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INVESTIGATION OF THE WORK OF THE ROAD CONSTRUCTION AT THE SITES BY PIPE DRENES FROM MATERIALS OF DIFFERENT ORIGIN

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Досліджено умови роботи нетипових дорожніх конструкцій з трубчастими дренами різних за походженням матеріалів під впливом власної маси та нормативного навантаження рухомого складу. Числові експерименти визначення напружено-деформованого стану проводилися за допомогою системи SCAD. Було визначено доцільність застосування труб, які за міцносними характеристиками витримують навантаження на дорогах найвищої I-ї технічної категорії

Ключові слова: дорожня конструкція, дренаж мілкого закладання, трубчаста дрена, полівінілхлоридна труба, бетонна труба

Исследованы условия работы нетиповых дорожных конструкций с трубчатыми дренами различных по происхождению материалов под воздействием собственной массы и нормативной нагрузки подвижного состава. Численные эксперименты определения их напряженно-деформированного состояния проводились с помощью системы SCAD. Была определена целесообразность применения труб, которые по прочностным характеристиками выдерживают нагрузки на дорогах высокой I-й технической категории

Ключевые слова: дорожная конструкция, дренаж мелкого заложения, трубчатая дрена, поливинилхлоридная труба, бетонная труба

1. Introduction

Reliability and durability of automobile roads are provided by the proper structures of road cover and earth roadbed, as well as the proper state, which in turn depends on loading and water-thermal mode (WTM). A mismatch between actual strength and geometrical parameters of an automobile road and a continued increase in the loading and motion speed leads to the destruction of road surfacing, which predetermines its elevated water-permeability. The accumulation of moisture in the lower layers of road surfacing and in a working zone of the earth roadbed occurs due to defects in road cover, non-levelled or damaged roadside, a divider strip, and because of destruction of the tubular drain structures of shallow laying. This generally leads to the loss of carrying capacity of a road structure.

At present, existing methods for determining the parameters of drain structures of shallow laying in a road structure are fragmented in character and are primarily aimed at providing for sufficient water flow capacity.

The presence of drain structures of shallow laying under the layers of road surfacing necessitates consideration of this issue from a different perspective. Such a road structure is non-typical, in contrast to standard ones. Draining should provide not only for the optimal mode of water removal, but, in addition, it should not decrease the strength of a road structure.

Tubular drain structures must withstand compressive stresses and maintain the required structural properties over a long time of exposure to the layers of road surfacing, located above, and to temporary loads of rolling stock. Methods for calculating the road surfacing do not take into consideration the presence of openings in the body of a road structure. We propose numerical modeling of the stressed-strained state of road structure, weakened by the tubular drain system, using modern computational complex SCAD. This makes it possible to determine stresses and deformations in the zone of a body of tubular drains. Such an approach ensures scientifically-substantiated approaches to designing non-standard structures and taking optimal design decisions.

2. Literature review and problem statement

The issues of designing, construction, and operation of drain systems at automobile public roads were addressed in papers [1–5]. At present, methods for determining para-

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meters of elements of drain structures are of fragmented character. Designing calculations frequently employ empirical dependences [1]. More attention is paid to the task on controlling water-heat regime of road structures, the distribution of systems for surface water removal [2, 3], influence of the state of a wet cover and damaged roadsides on traffic safety [4]. It was also important to analyze data on the field monitoring of the examined sections of motor roads in Ukraine [5], which made it possible to consider the impact of change in the thickness of a drain layer on the overall modulus of elasticity of road surfacing. The methods for calculation and design of drain structures of shallow laying, proposed in papers [1–5], are mostly based on determining the volume of water accumulation in earth roadbed and the diameter of tubular drains; they also lay the basis for the development of technological measures to control water-thermal mode of a road structure. The types of drain structures and the necessary nomenclature of materials are assigned based on the experience of designers and recommendations of customers. Up to now, no studies have been conducted on the stressed-deformed state (SDS) of a road structure that would take into consideration the weakening zones that occur due to the presence of round openings – drainage pipes.

One of the urgent problems in the functioning of drainage systems is the environmental aspects related to blocking with waste from construction, agricultural industries [6], pollution of urban water [7]. The focus of these studies is to determine the effectiveness of using sustainable materials of different origin in urban drainage structures (SuDS). The results reported in [7] allowed the authors to outline a series of measures to reduce pollution of surface waters, which contain solid substances, heavy metals. The research conducted in papers [6, 7], did not, however, tackle the issues regarding the characteristics of SDS of a road structure with circular openings – drainage pipes.

Most of motor roads in the Ukrainian network have a non-rigid road surface. Non-rigid road surfacing is a multilayered structure, which is erected using a variety of building materials, inorganic and organic, with different properties in terms of water absorption and water removal. A drawback of these covers is the enhanced sensitivity to repeated loads, especially at elevated temperatures. Normative loads make up 6 to 12.5 tons per axle of a vehicle depending on the category of a road, but the actual loads typically exceed the rules by 30–40 %.

At present, there is a tendency to increase the thickness of road surfacing by laying the upper layers of road cover that are more expensive. However, the destruction of non-rigid surfaces occurs not only when there is an overload, but also when the earth roadbed and the road surfacing base are deformed. More effective measures for improving the strength of earth roadbed is the installation of reinforcement layers or the regulation of its water-heat regime, rather than increasing the thickness of a road structure by the upper, costly layers. Particularly acute is this problem at the sections of automobile roads with an inclination exceeding the lateral one, in places of concave vertical curves for the longitudinal profile of the road, and at transitions from hollows to mounds where drain structures of shallow laying are typically built. At these sections, in order to ensure optimal conditions for draining a road surfacing base, a road structure includes tubular drain slits. Paper [8] investigated conditions for functioning respective sections of railroads where there are no drain structures of shallow laying; and considered the expediency of building drains in order to improve conditions of work of a bearing structure. The authors outlined measures to control water-heat regime of earth roadbed with subsequent selection of parameters for drainage pipes, which, however, disregard their impact on SDS of the structure in general.

Such an approach to the calculation of SDS under the action of load in road structures without tubular drains is generally accepted; it is based, according to [9–11], only on the physical-mechanical properties of layers in a cover and in a base.

Laboratory study [12] to estimate the impact of pipe made of high-strength polyethylene steel in drain structures of shallow laying made it possible to determine the deformation of road cover at cyclic loading due to the influence of mirroring the outline of the pipe onto the layers of road surfacing. To prevent the occurrence of subsequent deformations, the authors determined the depth of laying a tubular drain. The question, however, is about the match between the depth of laying a drain and the depth of water filtering flow formation under the road surfacing; conditions for using tubular drains with different physical-mechanical properties were not considered.

When physical-mechanical properties of materials of different origin are not appropriate, or when strength characteristics of drainage pipes are insufficient, or when loads exceed the normative ones, there may occur the destruction of drains themselves. The expediency of using polyvinyl chloride (PVC) pipes was considered in papers [13, 14]. The authors proposed a new method for measuring the rigidity of samples of PVC pipes after exposure to different environments and described operational characteristics for their use in soil environments with consideration of their own mass. Not addressed, however, is the issue of durability of the material of tubular drains under the action of load from rolling stock in road structures.

The consequences of progressive deformation and destruction of both tubular drains and road cover remain almost invisible over a long period, but their existence contributes to increased water accumulation under the layers of road surfacing. Accordingly, there is a need to study the distribution of stresses in road structures with drain structures of shallow laying because they are constructed in the lower layers of road surfacing base. These layers must ensure reduction in the deflection of the cover caused by the load of vehicles, as well as redistribute stresses on earth roadbed to permissible values [15, 16]. The work of these layers, as well as their stressed-deformed state, however, was not considered in combination with round openings in tubular drains.

It is necessary to establish a new effective approach to determining SDS of a multilayer structure, weakened by tubular openings. This predetermines the choice of the required design parameters for drain structures of shallow laying in order to ensure a general carrying capacity of a road structures at sections of motor roads with an inclination that exceeds the lateral one, in places of concave vertical curves for the longitudinal profile of the road, and at transitions from hollows to mounds.

3. The aim and objectives of the study

The aim of present work is to study the work of road structures at sections with transverse drain structures of shallow laying based on numerical experiments for determining the stressed-strained state. This would make it possible:

– to propose effective structural-technological solutions for the design of drainage systems in the working zone of road structures (a zone that accepts the largest loads from traffic flow);

– to predict the necessary measures to control water-heat regime taking into consideration dimensions of tubular drains, caused not only by the volumes of water accumulation, but also ensuring the required SDS of a road structure in general, as a multi-layered medium with round openings.

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

– to simulate road structures with tubular drains made form materials of different origin and to identify main factors that affect operational conditions under the action of own mass and the regulatory load from rolling stock;

– to examine the stressed-deformed state of road structures, weakened by tubular drains with different physical-mechanical properties, by applying the design-computational complex SCAD, using a motor road of category I as an example;

– to propose variants for using, in road structures, tubular drains made from materials of different, in order to ensure optimal operational conditions.

4. Simulation of the stressed-strained state of a road structure at sections with tubular drains

Design of the non-rigid road surfacing for motor roads in Ukraine complies with the sectoral and government standards VBN V.2.3-218-186-2004 «Road surfacing of the non-rigid type», DBN V2.3-4:2015 «Motor roads», which consider in calculations a multi-layered road structure. The presence of tubular drains, built in the layers road surfacing base at certain sections in order to prevent water accumulation, significantly alters the estimation scheme when designing a road structure. These tasks are not accounted by standard approaches based on the normative document «Album of typical structures of road surfacing of the non-rigid type for the estimation loads A1, A2, B». While conducting preset research, we used standard designs of road surfacing, which were supplemented with tubular drainage structures made from different materials.

The tool for studying the stressed-strained state (SDS) of non-standard road structures with round openings was the system SCAD, a design-computational complex based on the method of finite elements (FEM) [17].

We simulated in the SCAD environment the following types of road structures, presented in Fig. 1. We conducted four series of numerical experiments, with two types of tubular drain materials: PVC and concrete pipes. Layer-wise compaction of the fill was implied in trenches. According to each type of a tubular drain material, we simulated different materials as fillers for trenches: sand for a PVC pipe (Fig. 1, *a*); crushed stone and crushed sand mixture for a concrete pipe (Fig. 1, *b*). For the two types of materials for tubular drains we simulated both standard conditions, which imply uniform layer-wise compression of fillers throughout the entire thickness, and actual conditions of construction. Under such conditions, it is impossible to reach the layer-wise uniform compression due to technological complexity in the implementation of these operations, which was predicted in the estimation structural schemes with different coefficients of compaction and respective modules of elasticity of the filler layers of drain trench (given in Table 1, 2, entries 7, 8). Nomenclature and abbreviations for materials of elements of the examined structures, as well as specifications, are given in Table 1, 2.

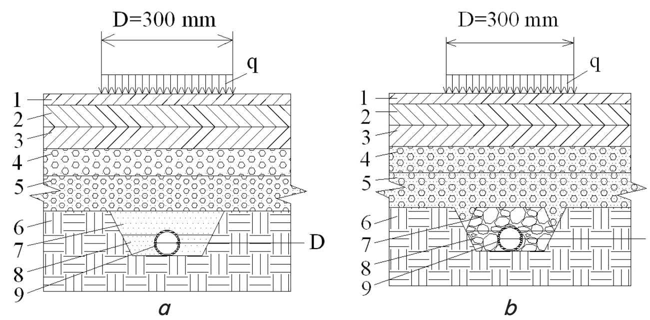


Fig. 1. Models of road structures with drain structures of shallow laying: *a* – with a PVC pipe; *b* – with a concrete pipe; *D* – diameter of the area of a wheel imprint, *q* – evenly distributed load, *d* – diameter of the pipe; 1–5 – layers of road surfacing; 6 – earth roadbed; 7, 8 – filler of the trench; 9 – tubular drain (Table 1, 2)

Table 1

Characteristics of materials of layers of a road structure with a drain structure of shallow laying, with a PVC pipe

Number of entry	Material	Elasticity module *E*, MPa		Layer height *h*, m	Poisson coefficient	Specific weight, t/m^3
		in line with standard requirements	according to actual requirements			
1	SMA with PDA-20 (stone mastic asphalt concrete)	6,000		0.05	0.27	2.4
2	AC.AMH.Cg.D.B.NC.Im.BMP 60/90 (coarse-grained asphalt concrete, dense, type B, non-intermittent composition of granulometry, grade I, with modified by polymers bitumen usage)	4,500		0.1	0.25	2.3
3	AC.AMH.Cg.P.B.NC.I (coarse-grained asphalt concrete, porous, type B, non-intermittent composition of granulometry, grade I)	4,500		0.1	0.25	2.3
4	CSM S-7 reinforced with cement M40 (crushed stone-sand mixture)	550		0.15	0.31	1.8
5	CSM S-5 (crushed stone-sand mixture)	350		0.2	0.31	1.8
6	Loam Wt (0.85)	25		–	0.35	2
7	Sand, 2 backfill (trench) compaction degree 0.98	42	26	0.15	0.3	1.7
8	Sand, 1 backfill (trench) compaction degree 0.95	42	16	0.1	0.3	1.7
9	Drain PVC pipe, SN 8, *d*=90–110 mm	3,000		0.11	0.3	1.4

Table 2

Characteristics of materials of layers of a road structure with a drain structure of shallow laying, with a concrete pipe

Number of entry	Material	Elasticity module E, MPa		Layer height h, m	Poisson coefficient	Specific weight, t/m^3
		in line with standard requirements	according to actual requirements			
1	SMA with PDA-20 (stone mastic asphalt concrete)	6,000		0.05	0.27	2.4
2	AC.AMH.Cg.D.B.NC.Im.BMP 60/90 (coarse-grained asphalt concrete, dense, type B, non-intermittent composition of granulometry, grade I, with modified by polymers bitumen usage)	4,500		0.1	0.25	2.3
3	AC.AMH.Cg.P.B.NC.I (coarse-grained asphalt concrete, porous, type B, non-intermittent composition of granulometry, grade I)	4,500		0.1	0.25	2.3
4	CSM S-7 reinforced with cement M40 (crushed stone-sand mixture)	550		0.15	0.31	1.8
5	CSM S-5 (crushed stone-sand mixture)	350		0.2	0.31	1.8
6	Loam Wt (0.85)	25		–	0.35	2
7	Rubble grade 20–40 mm, 2 backfill, compaction degree 0.98	550	500	0.1	0.31	1.8
8	Rubble grade 20–40 mm, 1 backfill, compaction degree 0.95	550	300	0.1	0.31	1.8
9	Concrete pipe, d=100–118 mm	4,600		0.118	0.3	1.4

Based on the analysis of papers [18–20], we accepted for calculation the scheme in *XOZ* plane, with constraints for displacements (Fig. 2) along the *OX* axis (on each side) and along the *OZ* axis (at the bottom of the model).

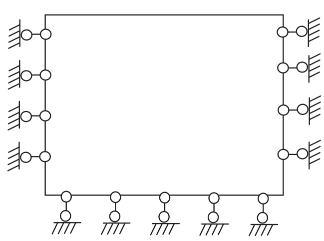


Fig. 2. Estimation scheme of a semi-space

During numerical simulation of the examined structures, we applied load NC100 with an equal diameter of the area of a wheel imprint – 300 mm. The load per axle was taken to be 25 t, per a wheel – 12.5 t, considering uniform distribution q=0.78 t over 16 nodes of the computational grid (Fig. 1). Dimensions of the estimated area were taken as 3×1 m, which is predetermined by the work of non-rigid covers of road surfacing taking into consideration parameters of deflection area under the load [21].

The initial conditions were assigned as follows. According to the size of the estimated area, we introduced coordinates of nodes that restrict this zone. Next, we introduce coordinates of the node that is a center of the drainage pipe. The pipe itself was set by a ring (whose external and internal diameter correspond to the parameters of the pipe). The ring is a polyhedron with 24 edges to form a wall thickness of the pipe. By using the software interface, we assigned characteristics of pipes based on Table 1, 2, entry 9. Next, we construct a triangular grid in accordance with the method of finite elements in the plane and considering the ring as a pipe wall. Next, in the estimated area (beyond the pipe) we combine 3-node elements into 4-node elements. A step of triangulation, assigned to be approximate to the length of an edge of the polyhedron, which simulates the pipe, is 2 cm. We delete elements that happened to be in the «middle» of the pipe ring. We establish links at nodes along the *OX* axis for vertical boundaries of borders in the examined area and along the *OZ* direction for a horizontal section. Using the toolbar, we assign the type of the element – beam-wall. We set characteristics for the elements that make up a road structure in accordance to those characteristics that are given in Table 1, 2 and load due to natural mass of the estimated zone. Next, we construct a scheme of operational uniformly distributed load from the wheels of rolling stock (Fig. 1).

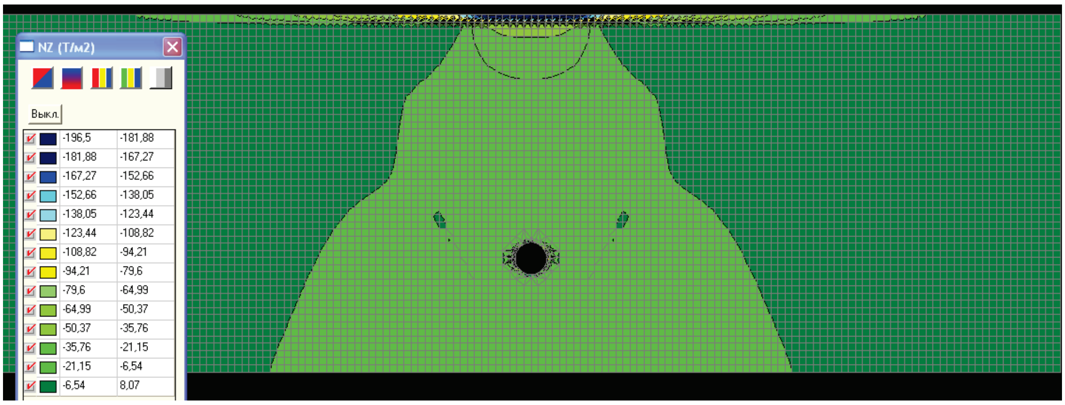
5. Results of research into the stressed-deformed state of a road structure with drainage openings

The results of numerical simulation allowed us to obtain diagrams of normal stresses and deformations of structural layers of road surfacing with a thickness of 80 cm, the backfill of trench and tubular drains with a thickness of 20 cm, the upper layers of earth roadbed with a thickness of 20 cm (Fig. 3, 5, 7, 8), diagrams of normal stresses in the body of pipes (Fig. 5, 7). Calculations were performed both for standard (Fig. 3–8, *a*) and actual (Fig. 3–8, *b*) compaction of the material of backfill of the trench for a PVC pipe and a concrete pipe, respectively.

The results of a series of numerical experiments on determining normal stresses in the body of tubular drains on estimation models (Fig. 5, 7) were compared to the permissible stresses of elongation for such materials as polyvinyl chloride and concrete.

According to the results of calculation based on the model with a PVC pipe under standard conditions for the compaction of trench backfill, the body of a pipe accepts maximum normal stresses of 1.38 MPa, which is 5.5 % of the permissible stress of a given material for elongation; under actual conditions – 1.46 MPa, which makes up 5.8 % of the same indicator [22].

Analysis of results obtained in the course of numerical experiments based on models with a PVC pipe indicates that the presence of an opening in the body of a road structure does not change the stressed-deformed state significantly.



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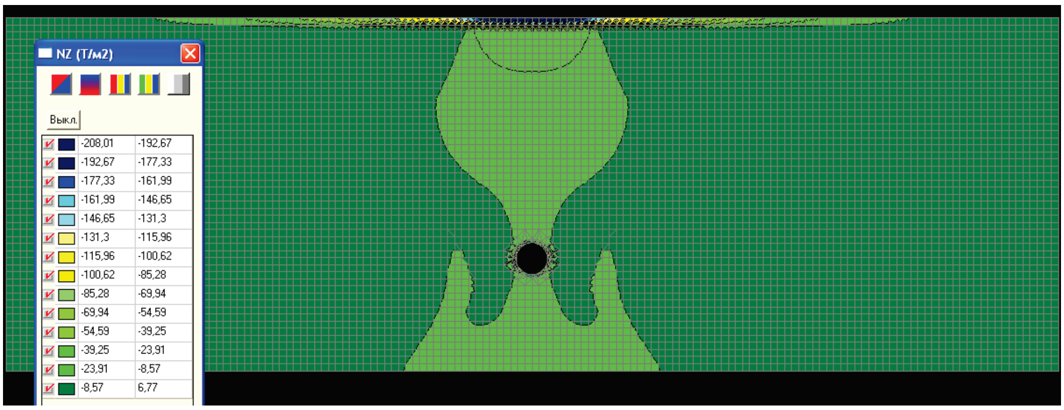
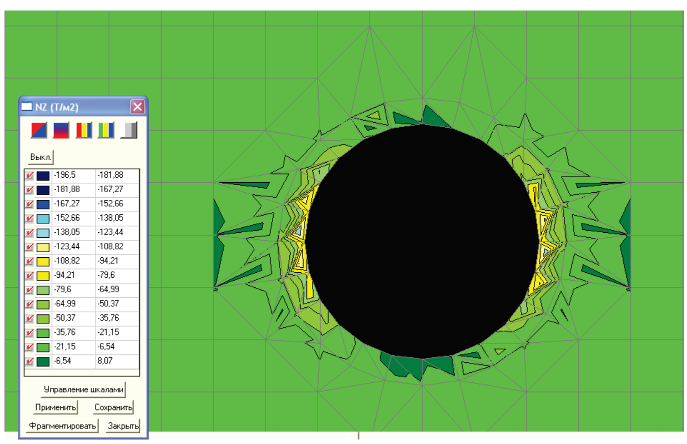


b

Fig. 3. Diagrams of distribution of normal stresses in road structures with tubular drainage of shallow laying with a PVC pipe: *a* – in line with standard requirements; *b* – according to actual conditions



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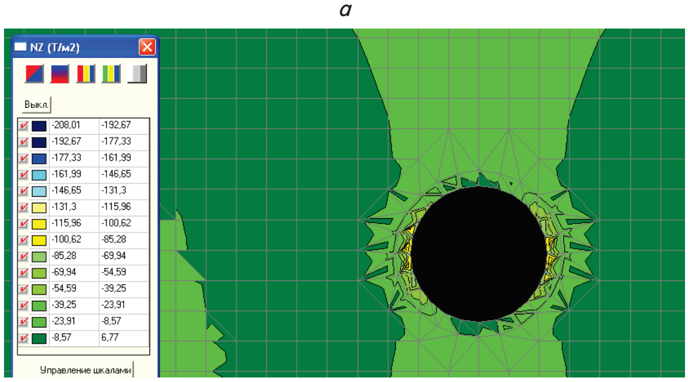
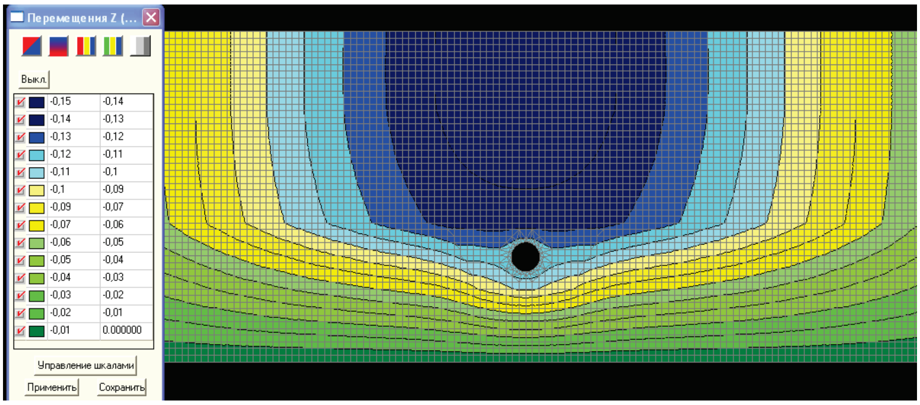


b

Fig. 4. Diagrams of distribution of normal stresses in the body of a PVC pipe: *a* – in line with standard requirements; *b* – according to actual conditions



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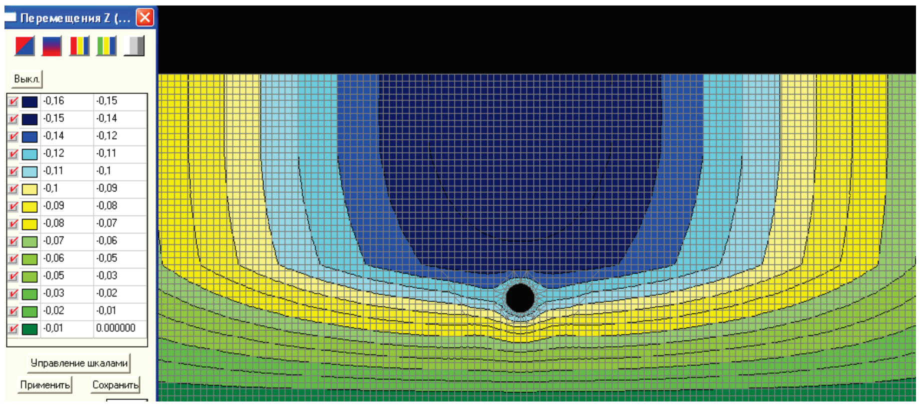
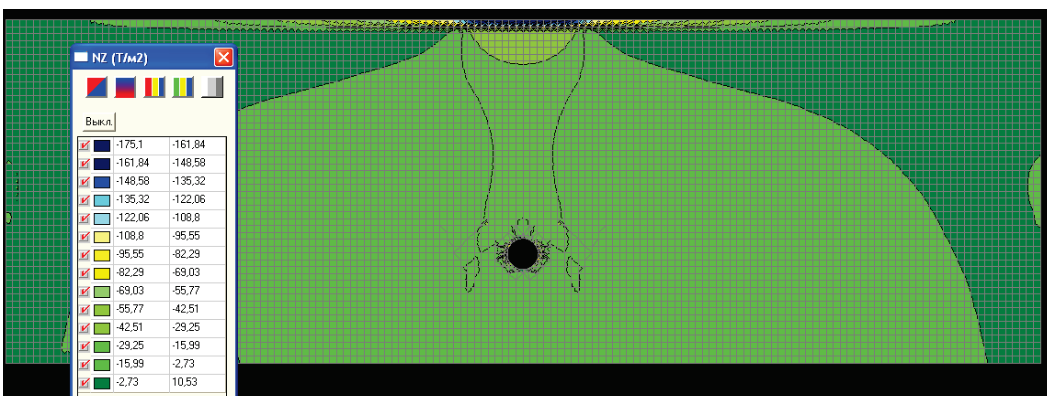


b

Fig. 5. Diagrams of distribution of deformations in road structures tubular drainage of shallow laying with a PVC pipe: *a* — in line with standard requirements; *b* — according to actual conditions



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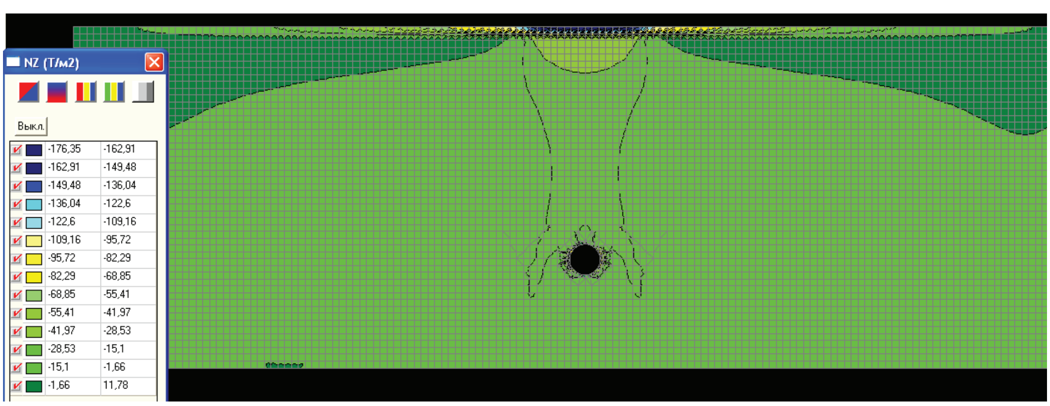

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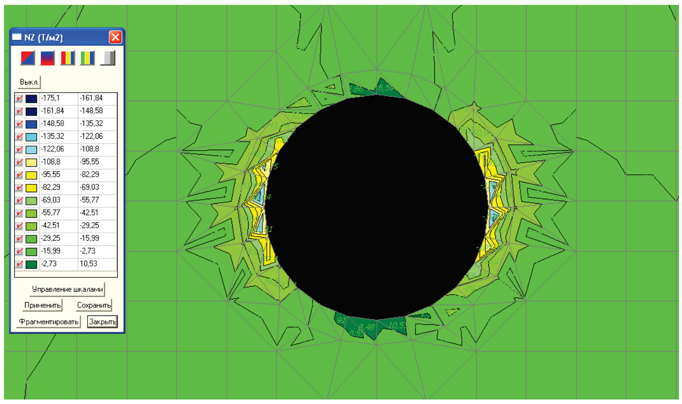
Fig. 6. Diagrams of distribution of normal stresses in road structures with tubular drainage of shallow laying with a concrete pipe: *a* — in line with standard requirements; *b* — according to actual conditions



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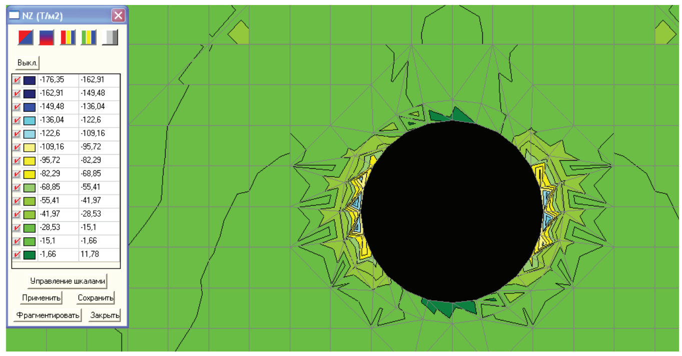
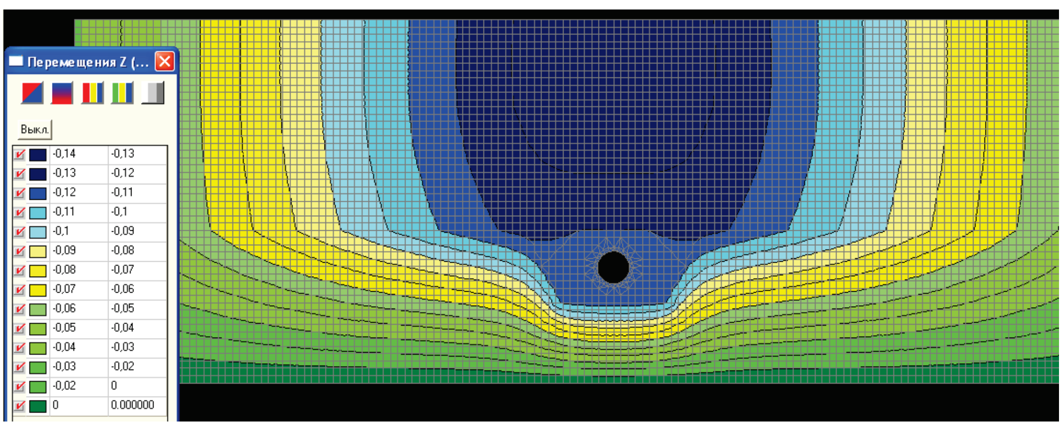


b

Fig. 7. Diagrams of distribution of normal stresses in the body of a concrete pipe: *a* – in line with standard requirements; *b* – according to actual conditions



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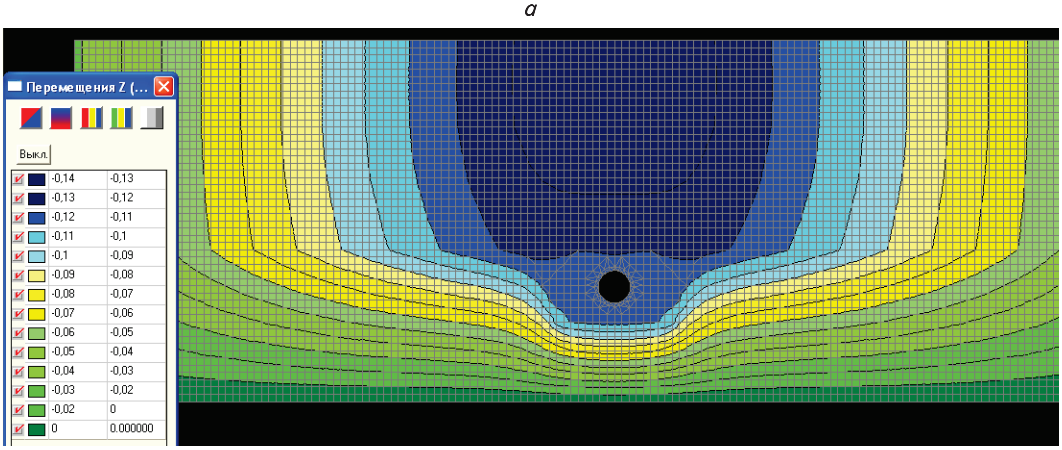

b

Fig. 8. Diagrams of distribution of deformations in road structures with tubular drainage of shallow laying with a concrete pipe: *a* – in line with standard requirements; *b* – according to actual conditions

In contrast, the model with a concrete pipe operates under the extreme-strained state. Consequently, we added crushed sandstone, which additionally accepted and redistributed the load on the body of the pipe (Fig. 1, *b*). Under standard conditions of compaction of the trench backfill, the body of a concrete pipe is exposed to maximum stresses of 1.35 MPa, which makes up 96.4 % of permissible stresses for elongation of concrete. The body of a pipe under actual conditions of compaction of the backfill is exposed to maximum stresses of 1.49 MPa, which amounts to 106.4 % of the same indicator [22]. Given that the stresses in the body of a pipe are exceeded by 6.4 %, there is a very high likelihood of destruction.

All models were loaded identically – 12.5 t per wheel and, accordingly, the deformations of structures were 0.12 mm in the region of drainage openings, which meets the regulatory requirements for these structures.

6. Discussion of results regarding the possibilities of using tubular drains made from materials of different origin in road structures

Consideration of tubular openings in solid layered road structures allowed us to estimate the actual SDS at the sections of roads that require control over WTM. The proposed method of study makes it possible to select individual design-structural parameters for the layers of road surfacing and drainage of shallow laying for public motor roads of different technical categories in contrast to the standard approaches implied by construction norms in Ukraine.

The analysis of research results for four models, the most common in the practice of road and urban construction, revealed that it is appropriate to use PVC pipes in drainage structures. Stresses in the body of these pipes make up approximately 5 % of the permissible stresses for elongation of this material.

The body of a concrete pipe under actual conditions accepts stresses that are 6.4 % larger than the permissible stress of concrete for elongation. It is not desirable to use such pipes for automobile roads of technical category I, which are intended for significant load with high intensity of traffic flow.

Destruction of a concrete pipe can lead to further significant deformations in the structural layers of road surfacing and a road structure in general and, as a consequence, to a substantial change in moisture-heat mode. Accumulation of moisture infiltrate, creating ice lenses results in the destruction of road surfacing layers in winter and spring periods.

It should be noted, however, that the proposed approach may give rise to some difficulties concerning the setting of initial conditions, the distribution of load, in contrast to the simplified standard engineering methods implied by VBN V.2.3-218-186-2004 «Road surfacing of the non-rigid type».

It is an important task to study the stressed-strained state in road structures, which are being built, due to extra loads from technological vehicles, the action of vibration rollers at layer-wise compaction of road surfacing; the present study has considered a finished structure. This requires further research in this direction.

It is also expedient to undertake additional research into the influence of temperature fluctuations on strength of the body of tubular drains.

7. Conclusions

1. We have analyzed operational conditions of non-standard road structures with tubular drains of different physical-mechanical properties under the influence of own weight and normative rolling load in line with construction norms of Ukraine. The reported results of research into the stressed-strained state of a road structure indicate the heterogeneity of stress distribution diagrams around the pipe. It enables to assess condition of the body of pipes made from materials of different origin in the designs of drainage of shallow laying. By performing numerical simulation, we refined parameters of an estimated region depending on the size of deflection area under a load. The numerical experiment was conducted both for standard conditions, which enabled a uniform compaction of layers in the backfill of a drainage trench around the body of the pipe and for actual construction conditions.

2. We have conducted numeric simulation of the stressed-deformed state of road structures with tubular drains made from materials with different physical-mechanical properties using the software complex SCAD. We obtained diagrams of normal stresses and deformations in structural layers of road surfacing, in the backfill for trenches and tubular drains, diagrams of normal stresses in the body of pipes. The results of calculation of the model with a PVC pipe indicate that the body of a pipe under actual conditions accepts maximum normal stresses of 5.8 % of the permissible stress of this material for elongation. The model with a concrete pipe operates under extreme-strained state with the stresses in the body of a pipe exceeding 6.4 % of the same indicator.

3. We have defined the most effective structural-technological solution concerning the use of tubular drains with a PVC pipe in a road structure for general purpose motor roads. The study was conducted at the automobile road of the highest category, which is exposed, in accordance with building norms of Ukraine, to the largest rolling load. The proposed variant meets the requirements to the construction of drain structures of shallow laying in line with the Ukrainian normative document DSTU-N B V.2.3-41:2016 «Guidance on the design of drainage structures of shallow laying on motor roads» for the roads of all technical categories.

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