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IDENTIFYING FEATURES OF THE STRESSED-STRAINED STATE OF A NON-RIGID ROADBED ALONG ASCENTS AND DESCENTS ON HIGHWAYS

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The object of this study is the asphalt-concrete layers of non-rigid roadbed on ascents and descents of highways before bridges.

Asphalt-concrete layers of highways on approaches to bridges are one of the most important elements for providing the strength and durability of the entire structure of non-rigid roadbed. On the ascents and descents of approaches to bridges, where the speed of vehicles changes most often, the roadbed is exposed to more intense damage than in other areas. Practical experience shows that one of the most common root causes of the types of destruction of asphalt-concrete layers is disruption of their integrity in the form of cracks, which creates dangerous situations for road users due to premature and more intensive destruction of all road surfaces.

This paper investigates features of the stressed-strained state of asphalt-concrete layers of roadbed on ascents and descents in the areas connecting bridges and overpasses with the embankment. A spatial finite-element model has been considered, which makes it possible to describe the stressed-strained state of each element in the road surface structure induced by the effect of traffic load on it.

Quantitative and qualitative analysis of deformations, displacements, and stresses in asphalt-concrete layers of the structure of roadbed was carried out. Circumstances that can affect the premature formation of cracks and lead to a decrease in the durability of roadbed structures have been identified.

This study makes it possible to identify and eliminate potential dangers that arise during the operation of roadbed. The results could be implemented in the design of roadbed in areas with difficult traffic in the area of ascent and descent, in particular before the bridge. Knowledge of features of the stressed-strained state of roadbed would contribute to the preservation of road infrastructure, could make it possible to improve the comfort and convenience when moving goods and passengers

Keywords: asphalt-concrete pavement, ascent, descent, non-rigid roadbed, stressed-strained state, cracking, durability

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1. Introduction

Asphalt-concrete layers of non-rigid roadbed are the most common on highways, including the ascents and descents before bridges. In recent years, certain features of the problem in their operation have appeared. This is due to an increase in the intensity of car traffic and an increase in the share of heavy-duty vehicles, including heavy-duty trucks. The increased intensity of traffic often leads to traffic jams and the changing mode of movement of vehicles (slowing down, braking, stopping, shifting, etc.), especially on descents and ascents. Such complications of traffic conditions cause certain features in the nature of the stressed-strained state of asphalt-concrete layers, which lead to a decrease in their durability.

Also, the strength and durability of asphalt-concrete layers on the approaches to bridges are negatively affected by the specific conditions of roadbed operation:

– heterogeneity of the road along its length and under different conditions of its operation, which leads to different levels of the stressed-strained state of road structure and different estimated periods of its operation;

– increased probability of traffic jams before bridges, which leads to an increase in the time of traffic loads on the roadbed and, as it is known, contributes to its faster destruction.

In addition, the asphalt-concrete coating along the entire length of an approach to the bridge rests on a base that has a different design. It, in turn, depends on the height of the embankment, the length and characteristics of the section of the floodplain, the structure of the transitional slab, etc.

Those features are not taken into account by the current regulatory documents when calculating the strength of the structure of non-rigid roadbed with asphalt-concrete layers on the approaches to bridges on descents and ascents. They are the cause of the premature formation of various unacceptable types of deformation and destruction, which affect the reduction of the service life of asphalt-concrete layers and the entire roadbed.

The main defects include longitudinal and transverse cracks. They disrupt the integrity of asphalt-concrete layers, reduce the distribution capacity, and are a place of stress concentration in all layers of the roadbed structure. With the onset of cracking, defects develop intensively, which significantly reduce the durability of roadbed: pitting, potholes, subsidence, ruts. All this significantly worsens the operational condition of the entire bridge crossing as a strategically important object, affects the comfort and safety of the movement of vehicles, leads to unforeseen significant material and energy costs as a result of frequent repair work. Therefore, it is a relevant task to investigate features of the stressed-strained state of asphalt-concrete layers in non-rigid roadbeds on the ascents and descents of approaches to bridges.

2. Literature review and problem statement

Currently, non-rigid roadbed with asphalt-concrete layers, which is able to withstand heavy and intensive traffic of vehicles, is the most common on highways with a capital type of coating both abroad and in Ukraine [1].

The calculation of such structure of roadbed is carried out according to the normative methodology, which was devised on the basis of fundamental provisions from the theory of deformable solids and the kinetic theory of solids, well tested, calibrated, adapted, and gradually improved over the past 50 years. At present, in accordance with current regulatory documents [2, 3], its essence is as follows.

During the design of non-rigid roadbeds, the largest load on the axle of motor vehicles, whose systematic movement is expected in the most unfavorable period of the year for the operation of roadbeds, is taken as the calculated load. Calculations are performed taking into account the composition and prospective traffic intensity for the first year of operation. The given estimated prospective traffic intensity is established on the basis of the average daily number of trips in the first year of all wheels located on one side of the vehicle within the limits of one lane of the carriageway according to the appropriate methodology [2], taking into account the lane coefficient, the total number of vehicle brands in the traffic flow, the average daily traffic intensity in both directions of cars of the *i*-th brand in the first year of service, as well as the total coefficient of reduction of the action on the roadbed of the *i*-th brand of vehicle to the calculated dynamic load. In the case of the presence of two-axle vehicles in the traffic composition, the influence of wheels of neighboring axles, located at a distance of less than 2.5 m from each other, as well as the adjacent wheels of a given axle, is taken into account using the appropriate nomograms.

At the same time, the long-term experience of using such a procedure testifies to the feasibility of improving a number of provisions related to the specificity of establishing the stressed-strained state of asphalt-concrete layers in roadbed.

Thus, existing practice indicates an increase in the traffic flow of heavy-duty multi-axle vehicles [4, 5]. Collected statistical data [6] of the traffic intensity, the composition of the traffic flow, and the composition of freight transport on state highways make it possible to characterize the current composition of freight vehicles:

– single-axle (one rear axle) – 43 %;

– two-axle (two rear axles) – 16 %;

– two-, three-axle (rear axles built with a tractor and doubled on a trailer) – 15 %;

– three-axle (rear axles built on a trailer) – 12 %;

– three-axle (rear axles built with a tractor and built on a trailer) – 14 %.

The action of such multi-axle heavy-duty vehicles creates certain features in the nature of the stressed-strained state of asphalt-concrete layers in roadbed [7]. When bending due to the load of pneumatic vehicles in a package of asphalt-concrete layers, tensile horizontal stresses of the appropriate nature [8] occur both in the lower fiber and on the surface. The interaction of closely spaced wheels causes the interaction of tensile stress fields. The specificity of their interaction differs from the nature of the interaction of vertical normal stresses and vertical deflections. However, to take into account the influence of wheels of neighboring axles, or adjacent wheels of a given axle, the corresponding nomograms of the current methodology [2] were built on the basis of experimental data of vertical normal stresses and vertical deflections of the surface [7]. This means that with such widespread mass use of multi-axle heavy-duty vehicles [9], it is necessary to more accurately take into account the nature and features in the stressed-strained state of asphalt-concrete layers in calculations.

Roads and approaches to road bridges are an integral part of the bridge crossing and have the same strategic importance as bridges for the efficient provision of road traffic [10]. However, existing practice of operation shows that only a fifth of them meet the requirements [11]. Today, according to official information, most of these objects in Ukraine need to restore their bearing capacity as a result of the presence of a significant amount of destruction, which characterizes the complete exhaustion of the criteria of the limit state of their roadbed structures, especially due to overloading of vehicles [12].

Analysis reveals that the vast majority of roads that are operated and built on ascents and descents have defects in the form of cracks and potholes [13], less often in the form of ruts [14]. And these, in turn, are the main reasons for the destruction of the asphalt-concrete cover.

Current theoretical and regulatory framework for the calculation of non-rigid roadbed does not take into account the different time of action of the load from vehicles, as well as the action of transport on ascents and descents of highways [15] and needs improvement. There is not enough information in the current normative documents for the design and installation of asphalt-concrete roadbed on ascents and descents for making technical decisions by design engineers at the stage of new construction, regarding the structure of roadbed on them. Using the example of approaches to bridges (overpasses), the authors of [16, 17] show that the studies performed so far did not make it possible to take into account the operating conditions of asphalt-concrete surface on the ascents and descents of highways on a single methodological basis.

In the majority of scientific works, it is proposed to increase the durability of asphalt-concrete through the improvement of a mixture recipe [18], the use of modifiers [10], dispersed reinforcement, and improvement of the work performance technology and in the part of connecting bridge structures with approach embankments [10]. However, as shown in works [11, 13], in many cases premature appearance of destruction and deformations on the surface was observed in the area of junction of the road with the bridge structure.

When analyzing the durability of the roadbed, additional attention should be paid to the peculiarities of traffic on inclined sections (downhills, ascents, and descents, etc.) and the associated additional stresses arising from acceleration or braking [8].

In recent years, many researchers have proposed various ways to improve methods for calculating roadbed structures. In recent years, more and more attempts are being made to use the finite element method to model the stressed state of roadbed under the influence of traffic loads [20]. The finite element method (FEM) provides a relatively good prediction of the stressed-strained state of elastic deflections (deflection cups, vertical and horizontal stresses, and strains) in all layers of multilayer asphalt-concrete roadbeds [21]. A number of limit state criteria are proposed, which make it possible to compare components of the stressed-strained state obtained by FEM for the design of rational structures of multilayer coatings under the action of modern loads from vehicles. However, it is believed that before the proposed limit state criteria can be applied to the design of new roadbeds and reinforcement layers during major repairs for resurfacing, it is necessary to resolve a number of issues related to the verification of the methodology for the purpose of its qualitative and quantitative calibration.

The above indicates that the problem of durability of the asphalt-concrete roadbed on highways was dealt with mainly to increase the durability of the asphalt-concrete roadbed through the improvement of the mixture recipe, improvement of the technology of execution of works. This was usually based on the improvement of structural solutions in the area of junctions of embankments and bridge structures. The studies carried out so far did not make it possible to take into account the operating conditions of the asphalt-concrete roadbed on the ascents and descents on highways on a single methodological basis.

3. The aim and objectives of the study

The aim of our study is to determine features in the stressed-strained state of non-rigid roadbeds in the areas of approaches to bridges under the influence of multiaxial traffic load from the point of view of the impact on the formation of cracks in asphalt-concrete layers.

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

– to build a spatial finite-element model of the effect of a multi-axle cargo vehicle on roadbed with asphalt-concrete layers on approaches to bridges;

– to determine the most significant features that affect the formation of cracks in asphalt-concrete layers on the ascents and descents of approaches to bridges;

– to investigate the influence of a typical cargo multi-axle vehicle on features of the stressed-strained state of asphalt-concrete layers in the zone of the transitional reinforced concrete slab on the ascents and descents of approaches to bridges.

4. The study materials and methods

The object of our research is the asphalt-concrete layers in a non-rigid roadbed on ascents and descents before bridges.

Research hypothesis assumes that durability of asphalt-concrete layers in a non-rigid roadbed on the uphill and downhill sections on approaches to bridges is exhausted with the formation of cracks and depends on the level and nature of their stressed-strained state.

Accepted assumptions are as follows:

– materials of structural elements in a roadbed are considered as quasi-homogeneous isotropic elastic bodies;

– methods from the linear theory of elasticity can be used to determine the stressed-strained state of roadbed under the action of a moving load.

Adopted simplifications are as follows:

– parameters of the traffic load on the structure of roadbed from a four-axle base car, as the most common cargo multi-axle vehicle on public roads, were used for research;

– we considered the most characteristic typical variants of structures of roadbed on highways used for heavy and intensive traffic;

– it is accepted in our study that the joint action of the third and fourth axles of the base car exerts the greatest influence on the stressed-strained condition of the roadbed;

– it is accepted that the trace of the contact of the wheel with the surface of the roadbed is a rectangle;

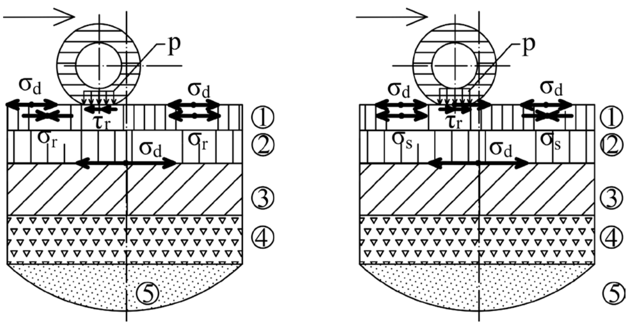
The research methods are analytical, based on a numerical experiment using the LIRA CAD software package. The calculated characteristics of road construction materials for the numerical experiment were taken on the basis of reference data.

5. Results of investigating the stressed-strained state of asphalt-concrete layers in a non-rigid roadbed on the ascents and descents of highways and approaches to bridges

5. 1. Construction of a spatial finite-element model of the structure of a non-rigid roadbed with asphalt-concrete layers

The most dangerous factor that leads to the formation of cracks in asphalt-concrete layers and affects their durability is the action of horizontal tensile stresses, which lead to the breaking of the structural bonds of asphalt-concrete with repeated action. Therefore, when building a spatial finite-element model of the structure of a non-rigid roadbed, the following features of the interaction of the pneumatics of the vehicle with the roadbed were taken into account.

The structure of roadbed on approach to the bridge perceives the effect of vertical loads from passing vehicles. When the asphalt-concrete layers bend due to the action of the transport load transmitted through the pneumatic tire with intensity p, horizontal normal tensile stresses σ_d (σ_x according to LIRA CAD) arise in the lower fiber and surface tensile stresses σ_r (σ_x according to LIRA CAD) on the surface of the coating before the wheel and after it [8]. It is also possible to experience tangential loads from traffic in cases of braking or displacement on slopes and ascents and as a result of the formation of traffic jams (Fig. 1). In the case of braking (Fig. 1, *a*) due to the action of tangential stresses to the surface of the coating under the imprint of the tire with intensity τ_d (τ_{xz} according to LIRA CAD), in addition to the horizontal surface stresses behind the wheel, horizontal normal stresses σ_h will be subtracted after the wheel (σ_x according to LIRA CAD). In the case of braking, it is the opposite (Fig. 1, *b*).



a *b*

Fig. 1. Calculation diagram of the operation of asphalt-concrete layers on approaches to bridges: *a* — under the action of vertical and horizontal traffic load during braking; *b* — the same during displacement; 1, 2 — asphalt-concrete layers; 3, 4 — base layers; 5 — lower layers of the roadbed structure and subgrade soil

The finite element method was used to model the stressed state of roadbed under the action of moving traffic loads. The FORD TRUCKS 4142M EURO5 concrete mixer (10 m^3), with a total weight of 33514 kg (Fig. 4), wheelbase – 8×4.5100 mm, was chosen as the calculation vehicle from the point of view of the location of the pneumatic tires on the model surface; total length 8860 mm; the distance between the 1st and 2nd axles is 2050 mm; the distance between the 2nd and 3rd axle is 3050 mm; the distance between the 3rd and 4th axle is 1330 mm. For the calculation, the load on the third and fourth axle was assumed to be 130 kN. It is assumed that the trace of the contact of the wheel with the surface of the roadbed is a rectangle.

In the study of the stressed-strained state of asphalt-concrete layers on the approaches to bridge, the most common use of transitional reinforced concrete slabs on the connection with the bridge pier was taken into account. The scheme of connecting the bridge structure with the embankment of the approach with the horizontal location of the transition plate is shown in Fig. 2. The length of the transitional plate is 6000 mm (P600.12 430-TA400C). In the studies, the two most common and technological options for arranging the transition plate in the structure were considered:

– semi-recessed (45 cm from the top of the slab to the top of the coating on the opposite side from the beginning of the bridge) inclined transitional slab with a slope of 1:13;

– transition plate arranged horizontally at the depth of the roadbed [22].

A spatial finite-element model was built to calculate the structure of roadbed, which makes it possible to determine the stressed-strained state of each element in the structure (Fig. 2).

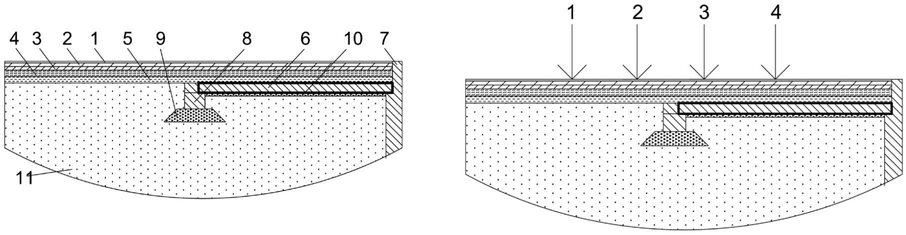
The stressed-strained state of the roadbed structure under the action of traffic loads depends on the nature of distribution of zones of normal σ and tangential τ stresses between the wheels of the truck, the influence of the imposition of stress fields depending on the interaxial distances and the distances between the wheels (Fig. 3, 4).

In the study, different schemes of the location of the truck (Fig. 2) were adopted on the surface of the asphalt-concrete cover of non-rigid roadbed in the zone of connection of the bridge structure with the embankment of the approach.

KE36 – a universal spatial eight-node and isoparametric finite element was used to model transitional reinforced concrete transitional slabs.

Volumetric elements in the backfill soil and base were modeled using KE271-276, which are intended for simulating one-sided compression of the soil, taking into account shear and KE36.

The base soil and the top layer of asphalt-concrete were modeled with KE41 plate finite elements – a universal rectangular finite shell element.



a *b*

Fig. 2. Scheme of connecting the bridge structure with the embankment of the approach: *a* — transition plate is arranged horizontally to the depth of the roadbed; 1—2 — layers of asphalt-concrete coating; 3—5 — base layers; 6 — transition plate; 7 — stoyan (shore support); 8 — lying down; 9—10 — crushed stone pillow; 11 — subsoil (drainage) — sand; *b* — load on a non-rigid roadbed from a four-axle vehicle

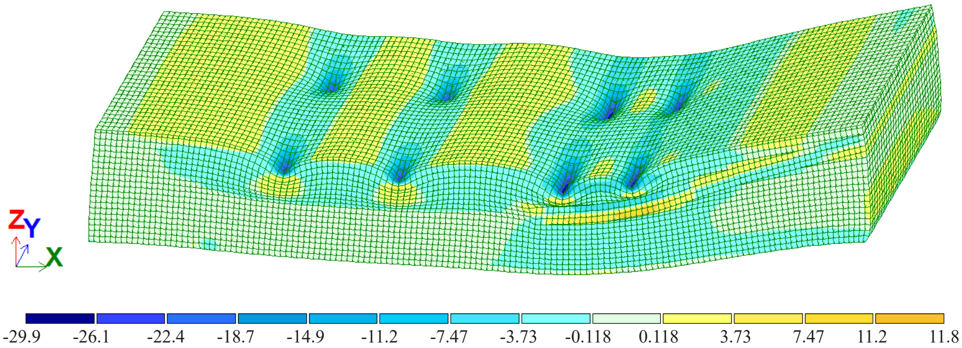


Fig. 3. Model of roadbed operation (built in the LIRA CAD software package) showing how horizontal normal stresses N_X act

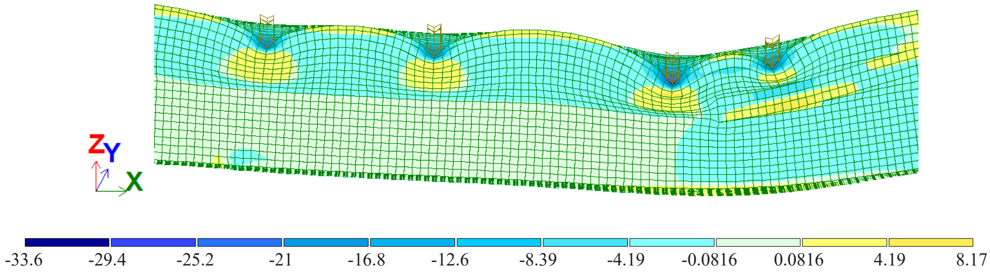


Fig. 4. Fragment of visualization of the stressed-strained state of a roadbed loaded by a base car

Calculations were carried out using LIRA CAD. Fragments of the visualization of the stressed-strained state of a roadbed are shown in Fig. 3, 4.

In the studies, the most characteristic variants of the design of non-rigid roadbed of different solid ability (No. 1–3) were considered, according to Table 1.

Table 1

Designs of non-rigid roadbed

No. of entry	Structural layer materials	Layer thicknesses for roadbed options, cm		
		No. 1	No. 2	No. 3
1	Crushed mastic asphalt concrete (SMA-15) on BMPA 70/100-55 bitumen	5	5	5
2	Dense hot asphalt concrete on BND 70/100 (Type A, Mark I)	10	10	10
3	Hot porous asphalt concrete on BND 70/100 bitumen (Coarse-grained, Grade I)	10	–	–
4	Crushed-sand mixture C-7 of optimal composition, reinforced with M 20 cement	20	20	–
5	Crushed stone-sand mixture C-5 of optimal composition	20	20	20
6	The subsoil is sand	>50	>50	>50

After entering all the necessary initial data and performing calculations with the LIRA CAD software package, transverse and longitudinal sections of the model were made with the help of the tools provided by the program (Fig. 4).

5. 2. Investigating the influence of nature of the action of traffic loads on the stressed-strained state of asphalt-concrete layers in a non-rigid roadbed on the ascents and descents of approaches to bridges

In the existing practice of calculating asphalt-concrete layers for the strength of non-rigid roadbed on the ascents and descents on approaches to bridges, the same approaches are used as for highways. That is, the fact is taken into account that when bending these layers from a vertical moving load, tensile horizontal normal stresses σ_x arise. Taking into account the fact that the greatest values occur in the lower part of the asphalt-concrete layers during bending due to the transport load, only these are used for calculations [2]. However, there are data that emerging horizontal tensile normal stresses of smaller values σ_x on the surface of the cover during repeated action of freight vehicles can also cause the breaking of bonds in asphalt-concrete with the formation of cracks [1, 8, 23]. The results of our numerical analysis also confirmed the occurrence of tensile horizontal normal stresses σ_x of smaller values on the surface of asphalt-concrete layers, adopted for consideration of the most characteristic options for the construction of non-rigid roadbeds under the action of the load from the adopted base car. Thus, Fig. 5 shows an example of the obtained fields of σ_x values in the layers of roadbed in the area of action of the extreme (4th) axis of the base car. In this case, the tensile horizontal normal stresses σ_x on the surface of the asphalt-concrete layers are only 7 % of the stresses in the lower fiber, but they act twice at the same point (before and after the passage of pneumatics). In addition, the duration of their action is longer than the stresses in the lower fiber, which more aggressively destroys the structural bonds of asphalt-concrete. At the qualitative level, the action of tensile horizontal normal stresses σ_x on the surface of asphalt-concrete layers (Fig. 1) and their longer duration can also be observed from the data shown in Fig. 5.

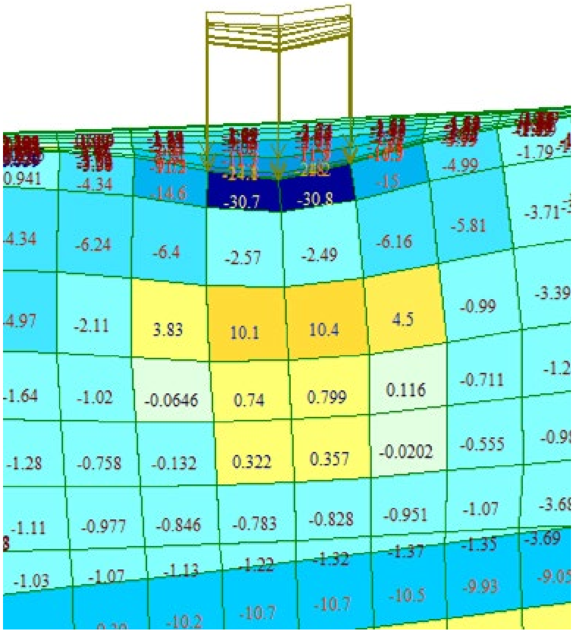


Fig. 5. Field of horizontal normal stresses (dimensionality 10^{-2} mPa) in the layers of the roadbed structure (option No. 2) in the area of action of the extreme (4th) axle of the base car with a load of 130 kN (all cells have dimensions of 10 × 10 cm; the upper row is 5 × 10 cm)

Attention should also be paid to some important features of influence of the nature of traffic loads on approaches to bridges. It involves the existence of an increased probability of the appearance of traffic jams [8]. This means that horizontal tangential stress will act on the surface of the asphalt-concrete roadbed during the stops of vehicles and their movement from the place after the stops. It will act with different intensity depending on the longitudinal slope of the road within the approach to the bridge and depending on the coefficient of adhesion of the pneumatic tire with the coating. Therefore, during numerical analysis, influence of the horizontal tangential stress on the level of the stress state of the asphalt-concrete roadbed was analyzed. In the numerical analysis, the value of the horizontal tangential stress was changed from 0 to 70 % of the value of intensity of the vertical pressure from the pneumatic tire to the surface of the asphalt-concrete roadbed.

On the basis of our numerical analysis, it was established that under the action of horizontal transport loads, in particular braking (Fig. 6), on the roadbed near the border with the imprint of the pneumatic tire on the opposite side from the direction of their action, increased surface horizontal normal stresses σ_r (σ_x) arise.

The results indicate that the maximum value of the horizontal normal surface stresses σ_r (σ_x) is observed at a distance of 0.4 m from the center of pneumatic impression and can exceed the horizontal normal stresses in the lower fiber of the coating when it is bent under the center of the pneumatic σ_d (σ_x).

At moderate values of tangential stresses (τ_d=30 % of p), additional tensile stresses in asphalt-concrete roadbeds can reach the level of maximum tensile horizontal normal stresses σ_x, which occur in the lower fibers of asphalt-concrete layers when they are bent due to the action of vertical transport load; Fig. 7.

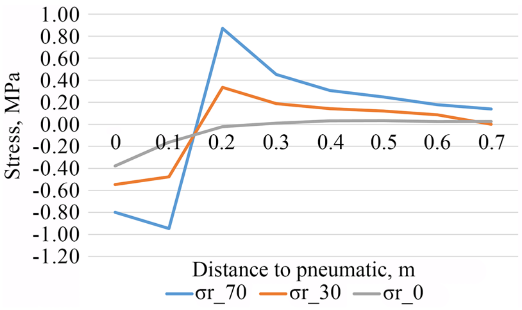


Fig. 6. Change in horizontal normal stresses σ_r (σ_x) in the asphalt-concrete roadbed under a load of 130 kN on axle and different modes of movement (normal movement – 0 %, deceleration – 30 %, and braking – 70 % of p) for the design of roadbed No. 2 with two layers of asphalt-concrete

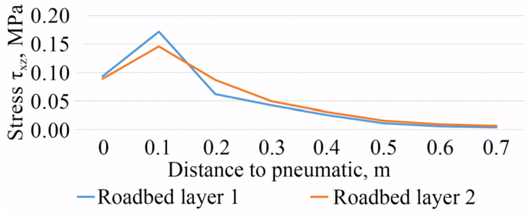


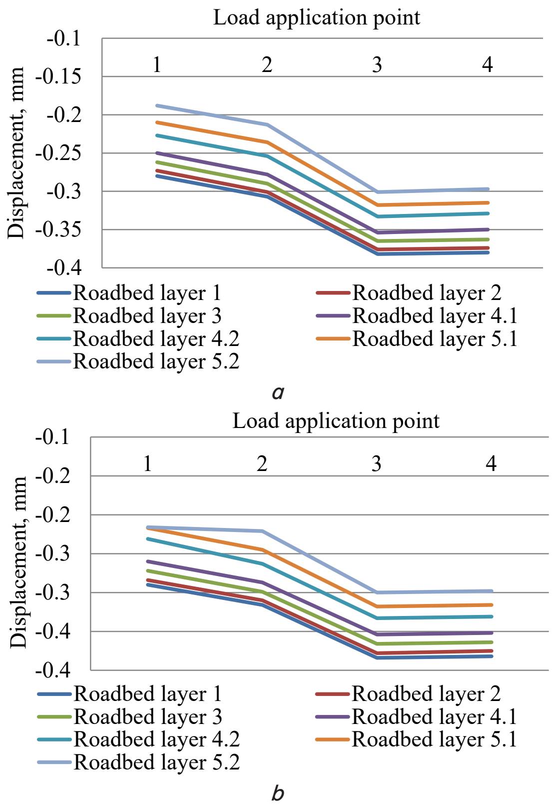
Fig. 7. Change in tangential stresses τ_{xz} in the layers of asphalt-concrete coating under braking from the pneumatic axle 4 at a load of 130 kN for structure No. 2 at a value of τ_d=30 % of p

5. 3. Investigating the effect of a typical cargo multi-axle vehicle on the stressed-strained state of asphalt-concrete layers in the zone of transitional reinforced concrete slab

It is known from practice that the most problematic, from the point of view of the destruction of asphalt-concrete layers, is the section of roadbed in the zone of the end of the transitional slab after leaving the bridge. Analysis of change in the vertical deflection from the location of the transport load in relation to the edge of the transition plate was performed on the example of the structure of roadbed with increased capital capacity (Table 1). The results show that its change towards the edge of the slab undergoes a sharp increase when the 3rd axle of the vehicle is located behind the edge of the slab (Fig. 8).

In this case, regardless of the angle of inclination of the transition plate, such a sharp change in the vertical deflection of the surface of the coating leads to a change in the curvature of the entire package of asphalt-concrete layers and causes more unfavorable conditions from the point of view of the action of horizontal normal tensile stresses in the asphalt-concrete layers of roadbed. Fig. 9 shows a change in the investigated horizontal normal stresses σ_y and σ_x depending on the location of the vehicle in relation to the transition plate – on the transition plate in position No. 3 (Fig. 9, *b*), where the 3rd axle of the vehicle is at a distance of 5500 mm from 0 bridge support, and outside the transition plate in positions No. 2 (6000 mm from 0 bridge support) and No. 1 (6500 mm from 0 bridge support).

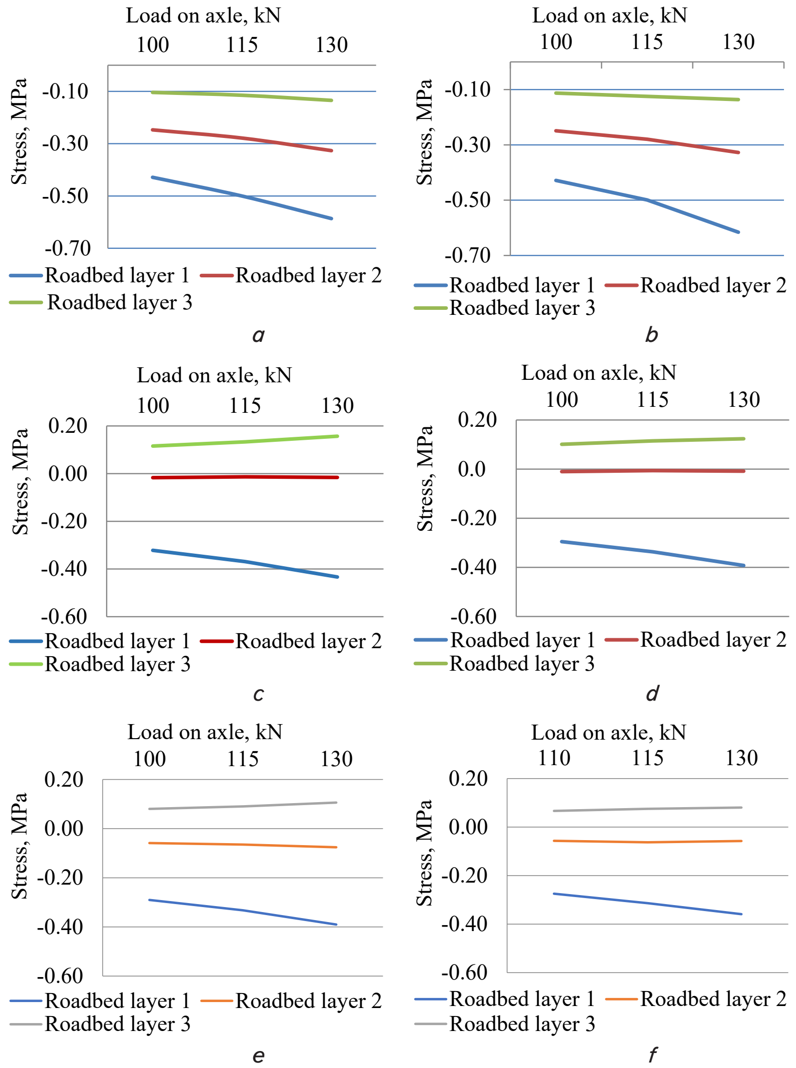
Such results indicate that the stresses σ_x, σ_y in the lower fiber of the asphalt-concrete layers are tensile, both for the location schemes of the 3rd axle above the transition plate (vehicle location scheme, No. 3) and behind the slab (vehicle location scheme, No. 2) regardless of the angle of inclination of the plate. Moreover, they are larger outside the plate than above the plate. In the case of a horizontal slab, these stresses outside the slab are 10–18 % greater than above the slab (Fig. 2, *b*). In general, the horizontal stresses outside the slab in the asphalt-concrete layers of the presented structure with a load change from 100 kN to 130 kN varied from 2 % to 26 %.



a

b

Fig. 8. Change in the vertical movements in layers 1–5 of roadbed under pneumatic stamp: *a* – horizontal placement of the transition plate; *b* – placement of the transition plate at an angle



a *b* *c* *d* *e* *f*

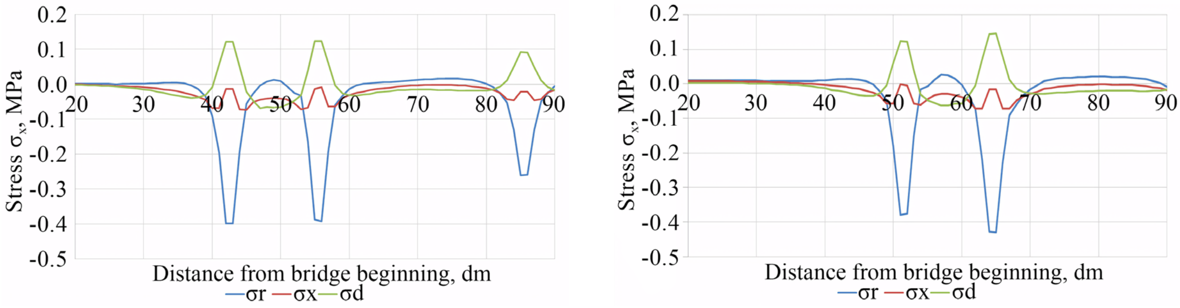
Fig. 9. Change in horizontal normal stresses σ_x, σ_y and vertical tangential stresses τ_{xz} under the pneumatic stamp depending on the load on the vehicle axle: *a* — τ_{xz} when the vehicle is located in position No. 3; *b* — τ_{xz} when the vehicle is located in position No. 3; *c* — σ_y when the vehicle is located in position No. 3; *d* — σ_y when the vehicle is located in position No. 3; *e* — σ_x when the vehicle is located in position No. 2; *f* — σ_x when the vehicle is located in position No. 2

Such a significant jump-like increase in tensile stresses in the asphalt-concrete layers outside the slab is due to the nature of change in the vertical movement of the surface of the coating (Fig. 8) and will affect the reduction of durability according to the criterion of tensile strength at bending by 1.5–2 times.

The nature of change in vertical normal stresses in the layers of roadbed depending on the arrangement scheme of the vehicle (its 3rd axle) to the position of the transition plate indicates that these stresses in the asphalt-concrete layers change almost the same for different schemes of the arrangement of vehicles and do not depend on changes in the angle of inclination of the transition slab in the lower layers of the base under the asphalt-concrete layers, these stresses are 20–40 % greater when the 3rd axle is above the transition slab (at a distance of 500 mm, 3000 mm, and 5500 mm from the beginning of the slab or the 0th support of the bridge) compared to the location of the load when the 3rd axle is outside the slab (at a distance of 6500 mm, 9000, mm and 11000 mm from the beginning of the slab, or the 0th support of the bridge).

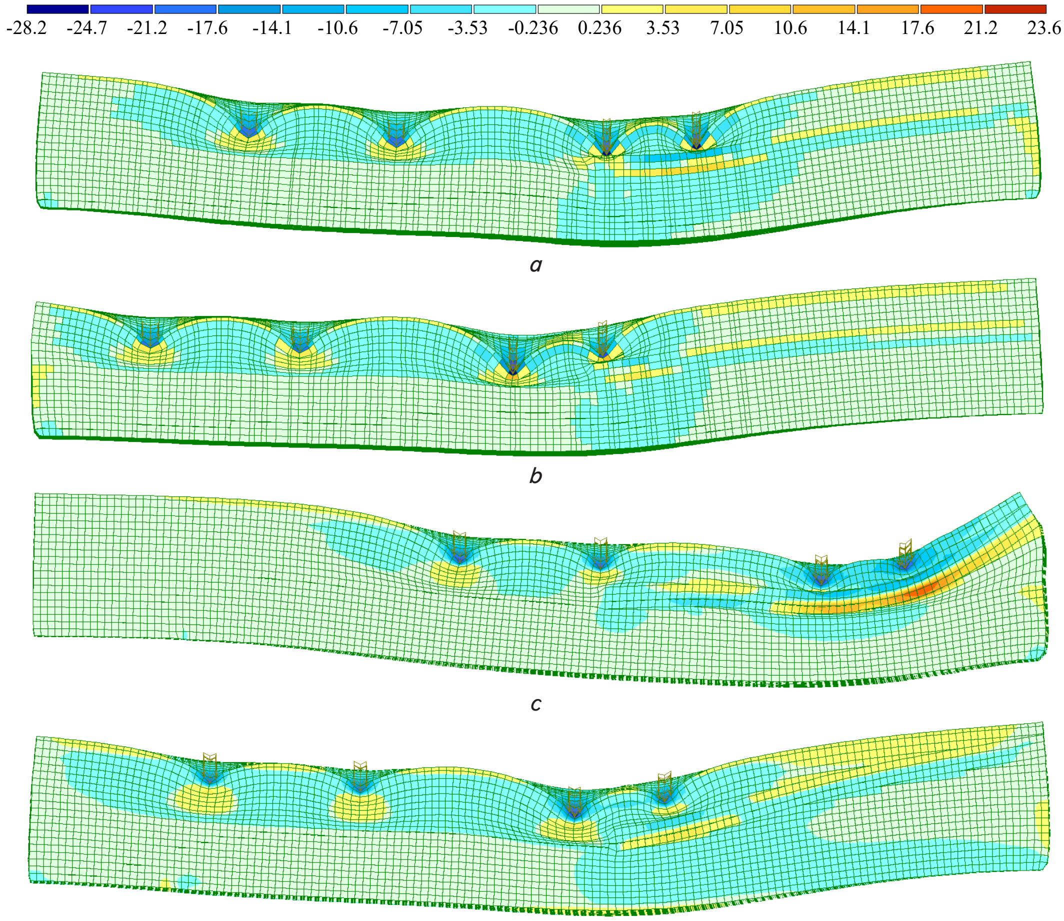
Of particular interest are the results of analyzing the diagrams of horizontal normal longitudinal stress patterns in the asphalt-concrete layers of the roadbed depending on the different layouts of the axles of the four-axle vehicle. So, for example, as can be seen from Fig. 10, *a*, when even the 3rd and 4th axles are on the transition reinforced concrete slab with load placement scheme No. 3 (practically on a rigid base), insignificant surface tensile stresses σ_x are observed in the upper layer of the coating between them. In arrangement scheme No. 2, when the third axle is outside the reinforced concrete transition plate, and the fourth axle is on the edge of the transition plate, the surface tensile stresses σ_x between the third and fourth axles of the truck have increased significantly and are almost 40 % of the maximum tensile stresses in the lower fiber of the second layer asphalt-concrete coating under the pneumatic stamp.

These results are confirmed by data in Fig. 11. It should also be noted that surface horizontal tensile normal stresses σ_x are observed between all axles of a loaded car, as well as in front of the front axle and behind the extreme axle. Moreover, the length of the area of propagation of their action is much greater than that of such stresses in the lower fiber of asphalt-concrete layers, which indicates a possible significant destructive effect of surface stresses σ_x.



a *b*

Fig. 10. Diagram of horizontal normal longitudinal stresses in asphalt-concrete layers of the roadbed with different layouts of axles in a four-axle vehicle (3^{rd} and 4^{th}): *a* – scheme 3; *b* – scheme 2



a

b

c

d

Fig. 11. Stress field σ_x (in t/m^2) of asphalt-concrete layers in roadbed structure No. 3 in the area of the transition plate with different schemes of location of the load from the base car: *a* – load scheme No. 3, position of the transition slab horizontally; *b* – load scheme No. 4, horizontal position of the transition plate; *c* – load scheme No. 4, position of the transition plate at an angle; *d* – load scheme No. 3, position of the transition plate at an angle

Thus, our numerical analysis has made it possible to establish features and nature of the stressed-strained state of asphalt-concrete layers on the ascents and descents on approaches to bridges. It was found that in addition to normal horizontal stresses σ_x in the lower fiber, it is also necessary to take into account the effect of surface horizontal tensile normal stresses σ_x. In addition, it is also necessary to take into account, together with the normal horizontal stress σ_x on the surface of asphalt-concrete layers, the effect of horizontal tangential stresses τ_d, which occur during braking and displacement of cargo multi-axle vehicles (Fig. 1).

6. Discussion of results based on investigating the features of the stressed-strained state of asphalt-concrete layers in a non-rigid roadbed on the ascents and descents of highways and approaches to bridges

Our numerical analysis of the stressed-strained state of asphalt-concrete layers of typical structures in non-rigid roadbeds under vertical loading from the action of a multi-axle vehicle has qualitatively confirmed the well-known feature of the occurrence of tension in the lower zone of the layers when they are bent under the center of the pneumatic stamp (Fig. 8).

Also, the obtained results showed that the double change of the surface curvature creates a zone of action of noticeable horizontal normal tensile stresses near the pneumatic contact (Fig. 9–11). Moreover, these data indicate that when the vehicle passes over one point of the roadbed, the effect of these tensile stresses will be doubled when the pneumatic of each axle pass. In addition, the duration of action of such surface stresses will be much longer than in the lower zone. Therefore, taking into account the rheological nature of asphalt-concrete and the power-law pattern of changes in its strength depending on the duration of load [22], such surface stresses can make a significant contribution to the destruction of its structural bonds and accelerate the process of crack formation. All this can be an additional explanation for the accelerated cracking of asphalt-concrete layers due to the passage of heavy-duty vehicles [3, 4, 7].

In this case, it should be noted that the features noted above will occur during the movement of vehicles without accelerations and decelerations, both on horizontal sections of highways and uphill and downhill sections. However, in the case of significant tangential forces from pneumatics as a result of braking or displacement of vehicles, new features of the stress-deformation state of asphalt-concrete layers of non-rigid roadbeds appear, as evidenced by the results shown in Fig. 9, 10.

Even more difficult working conditions of asphalt-concrete layers occur in the areas of ascents and descents of approaches to bridges in the zone of transition plate (Fig. 8–10).

Our qualitative and quantitative analysis of the research results indicates the need to improve the normative methodology for calculating asphalt-concrete layers of non-rigid roadbed structures on the uphill and downhill sections of approaches to bridges, taking into account the noted features of their stressed-strained state.

The results, on the example of the most characteristic structures of roadbed with asphalt-concrete layers under the action of a typical heavy-duty truck, demonstrated the features of the stressed-strained state, which affects the formation of cracks. They are general in nature. And for each specific case, it is necessary to perform calculations using the appropriate initial parameters depending on the road category, climatic zone, subgrade material, etc.

Possible areas of further research are as follows:

– consideration of thermo-viscoelastic properties of asphalt-concrete;

– study of the influence of vehicle speed and load time on the strength and durability of asphalt-concrete layers.

7. Conclusions

1. A spatial finite-element model of the action of a multi-axle cargo vehicle on roadbed with asphalt-concrete layers on the ascents and descents of approaches to bridges has been built. The model has dimensions of 14×4.4×1.97 m and consists of 133,245 nodes and 135,520 elements and makes it possible to determine the stressed-strained state of asphalt-concrete layers at any point of the structure. With its help, an attempt was made to evaluate the complex impact of vertical and horizontal traffic loads during braking or shifting of a cargo multi-axle vehicle on the features and nature of the stress-deformation state of asphalt-concrete layers in non-rigid roadbed structures with a transition plate on the ascents and descents of approaches to bridges.

2. When studying the influence of nature of the action of traffic loads on the stressed-strained state of asphalt-concrete layers in a non-rigid roadbed on the ascents and descents of approaches to bridges, the most significant features that affect the formation of cracks in asphalt-concrete layers were determined. The results of the numerical analysis confirmed that during the movement without acceleration of a heavy-duty multi-axle vehicle on a horizontal or inclined surface of the road on the surface of the asphalt-concrete layers of the structure of non-rigid roadbed, tensile horizontal normal stresses σ_r arise from the action of the vertical traffic load. These stresses on the surface of the asphalt-concrete layers reach lower values than the tensile stresses in the lower fiber σ_d, which, unlike the first ones, are directly used in the strength calculations of the asphalt-concrete layers. However, the stresses σ_r act twice at the same point (before passing and after passing pneumatics). In addition, the duration of their action is greater than the stresses in the lower fiber, which more aggressively destroys the structural bonds of asphalt-concrete and contributes to the formation of cracks under the action of heavy-duty vehicles.

Also, the research results indicate the need to take into account the particularity of the influence of the nature of traffic loads on approaches to bridges, which implies the existence of an increased probability of the appearance of traffic jams. This causes a horizontal tangential force to be exerted on the surface of the asphalt-concrete layers during the stops of vehicles and their departure after stops (especially on ascents and descents). On the basis of our numerical analysis, it was established that under the action of horizontal transport loads, in particular braking, on the roadbed near the boundary with the pneumatic stamp on the opposite side from the direction of their action, increased surface horizontal normal stresses σ_r (σ_x) and tangential τ_d (τ_{xz}) arise. The values of such stresses reach the same order as the stresses σ_d (which are directly used in the calculations of asphalt-concrete layers for strength). Therefore, the research results show the practical need to improve existing methodology for calculating the strength of asphalt-concrete layers under the action of heavy-duty multi-axle vehicles on approaches to bridges.

3. The study of the effect of a typical cargo multi-axle vehicle on the stressed-strained state of asphalt-concrete layers in the zone of the transition reinforced concrete slab on approaches to bridges has revealed the features of the stressed-strained state of asphalt-concrete layers, which are as follows.

Regardless of the angle of inclination of the transition plate, when the 3rd axle of the vehicle is located behind the edge of the plate, a sharp change in the vertical deflection of the surface of the roadbed is observed, which leads to a change in the curvature of the entire package of asphalt-concrete layers and causes more unfavorable conditions from the point of view of the action of horizontal normal tensile stresses in the asphalt-concrete layers of the roadbed. Horizontal normal stresses in the lower fiber of asphalt-concrete layers are tensile, and, depending on the load on the axle, these stresses outside the slab are 2–26 % greater than above the slab. Such a significant increase in tensile stresses in the asphalt-concrete layers outside the slab is due to the nature of change in the vertical movement of the surface of the coating and will affect the reduction of durability according to the criterion of tensile strength at bending by 1.5–2 times.

The nature of change in the vertical normal stresses in the layers of roadbed depending on the arrangement scheme of the vehicle (its 3rd axle) to the position of the transition plate indicates that these stresses in the asphalt-concrete layers change almost the same for different schemes of the arrangement of vehicles and do not depend on changes in the angle of inclination of the transition slab in the lower layers of the base under the asphalt-concrete layers; these stresses are 20–40 % greater when the 3rd axle is above the transition slab.

In arrangement scheme No. 4, when the third axle is outside the reinforced concrete transition plate and the fourth axle is on the edge of the transition plate, the surface tensile stresses σ_r between the third and fourth axles of the truck increase significantly and are almost 40 % of the maximum tensile stresses in the lower fiber of the second a layer of asphalt-concrete under the pneumatic stamp.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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