STUDY OF ROADBED STRESS STATE FROM THE IMPACT OF FREIGHT CARS WITH AXLE LOAD UP TO 30 TNF

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ABSTRACT

The stress state of the active area of the roadbed caused by the impact of freight cars with axle loads 23,5; 25; 27 and 30 tnf is studied on the basis of a finite-element model. Using Coulomb's wedge theory as per actually registered vibration impact levels, limit stress levels for the embankment of the roadbed of the section Golutvin–Ozery of Moscow railway have been determined. Experimental studies to determine stresses on the main site of the roadbed have been conducted and design and experiment data have been verified.

Keywords: stress state, roadbed, freight car, high axle loads, limit stresses; humidity, vibration impact.

Background. *The development of heavy traffic on Russian railways with the implementation of freight cars with axle loads 25 tnf (and in the long term of 27 and 30 tnf) raises the topical issue about the evaluation of the bearing capacity of the roadbed of embankments composed of excessively moistened clay soils under a simultaneous vibration impact. The development of the operating domain of trains with high axle loads on the railway network leads at some sections to an increased number of defects and deformations of the roadbed [1–3].*

Specialists of JSC VNIKTI have conducted theoretical and experiment studies of the stress state of the main site of the roadbed (MSRB) caused by the impact of freight cars with axle loads 23,5; 25; 27; 30 tnf. At the same time the influence of axle load values, running speed, elastic behavior of crushed-stone ballast, sand bed and also their thickness ratio on the roadbed stress levels have been studied.

The influence of vibration impact levels (soil vibration amplitudes on the MSRB obtained experimentally while conducting line tests), of soils humidity (flow index J_L) on limit stresses of the roadbed embankments has been studied. Theoretical studies have been conducted on the embankment model which geometrical parameters have been obtained using direct measurements on the testing track section where measurement equipment to register force factors and stresses on the subgrade was installed.

Objective. *The objective of the authors is to study roadbed stress state due to the impact of freight cars with axle load up to 30 tnf.*

Methods. *The authors use general scientific and engineering methods, comparative analysis, graph construction, experimental data.*

Results.

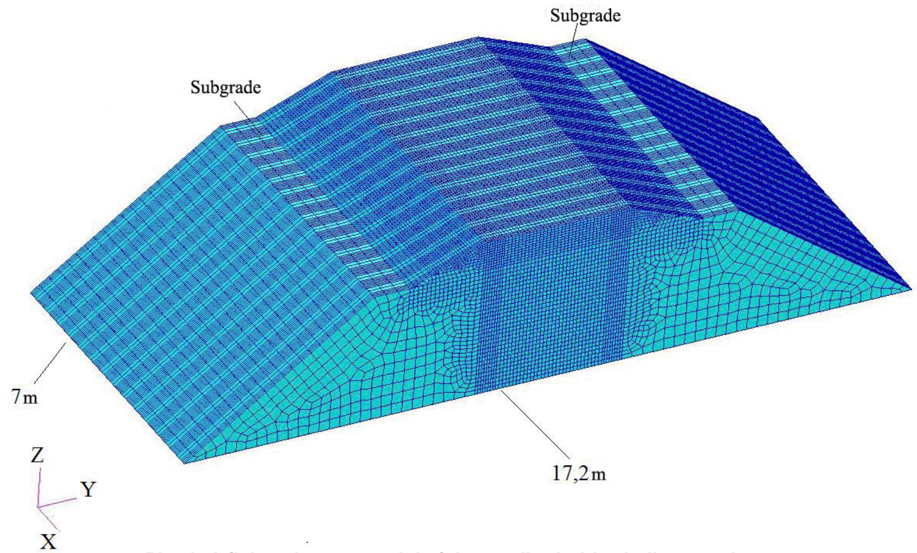
A finite-element model of the roadbed and its stress state estimate

Modeling and calculation were performed based on the finite-element method using such software packages as PATRAN, NASTRAN, MARC.

Pic. 1 shows a finite-element model of a track section (roadbed, ballast). Depending on the ballast height the number of Hex8-elements in the model changed from 336 896 to 355 488, the number of nodes – from 355 272 to 381 691.

The influence of the following factors on the embankment stress state has been studied during calculations:

- *magnitudes of vertical forces transferred from wheels to rails;*



Pic. 1. A finite-element model of the roadbed with a ballast section.

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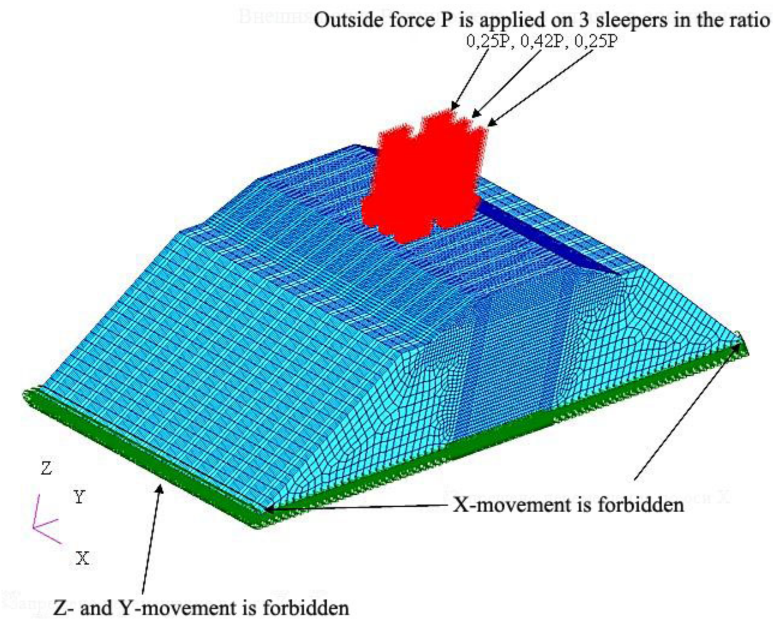


Pic. 2. The scheme of loading and fixing a finite-element model.

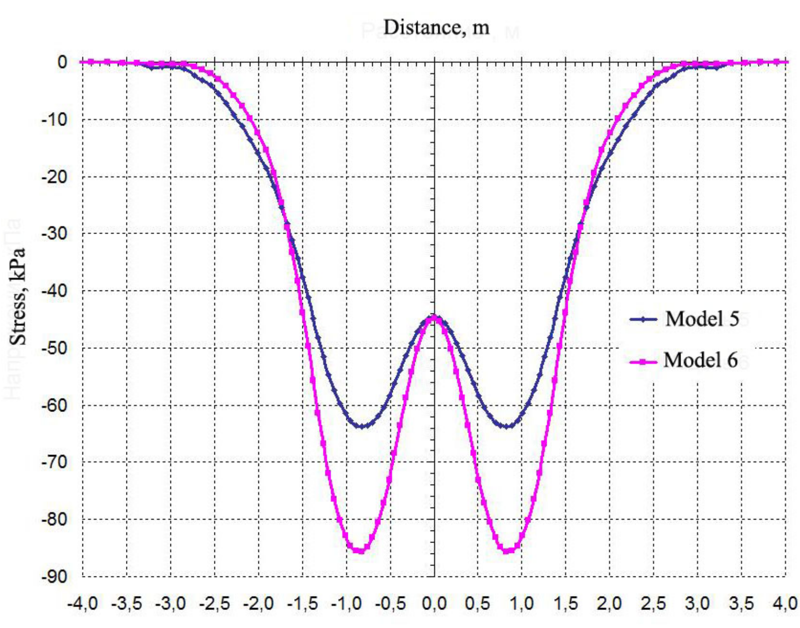
• train running speeds;

• thickness ratio of ballast layer components – crushed stone, subballast layer;

• elastic behavior ratio of ballast layer and roadbed components.

Loads obtained during dynamic tests of the train prototype with freight cars with axle loads 23,5; 25; 27 and 30 tnf [17] were taken as benchmark reference data for simulation. Pic. 2 shows boundary conditions and schemes of loads application. The axle load was assumed to be distributed on three sleepers in the ratio of 0,25, 0,42 and 0,25. The rest of the load (0,08) distributed on adjacent sleepers is neglected due to its small value.

The roadbed strength on the subgrade has been evaluated by comparing design compression stress with limit stress values. Limit stresses on the subgrade are assumed to be 80 kPa. In fact their value depends on physical and mechanical parameters of roadbed soils, their moistening intensity and vibration impact levels. In works [18–20] Young moduli at triaxial compression depending on the number of reduction cycles and pressure values were studied. It is shown that the value of Young's modulus of ballast materials



Pic. 3. The stress distribution with various Young modulus characteristics of ballast and subballast layers (axle load 30 tnf, speed 90 km/h).

Table 1

Design models to evaluate the influence of ballast layers' size and parameters

Model No.	Undersleeper foundation structure	Thickness of ballast and subballast layers, m	Design parameters of ballast and subballast layers	
			Deformation modulus E, MPa	Poisson ratio, μ
1	ballast	0,3	254	0,27
	sand bed	0,3	110	0,3
2	ballast	0,3	150	0,27
	sand bed	0,3	80	0,3
3	ballast	0,4	254	0,27
	sand bed	–	–	–
4	ballast	0,4	110	0,27
	sand bed	–	–	–
5	ballast	0,4	254	0,27
	sand bed	0,2	110	0,3
6	ballast	0,4	150	0,27
	sand bed	0,2	80	0,3
7	ballast	0,4	254	0,27
	sand bed	0,3	110	0,3
8	ballast	0,4	150	0,27
	sand bed	0,3	80	0,3
9	ballast	0,5	254	0,27
	sand bed	–	–	–
10	ballast	0,5	150	0,27
	sand bed	–	–	–
11	ballast	0,5	254	0,27
	sand bed	0,2	110	0,3
12	ballast	0,5	150	0,27
	sand bed	0,2	80	0,3
13	ballast	0,5	254	0,27
	sand bed	0,3	110	0,3
14	ballast	0,5	150	0,27
	sand bed	0,3	80	0,3

Note. Data on crashed-stone ballast Young modulus have been assumed as per results of testing crushed stone samples taken at the section Golutvin–Ozery of Moscow railway.

Table 2

Design stresses on the main site of the roadbed from maximum possible and average values of vertical forces

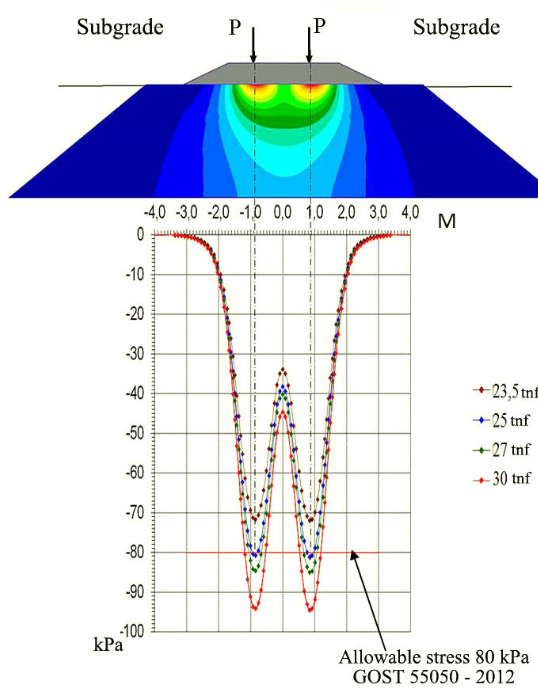
No.	Running speed, km/h	Axle load 23,5 tnf	Axle load 25 tnf	Axle load 27 tnf	Axle load 30 tnf
1	40	59,8/51,1	64,5/52,1	67,2/55,7	71,9/59,6
2	60	61,1/53,1	67,7/56,7	69,0/60,7	72,5/64,9
3	80	63,2/54,6	70,1/58,4	72,5/62,4	78,6/66,7
4	90	65,7/56,2	74,1/60,1	77,6/64,3	86,3/68,8

Note. Numerator – maximum possible values; denominator – average values of vertical forces.

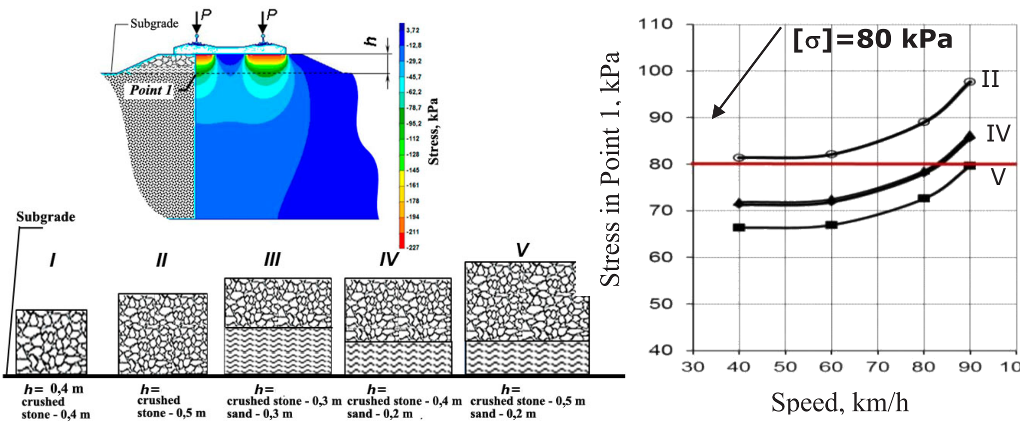
Table 3

Maximum stresses on the main site of the roadbed at the axle load 30 tnf depending on the speed and ballast layer structure

Model	Ballast structure	Stresses from the axle load 30 tnf (kPa) at the speed (km/h)			
		40	60	80	90
4	Crushed stone 0,4 m	101,3	102,2	110,8	121,6
10	Crushed stone 0,5 m	81,4	82,1	89	97,7
6	Crushed stone 0,4 m Sand 0,2 m	71,3	71,9	78	85,6
12	Crushed stone 0,5 m Sand 0,2 m	61,4	62	67,2	73,7



Pic. 4. Stress variations on the main site of the roadbed depending on axle loads at the running speed 90 km/h.



Pic. 5. The change of stresses on the main site of the roadbed depending on ballast and subballast layers' structure and running speed.

mainly depends on the extent of ballast consolidation, a surface pressure at triaxial compression and the material of crushed stone particles (granite, basalt). Similar studies have been performed by specialists of the Centre of testing of materials and structures – the branch of October railway, regarding ballast materials, sand and soil taken from the undersleeper foundation of the haul testing section Golutvin–Ozery.

14 design models have been considered to evaluate the influence of ballast layer and sand bed structure and elastic behavior on the MSRB stress state (Table 1).

To evaluate strength conditions maximum possible values of vertical forces calculated have been assumed in calculations as per the following expression:

$$\overline{P}_v^{\max} = \overline{m}_{Pv}^N + 2{,}5\overline{\sigma}_{Pv}^N,$$

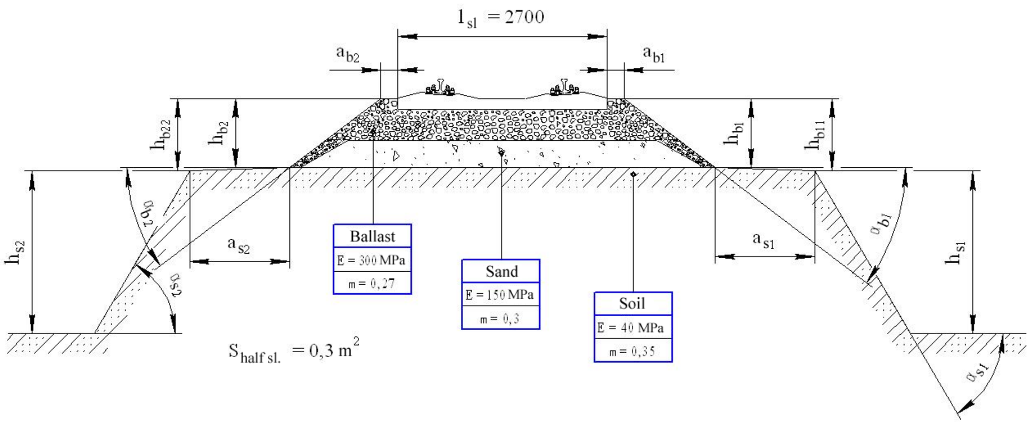
where $\overline{m}_{P_v}^N$ *is a mathematical expectation of vertical forces assembly from the impact of freight car wheels with axle loads 23,5; 25; 27 and 30 tnf, respectively.*

$\overline{\sigma}_{P_v}^N$ *is a mean-square deviation of vertical forces assembly caused by those freight cars.*

Under real operation conditions the probability of appearing maximum possible values is small. Thus to verify a finite-element model with an experimentally obtained stress magnitudes on the MSRB average maximum values of vertical forces which have been assumed as determined from the following expression:

$$P_v^s = \overline{m}_{Pv}^N + \overline{\sigma}_{P_v}^N.$$

To evaluate the influence of ballast layer and sand bed elastic behavior results of stress calculations on the MSRB are provided for two variants of model 5



Pic. 6. Schematic illustration and geometrical dimensions of the embankment in the instrumentation site.

Table 4

Geometrical parameters of the railway embankment cross section in the experimental site

Cross sections	Left side							Right side						
	a_{b2}, m	h_{b2}, m	h_{b22}, m	α_{b2}, °	h_{s2}, m	a_{s2}, m	α_{s2}, °	a_{b1}, m	h_{b1}, m	h_{b11}, m	α_{b1}, °	h_{s1}, m	a_{s1}, m	α_{s1}, °
5 m before	0,36	0,55	0,72	20,5	2,23	1,05	35	0,35	0,61	0,78	21,5	2,04	1,23	35,5
0 – in the section of the sensors	0,34	0,61	0,77	22	2,42	1,00	34	0,36	0,56	0,75	23	2,23	1,17	26
5 m after	0,37	0,63	0,76	23	2,28	1,12	36	0,35	0,56	0,75	22,5	2,32	1,21	35,5
Average	0,36	0,60	0,75	21,8	2,31	1,06	35	0,35	0,58	0,76	22,3	2,20	1,20	35,7

and 6. Pic. 3 shows the distribution of design stresses on the track formation cross section from maximum possible values of vertical forces of freight cars with axle load 30 tnf at the running speed 90 km/h.

The diagrams of the stress distribution on the MSRB show that elastic characteristics – Young modulus for ballast layer and sand bed have a significant effect on subgrade stresses. So for a similar subballast structure standardized for tracks Class I, II and III (0,4 m of crashed stone and 0,2 m of sand), stress values may differ by 30–40 %. For a design case (variants 5 and 6) the difference was of 34 %.

Pic. 4 shows the stress distribution in the undersleeper area for variant 2. Vertical forces values have been assumed to be maximum possible values obtained experimentally during running dynamic tests of open cars with axle loads 23,5; 25; 27 and 30 tnf.

Stress design values on the MSRB (for variant 2) depending on maximum possible and average maximum values of vertical forces are provided in Table 2.

Stress values in the MSRB for open cars with the axle load 30 tnf were calculated with the help of a computational model depending on the running speed, ballast and subballast layers' thickness. Results of calculations are provided in Table 3 and in Pic. 5.

Analysis of stressed state of the embankment due to the impact of freight cars with axle loading up to 30 tnf showed:

• there is a tendency of stress increase on the MSRB due to both growth of axle loading and raise of speed;

• MSRB stressed state is influenced by the elastic behaviour of the ballast layer and of the sand cushion, the thickness of each component and the total thickness of the ballast layer and the sand cushion;

• if thickness of the ballast layer is 0,3 m and of the sand cushion is 0,3 m (Pic. 5), and vertical forces have maximum possible values, at speed up to 90 km/h, the impact of freight cars with axle loads of 27 and 30 tnf causes MSRB stresses exceeding permissible values [σS] = 80 kPa, MSRB stresses from freight wagons with axle loads of 25 tnf are within the limit of 77,6 MPa;

• efficient distribution of the forces caused by freight cars with axle loading up to 30 tnf and increasing the thickness of the ballast layer make possible to obtain stress levels in the MSRB not exceeding standard values;

• using ballast layer structure recommended for Class I, II and III tracks at the thickness of the ballast layer 0,4 m and the sand cushion 0,2 m, the stresses in the MSRB from 30 tnf cars exceed standard values at speeds exceeding 80 km/h;

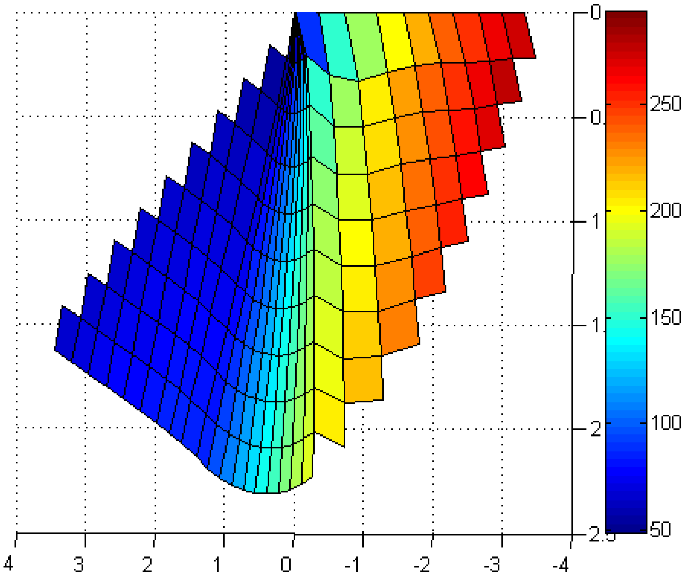
• changing (Table 4) the ratio of thicknesses of the ballast layer and the sand cushion changes accordingly stress state of the roadbed;

• when the ballast layer thickness is increased up to 0,5 m and the ballast bed thickness is 0,2 m, the stresses in the MSRB did not exceed standard values of 80 kPa from freight wagons with axle loading up to 30 tnf and speeds of up to 90 km/h.

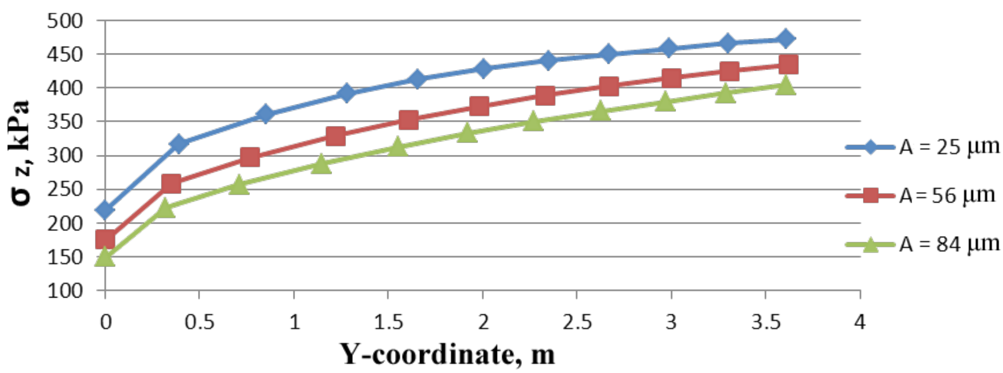
Limit stresses in the active zone of the roadbed

Coulomb's wedge theory was used to determine bearing capacity of the railway roadbed. Applicability of this theory to engineering calculations and good convergence of theoretical and operational load values are confirmed by works [8, 11, 12, 16].

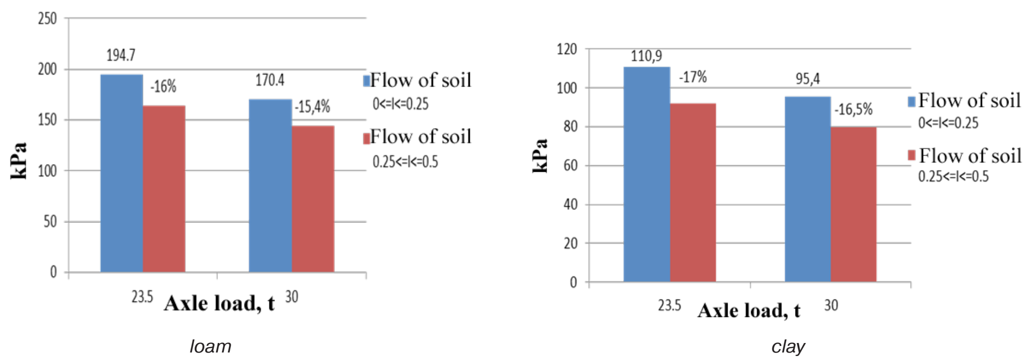
The limit stress state of the undersleeper foundation is the state at which the minimum increment of the static or dynamic load results in



Pic. 7. Distribution of limit stresses along sliding lines.

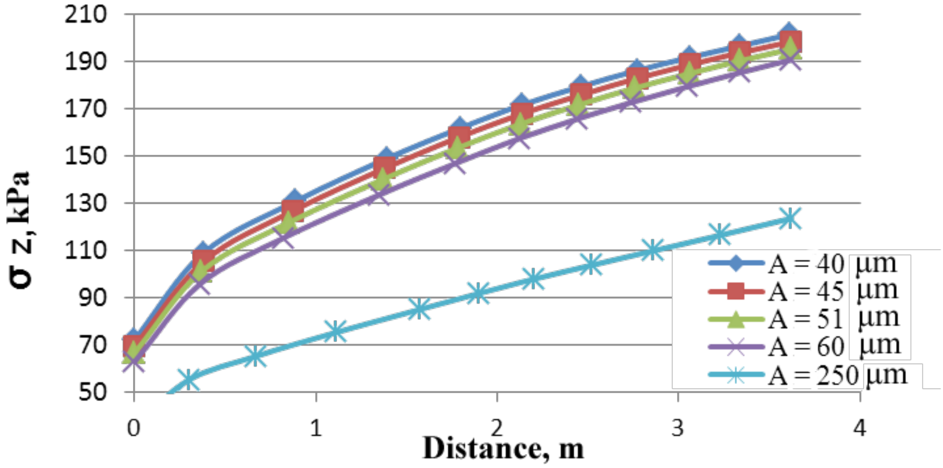


Pic. 8. Limit values of stresses in the main site of the roadbed.

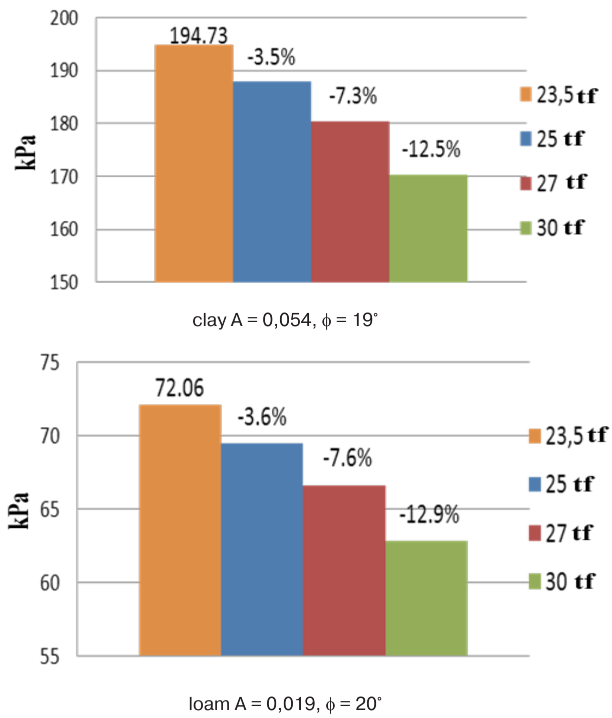


Pic. 9. Change of minimum limit stresses depending on soil moisture at different axle loads.

formation of closed sliding surfaces in the ballast and roadbed, where the shearing forces exceed the retention forces. Sliding surfaces are a group of separate area elements formed when the shearing forces exceed the retention forces. The tangent planes to the sliding surfaces coincide with the area elements of the sliding surfaces. Some area elements of the sliding surfaces can be formed in the soil environment and under loads not exceeding the limit ones, but they do not cause deformation of the soil body. Only under loads not lower than the limit ones, groups of area elements are formed. They represent



Pic. 10. Change of limit stresses depending on level of vibrations (loamy soil ϕ = 20˚, A = 0,019 MPa, flow index of soil 0 ≤ J ≤ 0,25).



Pic. 11. Change of minimum limit stresses depending on values of axle loads.

surfaces, over which shear deformation of the soil mass occurs.

Using the algorithms [11], the finite difference method is used to integrate the equations of characteristics and differential relations according to the program specially developed by JSC VNIKTI specialists.

Calculations were carried out for the embankment composed of clay soils.

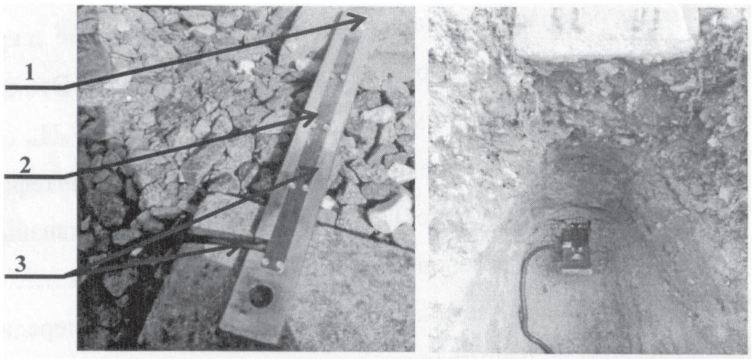
Pic. 6 and Table 4 show the geometrical parameters of the railway embankment cross section, the volumetric characteristics of soils and relevant coefficients for decrease in the strength characteristics of soils.

Calculations of bearing capacity of the roadbed are carried out for:

- *3,1 m height embankment with geometrical parameters which are determined by direct geometrical measurement along the section of installation of measuring instruments;*
- *roadbed composed of clay soils;*
- *for levels of MSRB vibrations observed due to the impact of freight cars with different axle loading while wheels rolling on rails without irregularities on the rolling surface;*
- *for the case of change in soil moisture with flow index changing from J < 0,25 to 0,25 < J < 0,5.*

As a result of experimental studies of vibration effects on the track superstructure elements, it has been established that with increasing axle loads on the wheel, the vibrations also have the tendency to increase. At the same time, the higher the running

a) b)



Pic. 12. Overview of the device for measurements of pressure values in the main site of the roadbed: a) a plate with a fixed load cell; b) device with load cells installed in the subgrade.

Table 5

Stress measured in the main site of the roadbed during the run of the locomotive 2TE116

Speed, km/h	11.05.2017	12.05.2017	Decrease,%
40	71,65	67,03	6,4
50	73,25	67,66	7,5
80	76,58	72,00	5,9
90	81,80	75,69	7,45

speed is, the higher are the acceleration levels. With the increase in axle loads from 23,5 to 30 tnf, the vibration levels in the subgrade varied from 40–48 µm to 57–84 µm. Distributions of normal stresses along the sliding lines (Pic. 7) and limit values of MSRB stresses for different levels of vibratory displacements (Pic. 8) are calculated for the embankment with the geometrical parameters shown in Pic. 6 and filled from clay with the angle of internal friction ϕ = 19˚ and relative adhesion A = 0,054 MPa.

Analysis of the design data showed that for clays with the considered physical and mechanical parameters at flow index J < 0,25, the stress levels, arising from freight wagons with axle loading of 30 tnf, have factor of safety for the bearing capacity of the embankment.

Calculations have been carried out for the limit stresses in the conditions of embankment made from clays and loams, as well as for the condition of soil moisture increase from J < 0,25 to 0,25 < J < 0,5.

It is found that the subgrade bearing capacity depends essentially on the type of soil and its physical and mechanical properties.

When cars with axle loads of 30 tnf move along the embankment composed of clay, the minimum limit stress is 170,4 MPa, while at passing to loams the values of limit stresses decrease to 95,4 MPa. With the increase in the flow index from J < 0,25 to 0,25 < J <0,5, the bearing capacity subgrade soils decreases on the average by 15,4–16 % for clays, and by 16,5–17 % for loams (Pic. 9).

Calculations have been carried out for the case of high vibration effects on the MSRB, what is typical for impact interaction between wheels and rails in the areas of bolted joints, for metal flaking from the tread surfaces with excessive parameters, etc.

It is found that increase of vibration levels on the MSRB leads to 1,26–1,36 times decrease of the limit stresses levels, that is by 26–36 % (Pic. 10).

Decrease of subgrade bearing capacity following change of axle load from 23,5 to 30 tnf due to increase of vibrational loading is 12,5–12,9 % (Pic. 11).

Experimental studies

To verify the results of computer simulation, experimental measurements of subgrade stresses were carried out at JSC VNIKTI testing site (Golutvin–Ozery section of Moscow Railway). The track superstructure included: R65 rails, reinforced-concrete sleepers, KB-65 fastenings, 0,3 m thick sand cushion, loam soil roadbed.

Analysis of stresses in the MSRB was performed using KDE-200KPA load cells (Japan). To provide the possibility of fast installation of the load cells under the track panel on the subgrade, the specialists of JSC VNIKTI developed a new design device. The overview of the device is shown in Pic. 12.

There are some certain difficulties with experimental roadbed stress determination caused by placing the earth pressure cell into the roadbed. This process causes the disturbance of the ground base solidity and the distortions in the field of forces created by the acting loads.

It determined the demand to develop advanced way of measuring stresses in a railway track roadbed. The device for measuring subgrade stresses consists of an earth pressure cell and a bearing plate (Pic. 12). The elastic membrane is placed in an upward position and contacts the ground while conducting measurements.

Inside the plate there is cable trunking 3 for wiring from measuring devices to the earth pressure cell. Calibration test of the earth pressure cell was conducted by incremental loading of the working membrane within regular intervals by a distributed load ranged from 0 to 200 kPa with an increment of 20 kPa.

The design of the earth pressure cell allows its installation without disturbing the solidity of the ground base on the roadbed under the sleeper base disposing an active zone under the rail on the depth 1 m below the ballast layer.

Approbation of the given device was conducted on a test running line Golutvin–Ozery. The earth pressure cell with a plate was placed below a sleeper

Table 6

Experimental stress in the main site of the roadbed due to freight cars with axial loads up to 30 tnf

Measurement No.	Speed, km/h	Car, 23,5 tnf		Car, 25 tnf		Car, 30 tnf	
		Bogie No. 1	Bogie No. 2	Bogie No. 1	Bogie No. 2	Bogie No. 1	Bogie No. 2
1	40	59,218	53,673	49,223	52,509	66,132	67,433
3	60	54,357	55,115	47,306	56,690	63,736	71,335
5	80	52,167	59,428	54,768	63,805	62,778	76,128
7	90	58,196	59,810	69,418	65,653	67,022	79,961
9	90	55,8	62,577	71,267	63,531	65,653	79,071
11	90	55,594	64,426	70,308	63,189	61,682	77,565
13	80	57,237	61,208	36,010	68,118	61,477	78,592
15	80	50,866	53,193	48,264	62,998	61,956	75,443
17	5	46,005	47,511	47,511	47,648	57,917	59,697
19	60	54,015	54,357	57,027	39,228	60,587	63,325

base under ballast aggregates and the sub-ballast at a depth of 650 mm. In the lateral direction the earth pressure cell was installed under a rail.

Measurements were carried out with a freight locomotive TE116 operating at speeds from 20 to 90 km/h. Measurements were carried out within two days. Results are presented in Table 5.

The analysis of measurements results showed:

• While the rolling stock passing over the measuring cross-section was increasing there was an average stress decrease of about 6–7,5 % that can be explained by the deformation locally compacted ground areas formed during the location of plates with fixed earth pressure cell into the subgrade;

• Stress levels were close to the estimated values;

• With an increase in traffic speeds there was an increase in stress levels in the MSRB.

The next step was determination of the MSRB stress under the impact of freight cars (of a serial one with a bogie 18–100 and of a coal hopper with axial loads 23,5, 25 and 30 tnf). Results of measurements are presented in Table 6.

The presented results of the measured MSRB stress were obtained during the test train run in the direction Golutvin–Ozery for the case when bogies No. 2 were the first in the direction of travel. The comparative analysis of estimated values (Table 2) and experimental data showed:

• The discrepancy between estimated values and experimental data of the MSRB stress measured do not exceed 15 %;

• Subgrade stresses under the impact of rolling stock wheels have 10 %-spread in values; it can be explained by the vibration of sprung parts of a rolling stock and different values of the vertical loads acting on a track area where earth pressure cell was installed.

Conclusions and suggestions

1. The accomplished theoretical research based on a finite-element model of the stress state of a roadbed of a railway embankment under the impact of freight cars with axial loads up to 30 tnf showed:

• Levels of MSRB stresses are monotonically increasing with the increase in axial loads and speeds: in accordance with the design data with maximum possible forces – by 16–24 %, in accordance with the experimentally measured data – by 20–21 %;

• Levels of MSRB stresses are influenced by the thickness of ballast and sub-ballast layers, their proportions and elastic characteristics – ballast and sub-ballast layer elasticity modulus. The values of stress can differ by 30-40 %;

• For the most widespread type of soil, which is loam soil, vibration effect levels, created by freight cars with axial loads of 30 tnf and the thickness of ballast layer of 0,5 m and sub-ballast layer of 0,2 m, MSRB stress levels are 77,6 kPa and do not exceed rated values 80 kPa at speeds up to 90 km/h.

2. The executed numerical calculations of the roadbed bearing capacity according to the Coulomb's wedge theory showed:

• Limit stress values depend on mechanical-and-physical properties of soils comprising an embankment, its geometrical parameters (height, slope angle values, etc.), moisture, vibration effect levels;

• The increase in vibration effect levels from 60 to 250 um (characteristic of impact interaction with defects on wheel threads or running surfaces of rails) reduces the bearing capacity of embankment by 26–32 %;

• The increase in soil moisture from $J < 0,25$ to $0,25 < J < 0,5$ reduces the embankment bearing capacity by 15–17 %;

• The increase in axial loads from 23,5 to 30 tnf reduces soil bearing capacity due to the average increase in vibration effect levels by 12,5–12,9 %.

3. The comparative analysis of MSRB design stresses based on vertical forces mean values has shown good convergence of estimated and experimental data. The divergence did not exceed 15 %.

4. Making of a decision whether to introduce freight cars with axial loads 27 and 30 tnf or not requires solving of additional problems:

• To determine effects of increased axial loads on stability of railway embankments on weak subgrade;

• To define the development rate of cumulated residual deformation within the active areas of the roadbed under the effect of increased axial loads taking into account high-plasticity of soils in section with poor drain systems, in frost-melting period and water saturation.

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Article received 01.08.2017, accepted 29.08.2017.

The R&D work has been accomplished within the project of the Russian Fundamental Research Fund 17–20–01088.