistance.

The search for modern studies aimed at the numerical calculation of the system "structure–soil" yields a lot of results for industrial and civil construction and any calculation complex. There are almost no papers in the field of the numerical calculation of motor roads involving the use of volumetric elements in software suits, which are based on the method of finite elements.

The purpose of work [9] is a detailed analysis of methods for constructing the analytical and numerical models of pile foundations. The authors examine seven models, of which five are numerical-analytical and two are implemented exclusively by the numerical method using the PRK SCAD Office. The cited work concluded that the model was built on the basis of volumetric finite elements and in the generalized calculation of "structure–soil" more accurately describes the SSS of soil. However, the authors recommend this estimation in conjunction with the numerical-analytical calculation regulated by acting construction norms. Calculation by the numerical model makes it possible to accurately enough identify areas of high concentrations of stresses in the pile foundations.

Work [10] focuses on the numerical-analytical procedures to calculate the structures of a motor road, which are well proven in practice in these countries. Today, for them, a more relevant topic is to determine the cost of road construction depending on the chosen procedure for calculating the layers of the road's base and coating.

The issue of calculating the soil arrays for the base of civil building structures is studied in mode detail, given that the model for soil bases of buildings can be similar to that applied for transport facilities. The authors of work [11], when analyzing the most common models of calculating the foundations of high-rise buildings and the possibility of their implementation in the PRK SCAD Office, made a conclusion as to their further development. Procedures will develop in the direction towards a phased loading of the base under a "MONTAGE" mode of the PRK SCAD Office.

The main drawback of such a development is the labor-intensity of the process that sets the variable coefficients for the road base C1 at each separate installation stage.

A study of the road structure at sections with tubular drainage made from materials of different origin is reported in paper [12]. The authors determined the expediency of using the pipes that could withstand heavy load on roads in terms of their strength characteristics. However, the results were obtained from a simplified flat scheme in the *XOZ* plane, with limited displacements along the *OX* axis (on each side) and along the *OZ* axis (at the bottom of the model).

Paper [13] studied the SSS of a road structure with a crack in the coating. The effect of an increase in the depth of a crack on the module of elasticity of the road base layers was examined. Work [14] proposed a comprehensive approach to studying the characteristics of the SSS of a road structure under the influence of a dynamic load that corresponds to the field conditions. The authors analyzed the parameters of bending a coating layer and reported the results of a numerical experiment on the simulation of the influence of the loss of adhesion between the layers of a non-rigid road base. However, the results of [13, 14] do not include a change in the SSS of an overwetted road structure.

Development and improvement of methods for calculating the building and road structures is a relevant task of construction mechanics. The use of numerical methods makes it possible to ensure the required accuracy in comparison with analytical methods, which are mainly used in the design of motor roads. Therefore, the question arises about the choice of a calculation method, analytical or numerical. The analytical methods of calculating the road elements include the models of general and local deformations, which are the basis for the normative estimation procedure. The most applied ones are a deformation model of the elastic half space, which relates to general deformations, and a Winkler model, which addresses the local deformations.

Determining the SSS and its approximation to the actual work of structures is the scientific task of modern calculations, as opposed to testing based on the boundary conditions that are described in detail in the acting normative documents.

3. The aim and objectives of the study

The aim of this study is to develop a method to forecast a humidity mode of the sandy drainage layer under the influence of the static excess load based on the numerical modeling of the stressed-strained state of a road structure. This will make it possible, when determining the materials for the drainage layers, to take informed decisions on their thickness, the ability of a road base to withstand the estimated load and work effectively to drain the road structure.

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

– to simulate the element of a three-dimensional linearly-elongated road structure with a draining layer using the method of finite elements and to determine the main factors that influence the operational conditions under the influence of standard and excess loading;

– to investigate the stressed-strained state of a road structure in the overwetted state of a drainage layer and the earth bed soil under the influence of standard and excess static loading, using a motor road as an example;

– to determine, taking into consideration a change in the elasticity module of a drainage layer, the amount of water squeezed under the action of excess load out of a soil layer of the earth bed.

4. Materials and methods of research

4. 1. Construction of a road structure model using the PRK SCAD Office

To build an estimation model of the elements of a motor road, we chose the PRK SCAD Office, designed to study numerically the strength and stability of a wide class of structural objects in construction, to determine the SSS of structures exposed to static and dynamic activities. The PRK SCAD Office is a versatile tool in the civil engineering sector and is not intended for the linearly-stretched road infrastructure objects. Such constraints require that the scientist should perform additional experimental studies and check the adequacy of the model in comparison with the analytical methods used in the field of transport construction.

The chosen basis for the model was the three-dimensional finite elements (FE) No. 36 (Fig. 1).

One of the most important characteristics of a finite element model is the maximum diameter of the elements:

$$h = \max_{e}\left(\sup_{x,y\in\Omega_e}|x-y|\right)$$

is the minimum diameter of the layer, which can host any finite element of the estimated model. The important role belongs to the choice of the degrees of freedom for an element, as well as the corresponding approximating functions that fully determine the convergence rate and the assessment of FEM errors.

The FE types No. 31–40 "Volumetric finite elements" have the same permissible attributes of the scheme and the estimation stresses and efforts (N_X, N_Y, N_Z, T_{XY}, T_{XZ}, T_{YZ}). They also have the same purpose and capabilities: "To solve a spatial problem of elasticity theory, for isotropic, transversal-isotropic, orthotropic, and anisotropic material". Therefore, when sampling the model, we took into consideration the geometric parameters of the structure; thus, FEs No. 36 and No. 34 were selected.

Fig. 1–6 show all necessary initial data for implementing the computational complex.

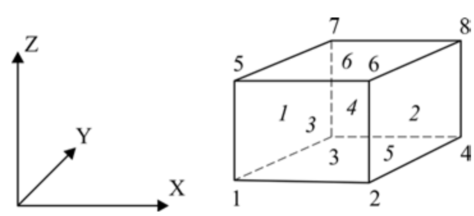


Fig. 1. Schematic representation of an eight-nodular isoparametric FE No. 36 in the PRK SCAD Office library

The following scheme of a model consisting of the above-mentioned FEs was chosen: a section of 4 m in length and the total width of 10.1 m (a coating width is 3.75 m; a curb width is 3.75 m; a slope width is 2.9 m; a structure height is 3.1 m). The model scheme chosen is a typical design solution for a motor road of category II in the cross-section of the extreme motion lane with a roadside and a slope inclined at 1:1.5. The construction of the finite-element grids was determined based on the conditions for a wheel stamp by motor vehicles for statistical load regulated by the sectoral and state standards GBN V.2.3-37641918-559:2019 "Road base. Non-rigid. Design", DBN V.2.3-4:2015 "Motor roads", and by recommendations from the user's manual for the PRK SCAD Office to ensure the slightest calculation error.

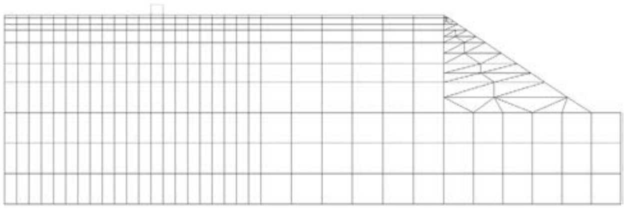


Fig. 2. Side view (façade) of the estimated model

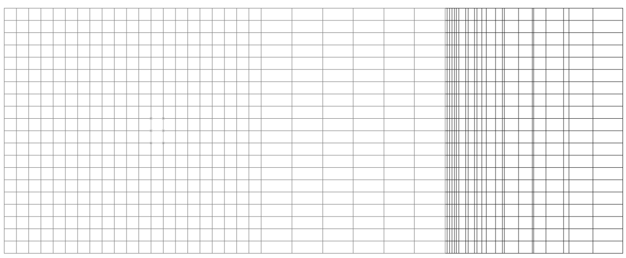


Fig. 3. Top view (plan) of the estimated model

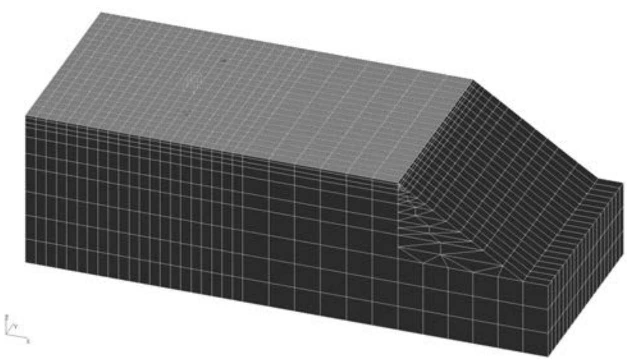


Fig. 4. The isometry of the estimated model

The physical-mechanical characteristics of a motor road structure's layers are given according to the typical project of the modern structure of a road of category II (Fig. 5). In the network of automotive roads in Ukraine, the roads of category II account for more than 58 % as regards international roads; for more than 56 % as regards national roads.

The modules of elasticity of the layers of a road base with an organic binder correspond to the static effect of the load (Fig. 5).

To ensure the geometric stability of the system, there is a need to overlap the ligaments of the support nodes. For the model under consideration, it was experimentally found that the ligaments are imposed only on the support nodes of the lower layer of soil to prevent the linear and angular displacements and to ensure the geometric stability of the system. According to the results reported in work [10], and to obtain the most possible deformities, we made a decision not to restrict the movement of nodes along the contour of the model.

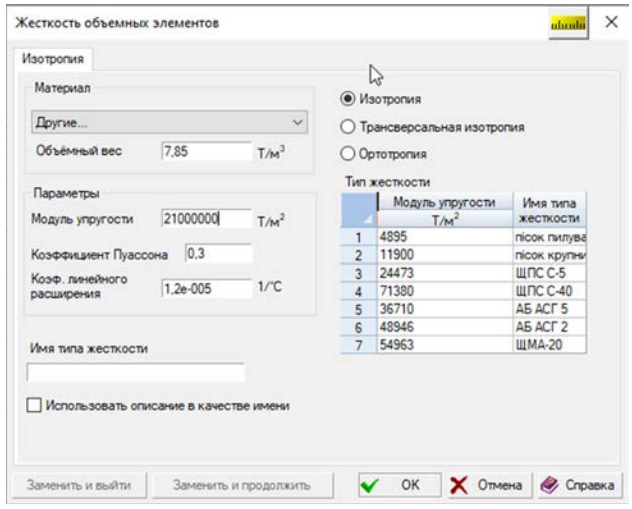


Fig. 5. Assigning the physical-mechanical characteristics to the layers of a road structure

4. 2. The nomenclature and abbreviations of materials for the elements of the investigated road structure

During the numerical modeling of the considered structure, we used loading for a road of category II according to DBN V. 2.3-4 of group A_2 – the rated static load on the surface of a coating from the wheel of an estimated car, 57.5 kN, with the equidistant diameter of the wheel stamp area, 303 mm. The loading time is 600 s. The static load was accepted, as the most unfavorable in duration during the formation of a humidity regime of the overwetted drainage layer and the EB soil. The axle load was accepted taking into consideration the uniform distribution over 6 nodes of the estimation grid at a rectangle measuring 300 mm by 240 mm (the area of the rectangle corresponds to the stamp area). The estimated model meets the conditions for a motor road in the recess with a ditch, taking into consideration the natural weight of the structure. The characteristics of the materials for a road structure are given in Table 1.

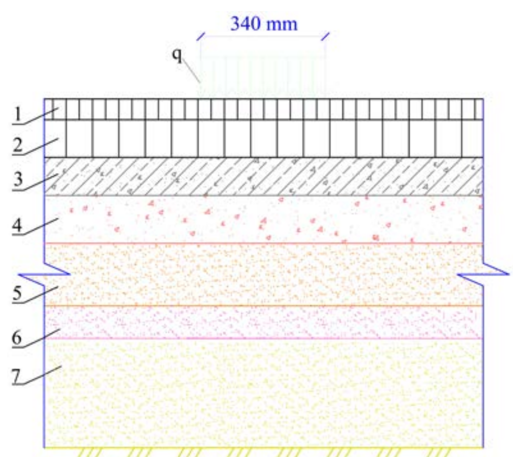


Fig. 6. A road structure model: q — an evenly distributed load, 1 — 6 — the layers of a road base; 1 — crushed stone and mastic asphalt concrete SHMA-20 based on the bitumen BMPA 60/90-53; 2 — dense asphalt concrete based on the bitumen BND 60/90, type A, Mark I; 3 — porous asphalt concrete based on the bitumen BND 60/90, coarse-grained; 4 — crushed stone-sand mixtures S-7, fortified with the cement M40; 5 — crushed stone-sand mixture S-5; 6 — coarse sand; 7 — dusty sand (EB soil)

Table 1

Characteristics of the materials for a road structure's layers

No. of entry	Material	Elasticity module *E*, MPa		Layer height *h*, m	Poisson coefficient	Specific weight, t/m^3
		according to standard requirements	at overwetting, according to [15]			
1	Crushed-mastic asphalt concrete SHMA-20 based on the bitumen BMPA 60/90-53)	539		0.05	0.27	2.4
2	Dense asphalt concrete on the bitumen BND 60/90, Type A, Mark I	480		0.1	0.25	2.3
3	Porous asphalt concrete on the bitumen BND 60/90, coarse-grained	360		0.1	0.25	2.3
4	Crushed stone-sand mixtures S-7, fortified with the cement M40	700		0.20	0.31	1.8
5	Crushed stone-sand mixture SHPS S-5	240		0.35	0.30	2
6	Coarse-grained sand Wt (0.87)	130	116	0.3	0.35	2
7	Dusty sand	52	48	4	0.3	1.8

A typical structure of a road base was used to conduct a series of numerical experiments, which included an increase in the regulatory loading by 10–50 % at overwetting the drainage layer and EB soil (Table 1, rows 6 and 7), which corresponds to the real conditions of road operation in certain areas. The excess load increase is due to statistical data, which are defined at the sites of the weighing system Weigh-in-Motion on the road sections with high traffic of heavy vehicles. The statistical data are processed and analyzed at the Department of Intelligent Transport Systems of the State Road Agency of Ukraine.

The proposed method of calculation is valid for any road structures.

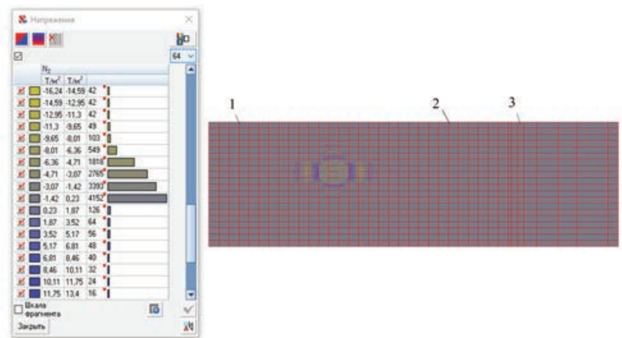
5. Results of studying the processes that form humidity conditions for a drainage layer under the action of loading

5. 1. Results of studying the stressed-strained state of a road structure with a drainage layer

To conduct a numerical study, three cases of applying a load with respect to the road axis were considered. The first case: the load was applied at a distance of 2.4 m from the axis; the second case – at a distance of 2.8 m; the third case – at a distance of 3 m (the most unfavorable place of application is at 1 m to the curb edge).

As a result of numerical modeling, we obtained the distribution of the isofields and isolines of the normal stresses N_z in the volumetric elements; the projection onto the $X0Y$ plane (top view) (Fig. 7, 8), the distribution of the isofields and isolines of the normal stresses N_z in the volumetric elements, the projection onto the $X0Z$ plane (in the cross-section) (Fig. 9, 10), and the distribution of deformations Z (mm) in the structural layers of a road base of the total thickness of 110 cm, for the EB (recess) with a depth of 4 m, the projection onto the $X0Z$ plane (Fig. 11, 12) under the normative and excess loads.

The distribution of the isofields and isolines of the normal stresses N_z in the volumetric elements, a projection on the $X0Y$ plane, in a road structure under the normative and excess loads on the axle make it possible to determine the parameters for a deflection bowl of the road surface and for a change in its configuration depending on the place of loading (Fig. 7, 8). When increasing the load, the deflection bowl, according to its size in the plan, grew by 5 cm.



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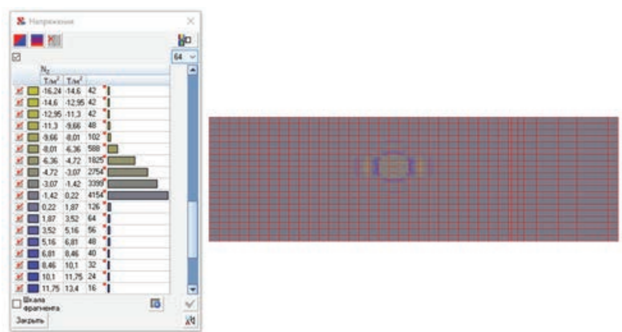

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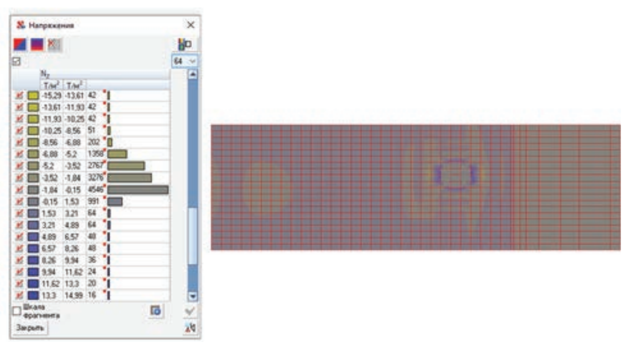

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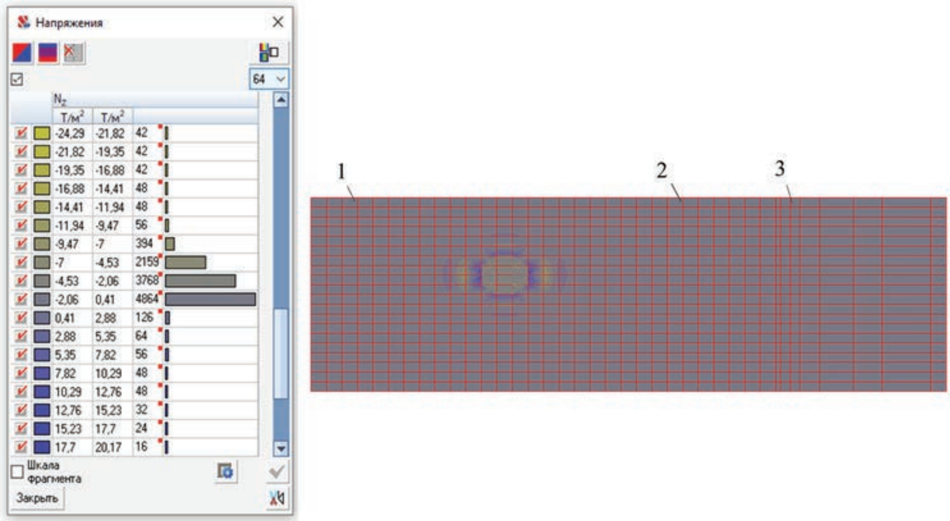
Fig. 7. The distribution of the isofields and isolines of the normal stresses N_z in the volumetric elements, a projection on the $X0Y$ plane, in a road structure under the normative load on the surface of the coating by the wheel of an estimated vehicle of 57.5 kN: *a* – at a distance of 2.4 m from the axis, *b* – at a distance of 2.8 m, *c* – at a distance of 3 m; 1 – a lane on the roadway; 2 – a stop lane on the sideline; 3 – the EB slope



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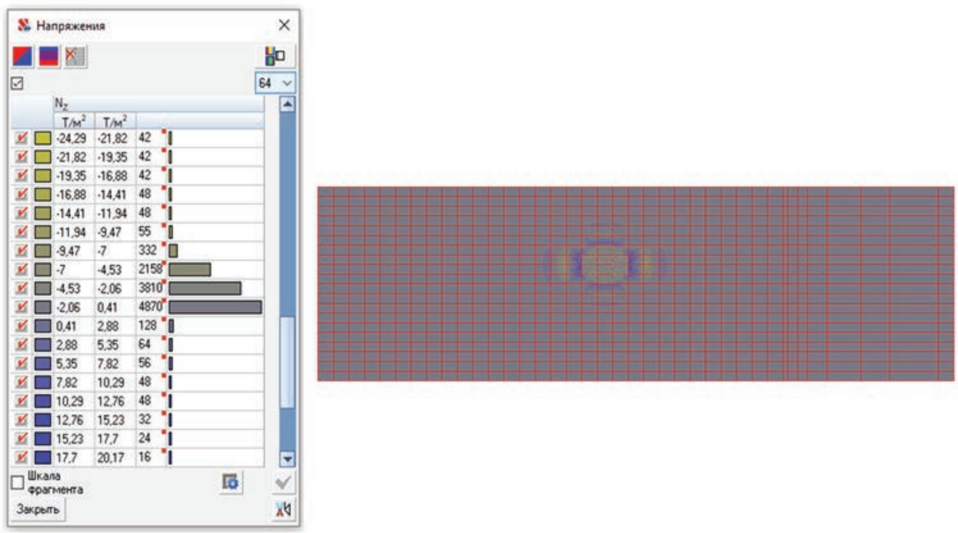

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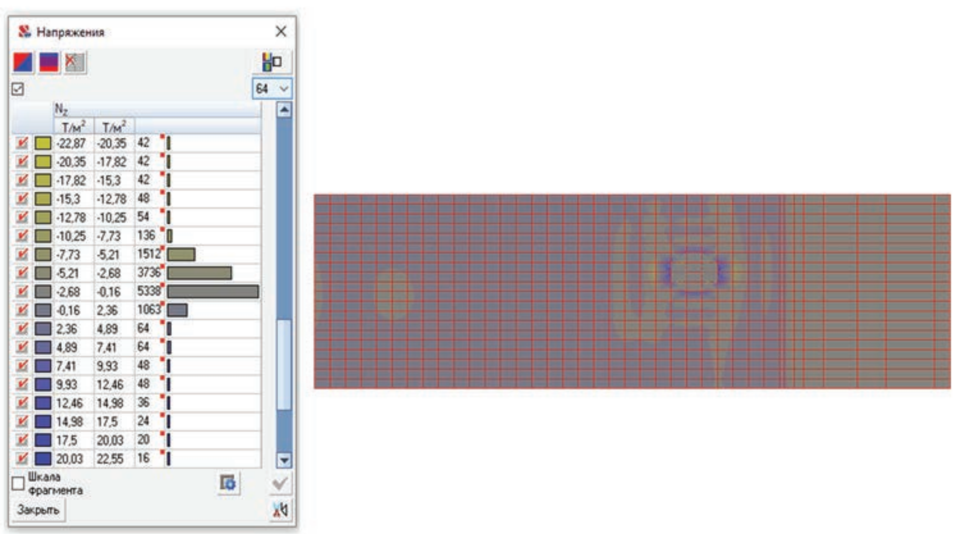

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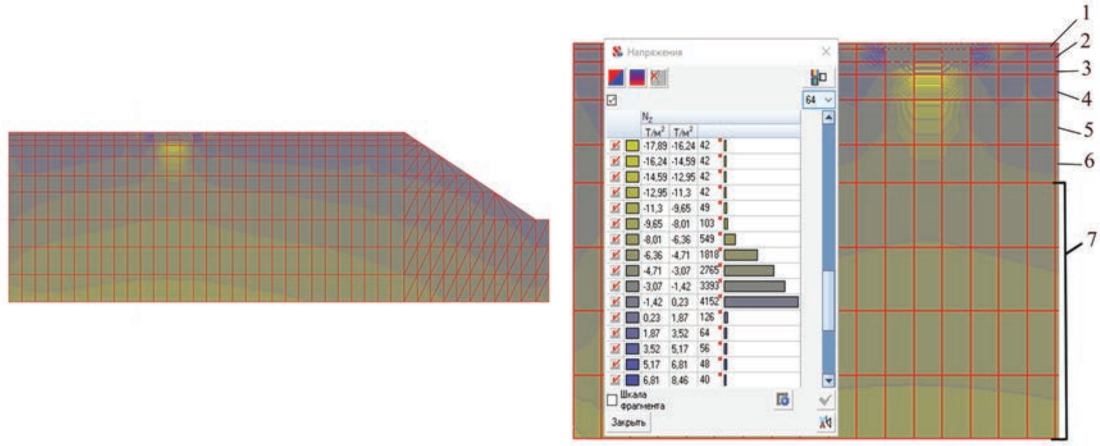
Fig. 8. The distribution of the isofields and isolines of the normal stresses N_z in the volumetric elements, a projection on the $X0Y$ plane, in a road structure under the excess load on the surface of the coating by the wheel of an estimated vehicle of 86.25 kN: *a* — at a distance of 2.4 m from the axis, *b* — at a distance of 2.8 m, *c* — at a distance of 3 m (view from the top downwards; 1 — a lane on the roadway; 2 — a stop lane on the sideline; 3 — the EB slope



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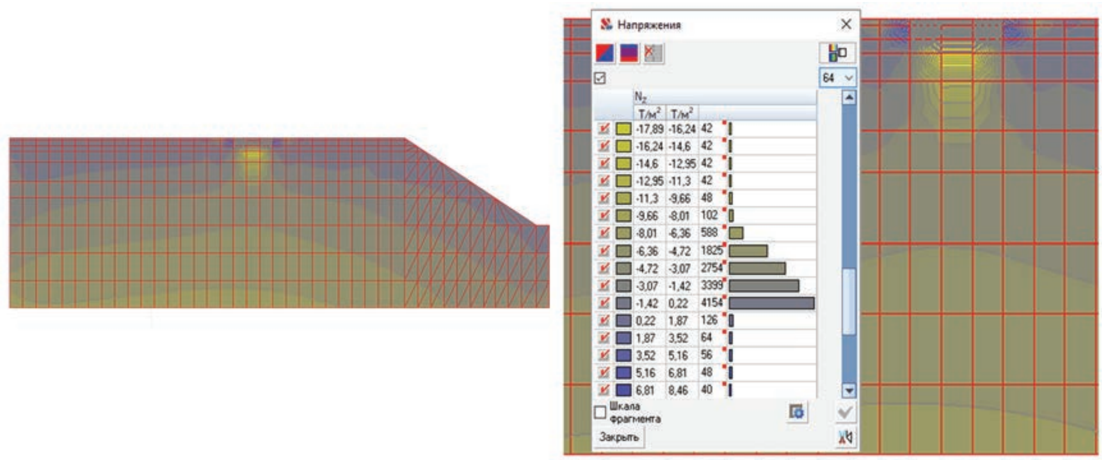

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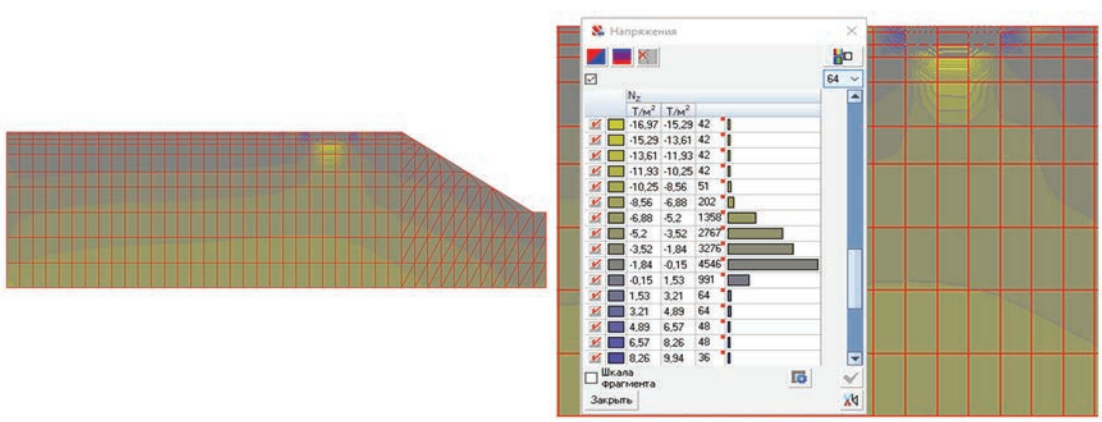

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Fig. 9. The distribution of the isofields and isolines of the normal stresses N_z in the volumetric elements in a road structure under the normative load on the surface of the coating by the wheel of an estimated vehicle of 57.5 kN, a projection on the *X*0*Z* plane, the cross-section: *a* – at a distance of 2.4 m from the axis, *b* – at a distance of 2.8 m, *c* – at a distance of 3 m; 1–7 layers of the road base and EB according to the list in Table 1

The results from a series of numerical experiments, namely the distribution of the isofields and isolines of the normal stresses N_z and the distribution of the deformations *Z* (mm) in a road structure in the volumetric elements of the structural layers of a road base, a projection on the *X*0*Z* plane, were compared under the normative and excess loads (Fig. 9–12). The distribution of the isofields and isolines of the normal stresses N_z in the volumetric elements makes it possible to determine the thickness of a soil layer located under the drainage layer, from which water would be squeezed under the influence of applied load (Fig. 13). This is possible due to the distribution of the minimum values of stresses, at which water would not be squeezed, according to [1], for sandy and loamy soils N_z=0.01 MPa.

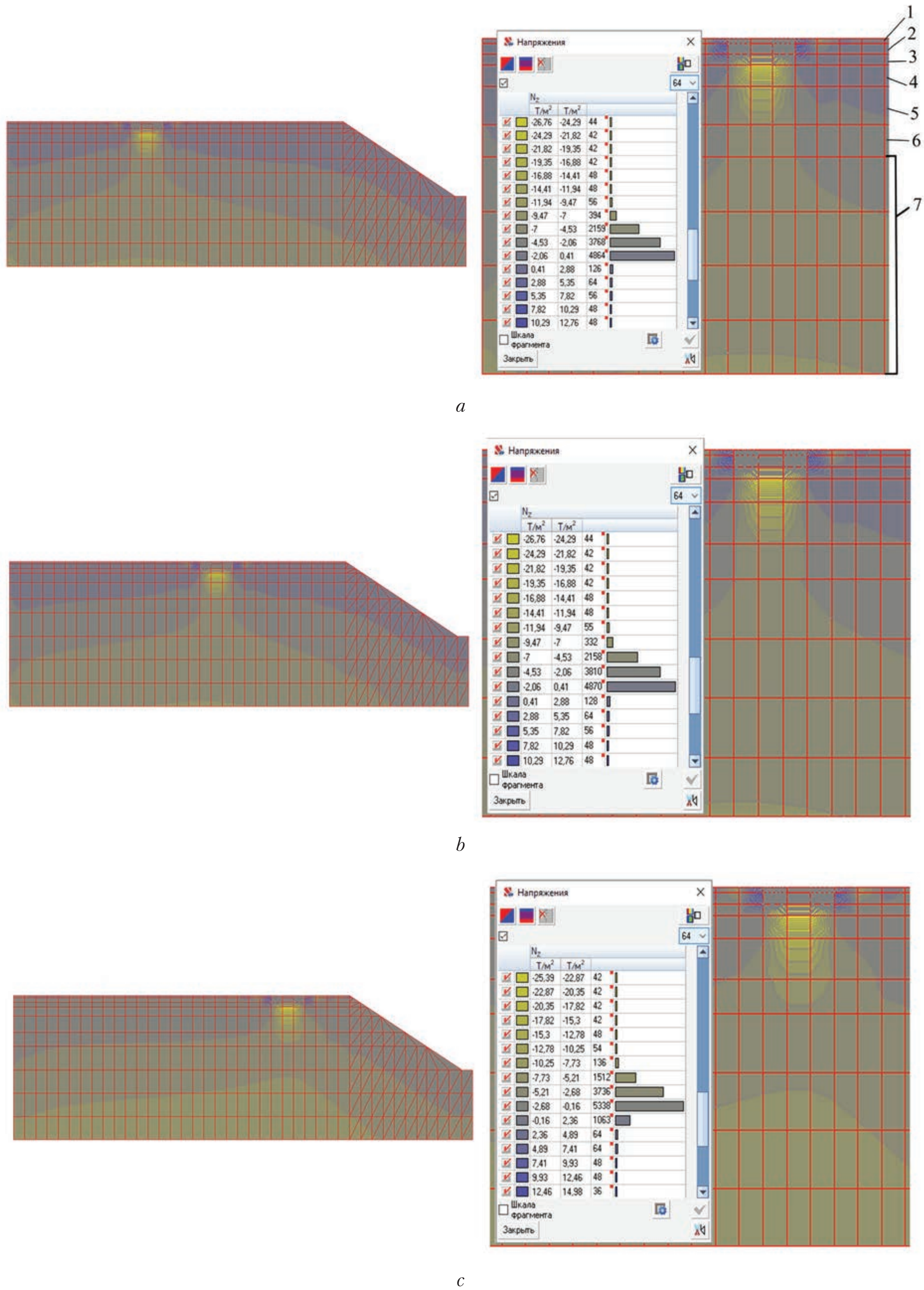
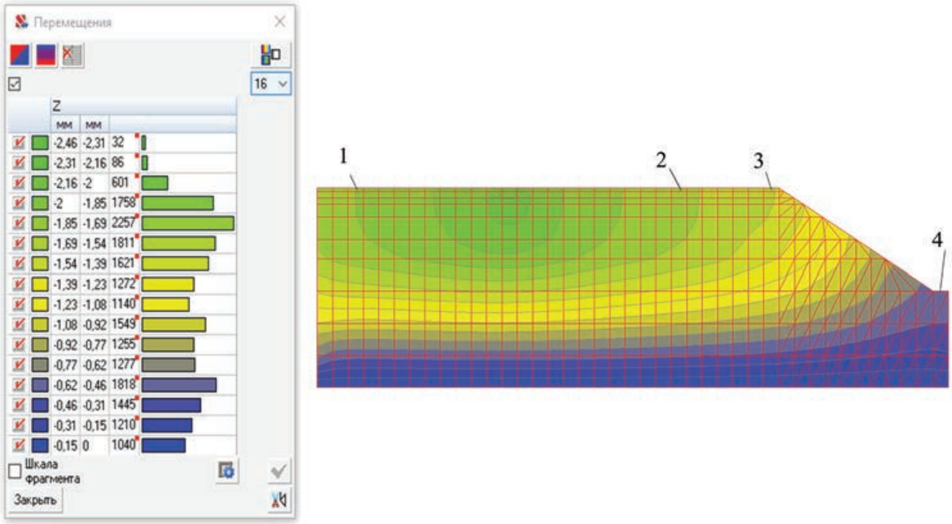


Fig. 10. The distribution of the isofields and isolines of the normal stresses N_z in the volumetric elements in a road structure under the excess load on the surface of the coating by the wheel of an estimated vehicle of 86.25 kN, a projection on the $X0Z$ plane:
a — at a distance of 2.4 m from the axis, *b* — at a distance of 2.8 m, *c* — at a distance of 3 m;
1—7 layers of the road base and EB according to the list in Table 1



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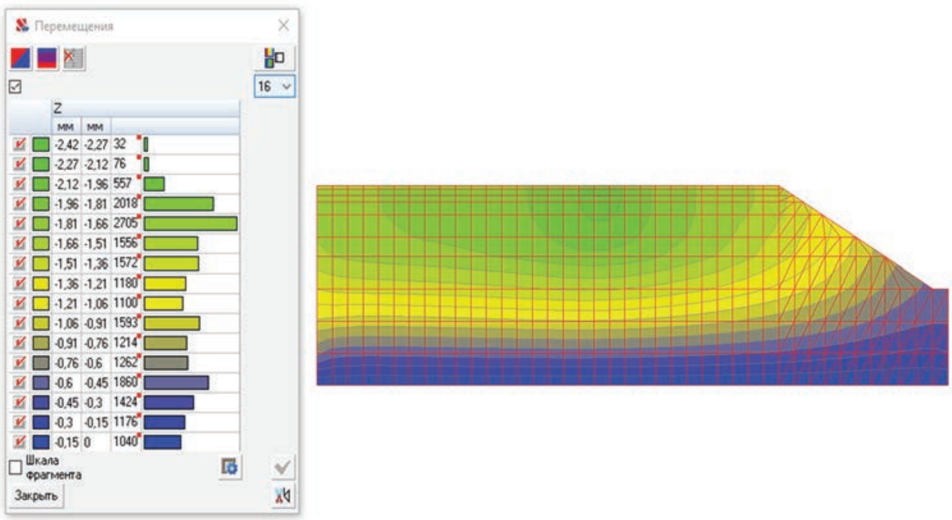

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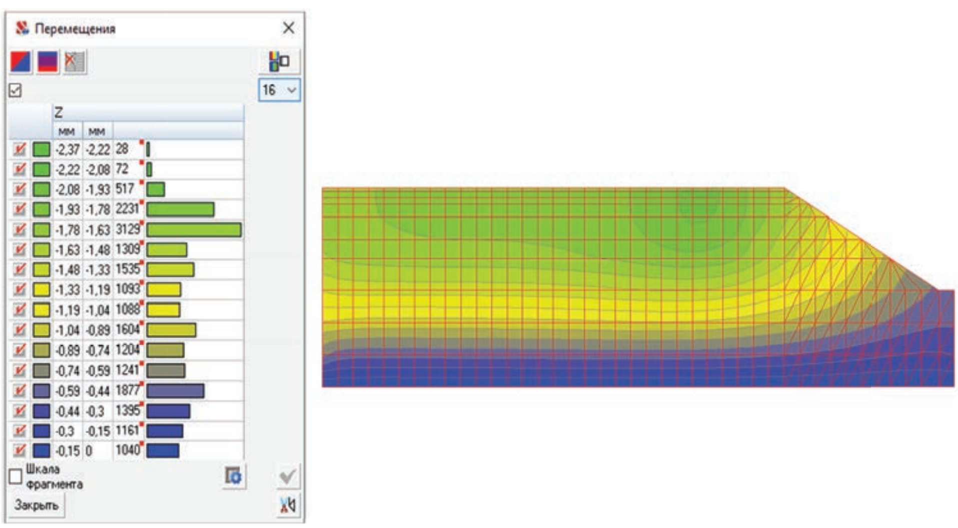
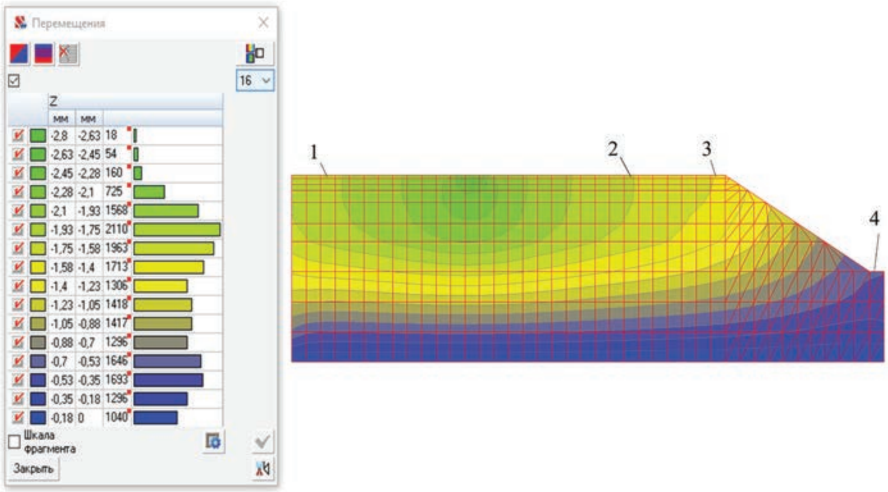
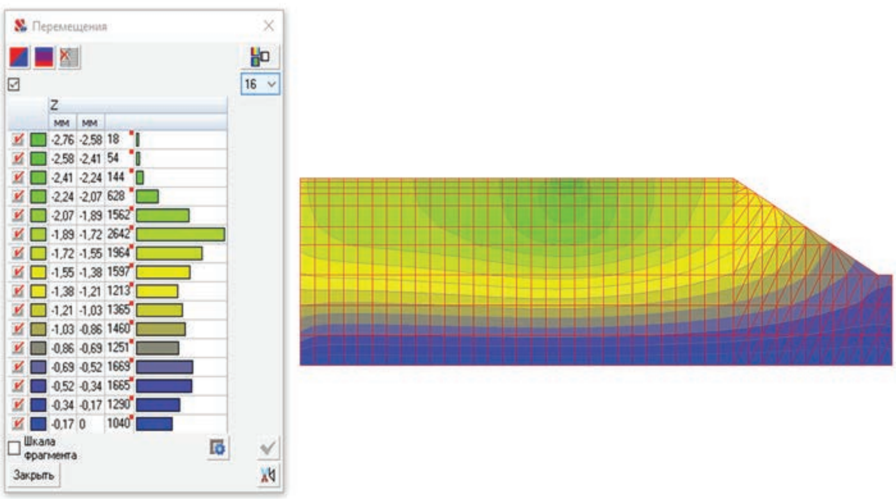


c

Fig. 11. The distribution of the deformations Z (mm) in a road structure, a projection on the $X0Z$ plane: under the normative load on the surface of the coating by the wheel of an estimated vehicle of 57.5 kN: *a* – at a distance of 2.4 m from the axis, *b* – at a distance of 2.8 m, *c* – at a distance of 3 m; 1 – a lane on the roadway; 2 – a stop lane on the sideline; 3 – the EB slope; 4 – a road ditch



a



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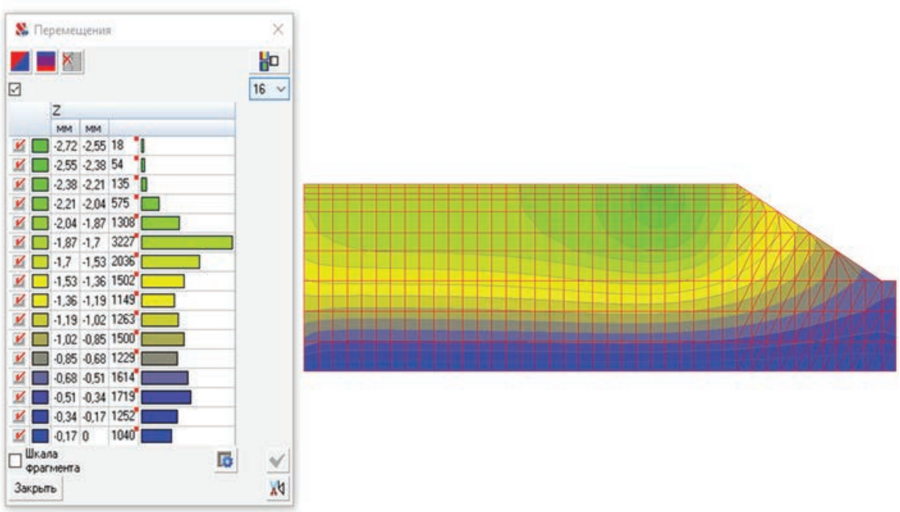

c

Fig. 12. The distribution of the deformations Z (mm) in a road structure, a projection on the $X0Z$ plane: under the excess load on the surface of the coating by the wheel of an estimated vehicle of 86.25 kN: *a* — at a distance of 2.4 m from the axis, *b* — at a distance of 2.8 m, *c* — at a distance of 3 m; 1 — a lane on the roadway; 2 — a stop lane on the sideline; 3 — the EB slope; 4 — a road ditch

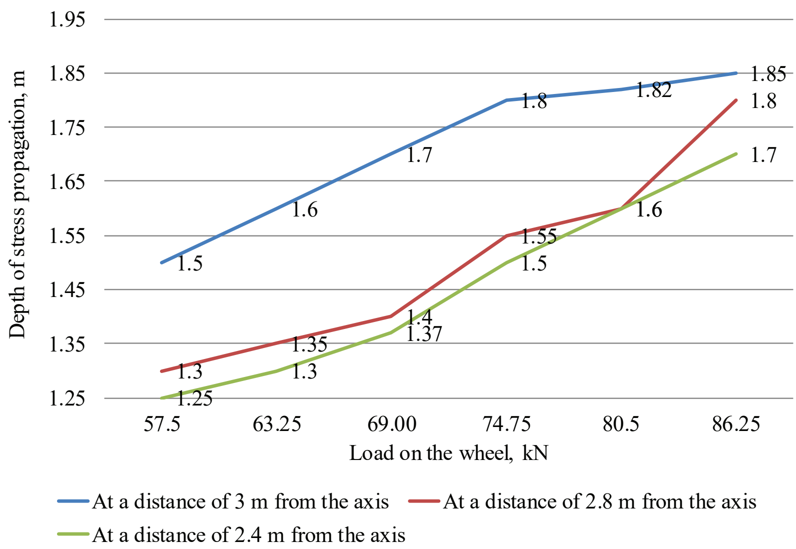

Fig. 13. The depth of stress propagation from the surface of a road base to the distribution of the minimum values of stresses, at which water would not be squeezed out of loamy soils N_z=0.01 MPa

Based on the results of a numerical experiment, one notes the increase in the propagation depth of stress $h_{\sigma_{min}}$ from the surface of a road base to the distribution of the minimum values of stresses at which water would not be squeezed out of the EB soil. Under a normative load, water is not squeezed out of soil.

5. 2. Determining the squeezing of water into a drainage layer under the influence of excess load

By analogy to the method, proposed in work [1], to determine the parameters of soil subsidence at drying out or when melting, we derive the dependences for relevant indicators under the influence of excess load on a road structure.

The relative subsidence of soil under the influence of excess load is determined from the following dependence:

$$Z_P = e_{sub.p}\left(h_{\sigma_{\min}} - h_P\right)\cdot 10^3, \qquad (1)$$

where $e_{sub.p}$ is the relative subsidence of soil under the influence of excess load, fractions of unity; Z_P is the deformation of a road structure at the depth level h_P under the drainage layer, in the projection onto the $X0Z$ plane under an excess load, mm; h_P is the total thickness of a road base, including the base drainage layer, m; $h_{\sigma_{\min}}$ is the depth of stress propagation from the surface of a road base to the distribution of the minimum values of stresses at which water would not be squeezed out of the soil, m.

Thus, from formula (1), we obtain

$$e_{sub.p} = \frac{Z_P}{\left(h_{\sigma_{\min}} - h_P\right)\cdot 10^3}. \qquad (2)$$

The calculation of the relative soil subsidence $e_{sub.}$ after defrosting was in [1] performed on the basis of the experimentally defined coefficient of the linear soil subsidence a_{sub}. Under a similar approach, we determine the relative soil subsidence $e_{sub.p}$ under the influence of loading from the following formula:

$$e_{sub.p} = 1 - \frac{1 + a_{sub.p}W_{opt}}{1 + a_{sub.p}W_{MC}}, \qquad (3)$$

where W_{opt} is the optimum soil moisture content, fractions of unity; W_{MC} is the full soil moisture content, fractions of unity; $a_{sub.p}$ is the coefficient of the linear soil subsidence under the action of loading, dimensionless quantity.

Based on the results of a numerical experiment employing the PRK SCAD Office, we determine the values of Z_P, $h_{\sigma_{\min}}$ and, according to dependence (2), $e_{sub.p}$.

Next, after transformation (3), represent in the form of the following ratio

$$a_{sub.p} = \frac{e_{sub.p}}{W_P\left(1 - e_{sub.p}\right) - W_{opt}}, \qquad (4)$$

where full moisture content is determined from the following ratio

$$W_{MC} = \left(\rho_s - \rho_{sk.\max}\right)\rho_w / \left(\rho_s \cdot \rho_{sk.\max}\right), \qquad (5)$$

where ρ_s is the averaged value of soil particles' density, kg/m^3; $\rho_{sk.\max}$ is the maximum density of the soil skeleton based on the method of standard compaction, kg/m^3; ρ_w is the water density, kg/m^3 (ρ_w=1,000 kg/m^3).

A soil compaction coefficient after the effect of excess loading can also be determined by analogy to when soil dries:

$$K_{com.p} = \frac{K_{com.\min}}{1 - e_{sub.p}}, \qquad (6)$$

$K_{com.\min}$ is the minimum allowable soil compaction coefficient.

Water is squeezed out of a layer of soil under the influence of excess loading from the level of depth h_P to the level $h_{\sigma_{\min}}$ Similarly to defrosting [1], while additionally considering the $a_{sub.p}$ coefficient, the squeezing of water under a roadway can be determined from the following dependence:

$$q_{pres.r.w.p} = \left\{ \begin{array}{l} \rho_{sk.\max 1}\cdot a_{sub.p1}\left(\begin{array}{l} K_{com.p1}\cdot W_{MC1} - \\ -K_{com.1}\cdot W_{opt1} \end{array}\right) h_{dr.l.} + \\ +\rho_{sk.\max 2}\cdot a_{sub.p2}\left(\begin{array}{l} K_{com.p2}\cdot W_{MC2} - \\ -K_{com.2}\cdot W_{opt2} \end{array}\right)\times \\ \times\left(h_{\sigma_{\min}} - h_P\right) \end{array} \right\} \omega_s / \rho_w, \qquad (7)$$

where $\rho_{sk.\max 1}$, $\rho_{sk.\max 2}$ is the maximum density of the soil skeleton based on a standard compaction method of the drainage sandy layer and a layer of the EB soil, respectively, out of which water is squeezed under the influence of loading, kg/m^3; $a_{sub.p1}$, $a_{sub.p2}$ is the coefficient of linear subsidence of the drainage sandy layer and a layer of the EB soil, respectively, out of which water is squeezed under the action of loading, a dimensionless quantity; $K_{com.1}$, $K_{com.2}$ is the coefficient of compac tion prior to load application of the drainage sandy layer and a layer of the EB soil, respectively, out of which water is squeezed under the action of loading; $K_{com.p1}$, $K_{com.p2}$ is the coefficient of compaction after load application of the drainage sandy layer and a layer of the EB soil, respectively, out of which water is squeezed under the action of loading; W_{opt1}, W_{opt2} is the optimum humidity of the drainage sandy layer and a layer of the EB soil, respectively, out of which water is squeezed under the action of loading, fractions of unity; W_{MC1}, W_{MC2} is the full moisture content of the drainage sandy layer and a layer of the EB soil, respectively, out of which water is squeezed under the action of loading, fractions of unity; $h_{dr.l.}$ is the thickness of a drainage layer, m; ω_s is the area of the cross-section of soil, m^2 (ω_s=1 m^2).

Calculate the squeezing of water out of a soil layer under the influence of excess loading on the surface of the coating by the wheel of an estimated vehicle of 86.25 kN at a distance of 2.8 m from the axis. We have the following source data for the considered road of category II: $\rho_{sk.\max1}$=2,000 kg/m^3, $\rho_{sk.\max2}$=1,800 kg/m^3, $K_{com.1}$=1, $K_{com.2}$= =0.98 (according to standard requirements [DBN]), W_{opt1}= =0.06, W_{opt2}=0.1, $h_{dr.l.}$=0.3 m (according to Table 1), h_P= =1.1 m, ρ_s=2,650 kg/m^3 for sand, $h_{\sigma_{\min}}=1.8$ m (according to Fig. 13), and Z_P=2.01 mm (according to Fig. 12, *a*).

The magnitude of the relative subsidence of a road base under the influence of excess loading, according to (2):

$$e_{\text{sub.}p}=\frac{2.01}{(1.8-1.1)\cdot 10^3}=0.0029.$$

The full moisture content, according to (5), of the drainage sandy layer and a layer of the EB soil, respectively, out of which water is squeezed under the action of loading:

$$W_{MC1}=(2{,}650-2{,}000)1{,}000/(2{,}650\cdot 2{,}000)=0.123;$$

$$W_{MC2}=(2{,}650-1{,}800)1{,}000/(2{,}650\cdot 1{,}800)=0.178.$$

The coefficients of the linear soil subsidence, according to (4):

$$a_{sub.p1}=\frac{0.0029}{0.123(1-0.0029)-0.06}=0.046,$$

$$a_{sub.p2}=\frac{0.0029}{0.178(1-0.0029)-0.1}=0.037.$$

The compaction coefficients after the action of excess load, according to (6):

$$K_{com.p1}=\frac{1}{1-0.0029}=1.0028,$$

$$K_{com.p2}=\frac{0.98}{1-0.0029}=0.982.$$

After preliminary calculations, according to (7), the squeezing of water out of a layer of soil under the influence of excess loading on the surface of the coating by the wheel of an estimated vehicle of 86.25 kN:

$$q_{pres.r.w.}=$$
$$=\left\{\begin{aligned}&2{,}000\cdot 0.046\begin{pmatrix}1.003\cdot 0.123-\\-1\cdot 0.06\end{pmatrix}0.3+\\&+1{,}800\cdot 0.037\begin{pmatrix}0.982\cdot 0.178-\\-0.98\cdot 0.1\end{pmatrix}(1.8-1.1)\end{aligned}\right\}1/1{,}000=$$
$$=0.0054\ \text{m}^3\ \text{per 1 m}^2$$

In other words, under the influence of excess loading, the drainage layer of a road base would receive additionally 5.4 liters of squeezed water per 1 m^2 of the area.

6. Discussion of the results of forming humidity conditions for a drainage layer in a road structure under the influence of loading

Based on the model of an element in the three-dimensional linearly-stretched road structure, we have investigated its strained-deformed state and predicted the humidity mode for the drainage layer under the influence of normative and excess loading. The estimated model of such a linear element of the motor road is significantly different from the planar facilities related to civil construction examined in works [9, 11]. In a place where the normative and excess loading is applied, there is a change in the configuration of the deflection bowl (Fig. 7, 8). When increasing the load by 50 %, the size of the bowl in the plan increases by 2 %. As regards the distribution of vertical stresses within the roadway, water would start to be squeezed already at the normative loading under the roadsides and in the zone of the EB sloped part (Fig. 9, *a*, *b*, 10, *a*, *b*). Under the excess loading on the surface of the coating by the wheel of an estimated vehicle of 86.25 kN, the migration of moisture from the bottom upwards under the roadway would occur from a layer of the EB soil of thickness 60–70 cm (Fig. 13). The deformation in this layer could reach 2.01 mm, and on the roadway, at such an increase in loading, increases to 2.76 mm, which is 12 % larger than the effect exerted by the normative loading (Fig. 11, *a*, *b*, 12, *a*, *b*).

When applying the load in the most unfavorable place, at the strengthened lane of the curb, the distribution of vertical stresses is significantly changed, especially at the slopes of the structure (Fig. 9, *c*, 10, *c*). This is confirmed by many field observations regarding the emergence and distribution of deformations of a road surface and the EB slopes. There is the destruction of the edges of the road base, ranging from individual cracks to chipping and breaking the edges of the roadway. Under the influence of the normative loading (Fig. 9, *c*), this zone experiences the process of squeezing out moisture from a layer 40 cm thick. This can be determined from the fact that the total thickness of a road base is 110 cm, and the isoline of the distribution of the minimum values of stresses at which water would not be squeezed is within the depth of 150 cm. When increasing the loading by 50 % above the normative loading, the migration of moisture would occur in the EB soil layer with a thickness exceeding 75 cm (Fig. 10, *c*). The deformations would spread to the edge of the EB slopes where they amount, under the normative loading, to 1.68 mm (Fig. 11, *c*), under the excess loading, to 1.81 mm (Fig. 12, *c*). The deformation on the roadsides is 1.98 mm and 2.15 mm, respectively. Water would also be squeezed under the strengthened lane of the curb and in the zone of an EB slope, which could further weaken the vulnerable zones of a road structure.

The numerical experiments allowed us to determine a change in the depth of the squeezing of moisture from the EB soil to the drainage layer based on the depth of the spread of the stress from the surface of a road base to the distribution of the minimum values of stresses at which water would not be squeezed out of loamy soils (Fig. 13). The source data for a II category road correspond to the conditions of the road-climatic zone I in Ukraine. For this zone, according to [16], the level of the total excess water (due to infiltration and defrosting) entering the drainage layer, from the highest to the lowest, fluctuates over a wide enough range: 0.03–0.017 m^3 per 1 m^2. Given this, the total specific water volume, taking into consideration the squeezing out of a soil layer under the influence of excess loading of 86.25 kN, would reach from 35.4 to 22.4 liters per 1 m^2. This would significantly change the humidity condition of a road base and worsen the general module of elasticity. The forecast about the amount of squeezed water under the roadway may be obtained, according to (7), based on the values of relative soil subsidence (2), the linear subsidence coefficients (4) and soil compaction coefficients under the influence of the excess loading (6). Failure to follow the requirements for the operation of highways due to increasing the loading above the normative loading leads to a change in the humidity regime of the entire road structure exactly in one of the most dangerous spring periods. This underlies the development not only of the track formation but also the formation of recesses in the newly built section of a road.

The acting method to calculate the humidity condition of a road structure under the influence of loading [1] is outdated and does not meet modern regulatory requirements. Current estimated loading exceeds the loading based on which a road base was designed, by two times. These circumstances predetermined significant changes in the approaches to the calculation of road structures in terms of moisture migration and the need to involve modern calculation complexes for determining the stressed-strained state (SSS) of an overwetted road structure.

The proposed prediction of the humidity mode of the drainage layer of a road structure under the action of the static load has been determined from the conditions of the impact exerted by the stamp from a single wheel of a vehicle. More detailed could be forecasting under the influence of loading on the axle, by two or four wheels, which is the next step of our study.

7. Conclusions

1. Underlying a road structure model with the draining layer in the PRK SCAD Office are the volumetric finite elements, which are used to solve a spatial problem from the elasticity theory, for the isotropic, transversal-isotropic, orthotropic, and anisotropic materials. The structure of the finite-element grids was determined based on the conditions of a vehicle wheel's stamp under statistical loading. When applying the ligaments of the support nodes to the proposed model, we decided not to limit the movement of the nodes along its contour, so that the assignment of such ligaments would not reduce the deformation of the model and could be consistent with the actual conditions of a road structure operation.

2. Numerical modeling of the SSS of a road structure under the influence of the normative and excess static loading was performed, using an example of the road of category II. The derived distribution of the isofields and isolines of the normal stresses N_z and deformations Z in the volumetric elements has allowed us to determine the configuration of the deflection bowl depending on the place of load application. In addition, we defined the amount of deformation in a road structure under the drainage layer, which ranges from 2.01 to 2.04 mm under the normative and excess loading. The squeezing of water, accordingly, occurs from a layer of the EB soil with a mean thickness of 0.27 to 0.67 m.

3. To predict the humidity regime of the drainage layer, we derived the estimation dependences of the value for the relative soil subsidence, the coefficients of linear subsidence and compaction of soil under the influence of excess loading on a road structure. We have determined the value of the specific squeezing of water out of a layer of soil under the influence of excess loading. Under the load from a wheel of 86.25 kN under conditions of the road-climatic zone II of Ukraine, the level of the general specific excess of water entering a drainage layer can increase by 18–32 %.

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PREDICTING DEFORMATIONS IN THE AREA OF IMPACT EXERTED BY A BRIDGE CROSSING BASED ON THE PROPOSED MATHEMATICAL MODEL OF A FLOODPLAIN FLOW

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To develop the methods for predicting deformations on floodplain areas in the zone of influence of bridge crossings, a mathematical model of a suspended flow with grass vegetation was developed. The problem of calculating the hydrodynamic fields of velocities and pressure in artificially compressed flows refers to the theory of shallow water since the vertical size (flow depth) is substantially smaller than the horizontal dimensions, such as length and width. In accordance with this, the proposed model is based on the equation of distribution of velocity structure and the depth of a floodplain flow in approximation to two-dimensional dependences taking into consideration force factors. Force factors determine resistance at flowing around vegetation in floodplain areas and resistance of washout of fine-grained soil.

To obtain an unambiguous solution of the considered problem, boundary and initial conditions were added to the presented closed system of original equations. These conditions make it possible to determine the level of a free surface of flow and the zone of influence of a bridge crossing at different stages of the estimated flood. Based on finite-difference analogs of transfer equations, the distribution of velocities and depths in estimated sections was calculated. By iteration, the longitudinal velocity in a flood flow with vegetation elements was determined. The results of the calculation of washout on floodplain areas of a sub-bridge watercourse of the lowland river Siversky Donets were obtained. The depth of a flood flow after a washout was determined based on the ratios of actual and flood-free velocities. When compared with the initial bottom marks, the washout of the larger floodplain is 0.96 m, that of the smaller floodplain – 1.28 m.

The proposed scientifically substantiated solution for ensuring optimum interaction of floodplain flows with bridge crossings makes a certain contribution to improving the reliability of their operation due to the quality of design works and the corresponding reduction of construction and operating costs

Keywords: zone of bridge influence, bridge crossing, floodplain vegetation, suspended flow, deformation on floodplains, floodplain flow, turbulence models

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1. Introduction

The relevance of research is proved by the analysis of destructions of bridge crossings, which suffer most from natural disasters – high floods. Deformation of a watercourse, floodplain areas, washouts of intermediate supports and props can reach such critical dimensions, which become the main cause of emergencies on bridges. The main requirement