ORIGINAL ARTICLE
DOI: https://doi.org/10.30932/1992-3252-2023-21-6-9

World of Transport and Transportation, 2023, Vol. 21, Iss. 6 (109). C. 238–250

Simulation of the Dynamic Impact of High-Speed Rolling Stock on Buried Structures of the Tunnel Type

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ABSTRACT

The article considers the problem of assessing the rate of influence of the vibrational impact of high-speed rolling stock on the bearing elements of a tunnel-type buried culvert. In particular, it studies the process of formation of a directed impulse of mechanical vibrations emitted by a rail-sleeper grid under the influence of a moving, dynamic load, with the presence of a two-fold phase transition between soil layers with different physical and mechanical properties. Numerical simulation was carried out in the Comsol environment in a non-stationary formulation with construction of systems of differential equations of motion and their subsequent solution using the finite element method. The study has found the wave nature of distribution of deformations and accelerations in the soil thickness with a tendency to a sharp decrease in the intensity of energy processes within the depths of 5–7 m. For sewers of considerable thickness of the lining, the structure is mostly subject to bending, while a structure with a smaller wall thickness and a larger diameter of the tunnel is subject to high longitudinal and vertical loads.

Keywords: railways, tunnel-type structures, stress-strain state, dynamic study, distribution of modal (effective) mass fractions of the structure.

For citation: Vataev, A. S., Vatulin, Ya. S., Kavkazsky, V. N. Simulation of the Dynamic Impact of High-Speed Rolling Stock on Buried Structures of the Tunnel Type. World of Transport and Transportation, 2023, Vol. 21, Iss. 6 (109), pp. 238–250. DOI: https://doi.org/10.30932/1992-3252-2023-21-6-9.

The text of the article originally written in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

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INTRODUCTION

A significant problem arising in the process of construction and reconstruction of high-speed railways is associated with assessment of operational dependability of the structure at the intersection of tracks with buried tunnel-type objects.

Improvement of design solutions requires a system approach to the analysis and generalisation of data on operational dependability of structural elements considering both man-made and natural factors of external impact.

Direct collection of data on the current state of engineering structures is extremely time consuming and is associated with a risk for safety for experts while they are in the tunnel. The solution to the problem can be found using a numerical experiment based on mathematical modelling.

Modelling of loading modes of tunnel structures was carried out as part of a comprehensive study on engineering and geological conditions while obtaining materials necessary for development of design documentation for reconstruction of the technological site of Obukhovo station in St. Petersburg, on the sites near Fermskoye and Yuzhnoye Highways and Obvodny Canal.

Generally, the article is a presentation of the results of a study of technological sites of several station sites located in the city of St. Petersburg and being reconstructed. The construction of the roadbed and the design of infrastructure elements correspond to the real prototype. Clause 4 of the Technical Regulations of the Customs Union «On the safety of high-speed railway transport» (TR CU 002/2011, as amended on September 14, 2021), as well as GOST R [Russian state standard] 55056–2012 «Railway transport. Basic concepts. Terms and definitions» (Article 39) provide a definition of high-speed rolling stock, namely: «high-speed railway rolling stock» is railway rolling stock consisting of motorised and non-motorised wagons and intended for transportation of passengers and (or) luggage, as well as postal items with a speed of more than 200 km/h». The authors were guided by this definition.

Objective of the work was to analyse the stress-strain state of load-bearing elements of tunnel-type buried structures under the influence of high-speed rolling stock (HSRS) based on finite element modelling techniques.

RESEARCH METHODS

The high-speed traffic is a factor of technogenic seismicity, in which a directed periodic mechanical displacement of the underlying medium under track superstructure is formed, with an oscillatory effect on it from the side of a moving rolling stock. This dynamic study focuses on the forces caused by the relationship between translational and torsional vibrations due to the presence of eccentricity between the centres of mass and rigidity of the structure.

This article understands as the structure a tunnel structure, a sewer. The article mainly focuses on the process of dynamic loading of the sewer, while the elements of the track superstructure are reduced and replaced by an equivalent.

Regarding the sewer, attention should be paid to the design features of the sections, as well as the properties of the material of its constituent elements, which determine the corresponding Young's modulus and the moment of inertia of the current section. The emerging characteristic displacements during oblique bending determine a plane located perpendicular to the neutral line of the section, along which the centre of gravity of the section will move relative to (i.e., with eccentricity) this neutral line [1] (see further Pic. 2).

The functional mathematical model of an object is a kind of «equivalent», consisting of relationships that connect phase variables, i.e., internal, external and output parameters of the system. Practical implementation of the model is based on the finite element method, which makes it possible to formalise in mathematical form the structure of the object, the geometry of the components, the conditions and laws of their interaction with each other and with the environment. This definition is used in the literature, in particular, in [2].

This paper considers numerical simulation in the Comsol environment in a non-stationary formulation: kinematic and dynamic research with construction of systems of differential equations of motion with subsequent solution, as well as analysis of the stress-strain state of an object using the finite element method.

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[1] Belarusian-Russian University. Tutorials. Strength of materials. [Electronic resource]: http://cdo.bru.by/course/distan/PGS/sopromat_6sem_pgsdz/Fail/lekcher_11.pdf

[2] Shmitko, E. I. Processes and devices in the technology of building materials and products: Study guide: Vol.1 (theory issues). Voronezh, Voronezh state arch.-builds. univ., 2009, 348 p., P. 50.

RESULTS

Any generalised digital model of a researched object is reduced (simplified) in a descriptive sense relative to a real prototype. In this case, the object initiating the force action (rolling stock), as well as the transmission element (the arrangement of the track superstructure), to reduce the dimension of the problem, are replaced by an equivalent in the form of a mechanical excitation emitter, presented as a trace (imprint) of a rail-sleeper grid on the land surface of the soil massif, to which a dynamic train load is applied[3].

When the wave front passes through layers of a soil massif with different acoustic rigidity, elastic waves change their direction, wave reflection and refraction phenomena[3] arise, because of which the studied object – the sewer – is subjected to mechanical action by the energy of the elastic wave.

This fact is confirmed by the configuration of the diagram of the vector representation of the propagation of the elastic wave front (see further Pic. 9).

The culvert under consideration is a two-component tunnel reinforced with a reinforced concrete jacket, with a reinforced concrete tray and shotcrete of the arch, located at a depth of 11–7,46 m from the day surface of the soil massif.

The massif consists of the ballast layer of the track and the soil. On the day surface of the massif there is a rail-sleeper grid, which is represented by two shaped profile beams (rails), supported by sleepers with a plot of 1840 pcs/km. The rail-sleeper grid is loaded with concentrated forces located at the points of contact of the rolling surface of the rail head and the rim of the wheels of the bogies of the moving rolling stock.

The peculiarities of the problem under consideration include the formation of a directed impulse of mechanical vibrations emitted by a rail-sleeper grid under the influence of a moving, dynamically changing load with the presence of a double phase transition between soil layers with different physical and mechanical properties.

To assess the loading of the roof of the culvert, it is necessary to establish the mechanism for formation of the conditions for interaction between the under-sleeper foundation and the track superstructure, considering the dynamic load from the rolling stock, the conditions for the transfer of dynamic loads between the ballast layer and the soil, and of the soil with tunnel elements.

To this end, it is necessary to implement the following algorithm:

1. To draw up a calculation scheme for determining the bending of the roof of a culvert tunnel with finite elements using the approaches of the theory of elasticity. The complexity of the analytical solution lies in the fact that the object is a system of interacting media with different elastic-plastic properties, as well as owns a dynamic loading mode.

2. To determine the mechanism of formation of a directed impulse of mechanical vibrations emitted by a rail-sleeper grid under the influence of a dynamic load that occurs during movement of a high-speed train of the Sapsan type (VelaroRus).

3. To establish a mechanism for transferring the directed impulse of mechanical vibrations in the discrete medium of the ballast layer in the under-rail zone, soil and roof of the tunnel structure.

4. To construct a vector surface of the dependence of the pressure distribution over time in the cross section of the «ballast layer–soil–tunnel» system.

5. To determine the values of the buckling of the roof of the tunnel structure.

The kinematic model of the rolling stock (the VelaroRUS high-speed passenger train (EVS1/EVS2 Sapsan) and the electric cargo locomotive (2ES10) is a combination of reduced mass-dimensional models of rolling stock undercarriages. Depending on the locomotive type and speed, the average value of the vertical wheel load on the rail is adopted in accordance with the requirements of the Rules for calculating the track, GOST R 55513–2013 «Locomotives».

The functional dependence of the loading force of the track superstructure was obtained as a result of kinematic modelling of the oscillatory process of the bolster part of the rolling stock, taking into account the conditions of contact of the wheel rim with the rolling surface of the rail head [1].

To adequately describe the nature of resting of the rail-sleeper grid, it is necessary to consider the characteristics of the resistance of the bed of sleepers. The dependence of the pressure under the sleeper bed on the parameters of the track superstructure was studied by M. F. Verigo [2],

[3] The basis is Huygens' principle: each point of the medium involved in wave motion becomes a source of a new wave of radiation of vibration energy into the environment.

A. N. Yashnov [3], M. A. Chernyshev [4], G. M. Shakhuyants [5]. According to the recommendations [5], settlement due to deformations of reinforced concrete sleepers and fastenings is taken to be 5–25 % of the total rail settlement, settlement due to deformations of the ballast layer is to be calculated as 75–95 %. According to the known values of E_{po}, the modulus of elasticity of the ballast layer, E_b, is within the range of 50–400 MPa [3].

The distribution of pressure in the ballast layer, considering the non-uniformity of its transmission through the sleepers along and across the track axis, is determined by solving the Boussinesq problem. For ballast, it is possible to use the concept of «homogeneous soil» (S. N. Popov, [6]). The pressure transfer angle in crushed stone of a fraction of 25–60 mm, which corresponds to GOST 7392–2014, is 45°–50°, which allows using formulas of continuum mechanics and, as a consequence, the finite element method [4; 5; 7] to calculate pressure in the ballast.

The rail is considered as an extended Timoshenko beam exposed to shear deformations. The rigidity of bracing in the longitudinal direction of the track axis is 250 MN/m, in the transverse direction of the track axis – 140 MN/m. The compressive stiffness of the bonds is 110 MN/m (Huan Feng, [8]).

The simulation of the contact of the sleepers with the ballast and the ballast with the soil is carried out with the help of elastic links, which allow the ballast to «slide» along the surface of the roadbed, while the sleepers have a one-way connection with the ballast surface. The refined modelling of the ballast layer was carried out with the help of elastic links («spring» type element) connecting the sleepers and the ballast.

The rails and sleepers are connected at adjacent nodes in the area of pads by elastic connections, the rigidity of which allows the rail to move relative to the sleepers. Longitudinal stiffness of elastic «rail–sleeper» connections with reinforced concrete sleepers was assumed according to the data of experimental studies [9] of KB fastenings as S_x = 8900 kN/mm at the standard bolt twisting.

The deformation characteristics of volumetric finite elements used in the modelling of the ballast layer are determined in the works by S. V. Efimov [10], A. N. Yashnov [3], W. DeCorte and Ph. Van Bogaert [11].

Problem Statement

The model of the surface section is a rectangular parallelepiped with dimensions of 60 x 60 or 30 x 30 meters and a height of 15 m. To eliminate the influence of edge effects, the geometric dimensions of the calculated soil massif are five times larger than the cross-sectional dimensions of the tunnel structure. Along the axis of the parallelepiped, there is a model of an embankment in the form of a rectangle 0,4 m high. The railway track is presented as a simplified model, in which there is no detailed display of the rail and sleeper. The dimensions of the sleeper base are 2,7 x 0,3 m. The height of the rail corresponds to type R75. The distance between the axes of the sleepers (0,54 m) corresponds to the plot of 1840 pcs/km. The sewer is considered in the form of a cylinder with an outer diameter of 2094 mm and an inner diameter of 1500 mm. The cross section of the tray is determined in accordance with the technical documentation of the customer. The depth of the tunnel varies in accordance with the terms of reference and ranges from 7,46 (section near Yuzhnoye Highway) to 11 meters (section near Fermskoye Highway) from the daylight surface. When modelling oscillatory processes, two tracks are considered. The first track is laid along the axis of symmetry of the model and is parallel to the X axis. The second one runs parallel to the first one. The distance between the track axes is 6500 mm.

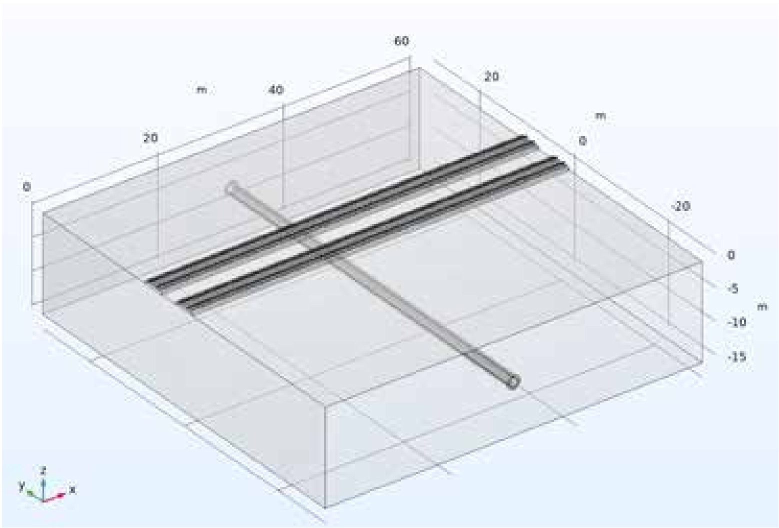
The cases of the passage of HSRS along the main track with a cargo train on the adjacent track, as well as with a free track, are considered.

Pic. 1 shows a general view of the design model of the intersection of tracks and the sewer.

When modelling, the following simplifications and assumptions were used:

1. The soil in which the sewer is located is an isotropic medium with constant parameters. The layered structure is not considered. Soil properties are described using the Mohr–Coulomb model with the following parameters: soil density is 1850 kg/m³, Young's modulus is 20 MPa, Poisson's ratio is 0,27, specific cohesion is 29 kPa, internal friction angle is 18° [12].

2. Ballast is an isotropic medium, the properties of which are described using the Mohr–Coulomb model with the following parameters: soil density is 1850 kg/m³, Young's modulus is 18 MPa, Poisson's ratio is 0,3, specific adhesion is 1 kPa, internal friction angle 15° [6].



Pic. 1. General view of the model [developed by the authors].

3. Concrete of the sewer and sleepers is considered as an elastic linear material with a density of 2300 kg/m^3 and elastic properties presented in Table 1.

4. There are no voids between the surface of the sewer and the soil either between sleepers and ballast.

5. The shape of the cross-section of the rail and sleepers has a negligible effect on the oscillatory processes and distribution of stresses in the soil and in the volume of the sewer.

6. The elastic properties of rail fastening are modelled using a thin elastic layer located in the contact zone of the sleeper and rail surface. The rigidity of the rail fastening corresponds to the properties of the ARS-4 fastening [4; 10; 13], namely: along the *X* and *Y* axes (horizontal displacement) it is of 346•10^6 N/m, along the *Z* axis (vertical displacement) it is of 37•10^6 N/m. This type of fastening was chosen due to its use on high-speed and high-load sections.

Static Analysis of the Stress-Strain State of the Sewer

To preliminarily assess the bearing capacity of the structural elements, the maximum values of stresses in the sewer's concrete along the *X*, *Y* and *Z* axes (see Table 1) from the impact of a static load were determined.

The analysis of the results shows that the maximum stress values are typical for the sewer's section located near Yuzhnoe Highway, which is explained by the shallow depth of the sewer (7,46 m). The result of calculating the sewer deformations for the indicated section is shown in Pic. 2. It can be seen from the picture that the maximum stresses correspond to the extension of the lower surface of the collector.

The obtained values of stresses and deformations of the sewer from train loads in the static mode are insignificant for all sections and do not significantly affect the state of the structure.

Dynamic Calculation of the Stress-Strain State of the Sewer

The concept of dynamic calculation is well known: «The calculation of a structure considering inertial forces and the resulting vibrations is called dynamic calculation»[4].

The simulation was performed in the Comsol[5] software environment in a non-stationary setting. The parameters of the geometric model, grid, as well as the boundary conditions are left unchanged (corresponding to the static calculation). The time range from zero to two seconds is considered, which corresponds to the time of passage of three train wagons along the side track above the sewer [14]. The train moves over the sewer at a speed of 55 m/s. On track 1 there is a cargo electric locomotive at rest. The results of the calculation

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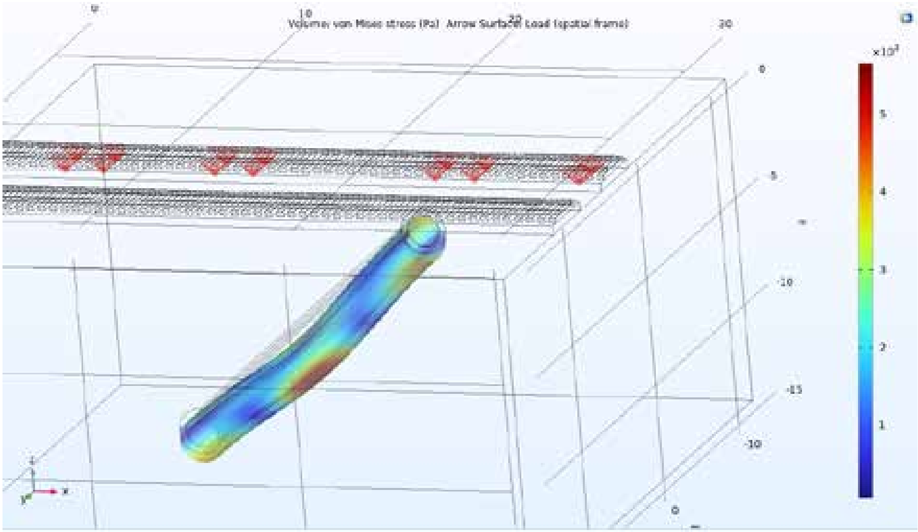
[4] Dynamics of transport structures: Method. Instructions. Compiled by S. A. Galansky, G. R. Mayerov. Samara: SamGUPS, 2016, 48 p.

[5] COMSOL Multiphysics v 6.0 Reference manual. ComsolInc, 2021, 1742 p. [Electronic resource]: https://doc.comsol.com/6.0/doc/com.comsol.help.comsol/COMSOL_ReferenceManual.pdf. Last accessed 14.03.2023.



Pic. 2. The result of the calculation of sewer deformations in the section near Yuzhnoye Highway under the action of a static train load. The scale of deformations is increased for clarity [performed by the authors].

of static deformations are taken as initial conditions when performing a dynamic calculation [12; 15].

Pic. 3 shows the result of calculating the deformations of the ballast, sewer and rail track at a time slot of 1,8 s. The considered moment of time corresponds to the maximum value of the sewer deformation.

By analogy, the calculation of the maximum values of stresses in the concrete of the sewer along the *X*, *Y* and *Z* axes was carried out for three sections of the sewer under consideration, which differ in the cross-sectional shape, diameter and depth. As an example, the calculation results for the section near Yuzhnoye Highway are presented (Pic. 4).

The analysis of the obtained results revealed the maximum stress values in the concrete lining of the sewer, the amplitude of which does not exceed 45 kPa. Dynamic loads on the sewer, caused by the action of passing trains, have pronounced harmonic components with a frequency of about 2,5 Hz. It should be noted that for sections of the sewer, which have a significant thickness, higher values (compared to other components) of the stress tensor along the *Y* axis are characteristic. This indicates that the sewer's structures are subject to bending here. With a decrease in the wall thickness and an increase in the diameter of the tunnel, the moment of resistance to bending decreases, which means that the longitudinal and vertical loads increase (tensor components along the *X* and *Z* axes).

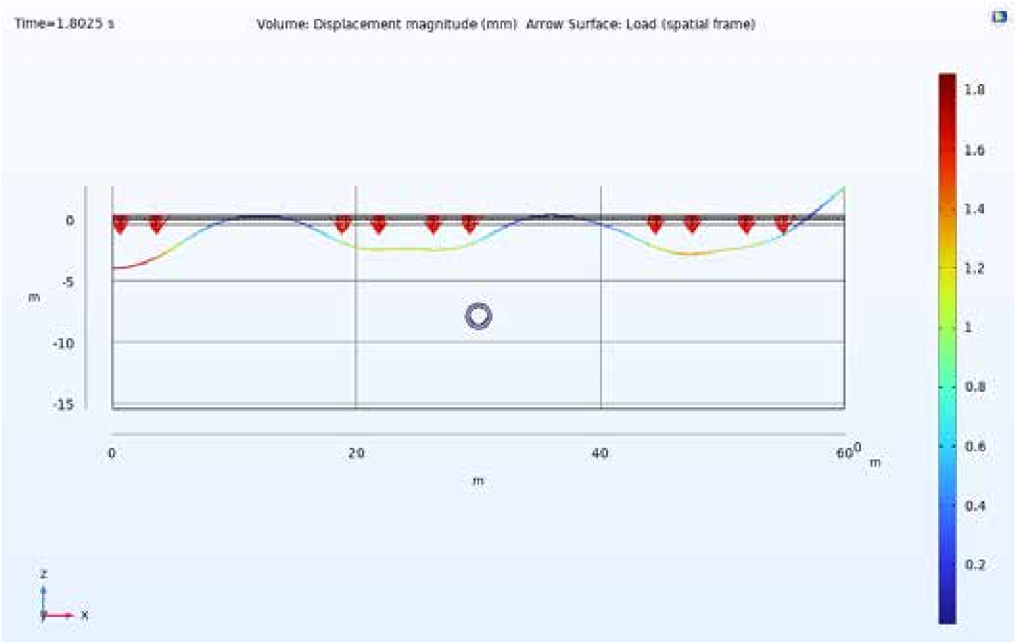
The sewer is under the influence of disturbances from a passing train and performs oscillations of a complex shape, the amplitude of which does not exceed 0,13 mm. As an example, Pic. 5 shows the result of calculating the deformations of the sewer along the *X* axis, calculated on the outer surface of the sewer in the area near Yuzhnoye Highway.

Oscillations have a complex shape, and vertical oscillations (along the *Z* axis) mainly predominate. An increase in oscillations may

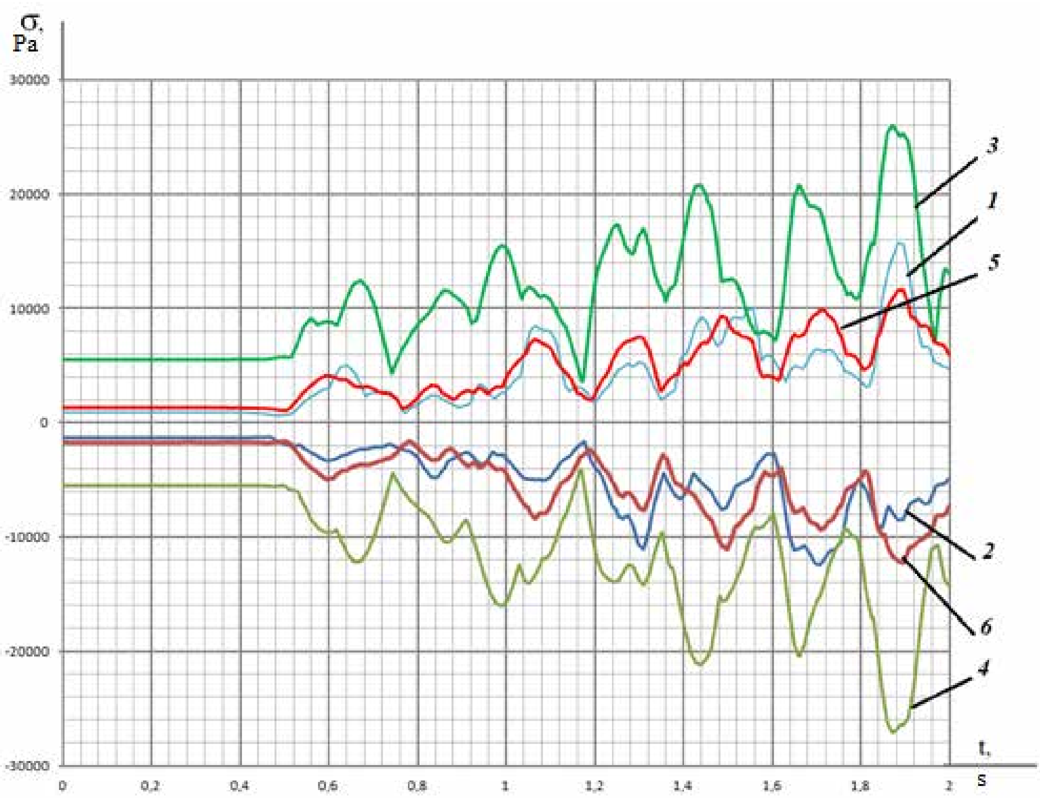
Table 1

Components of the main tensor of maximum stresses in the presence of a train above the sewer, Pa [performed by the authors]

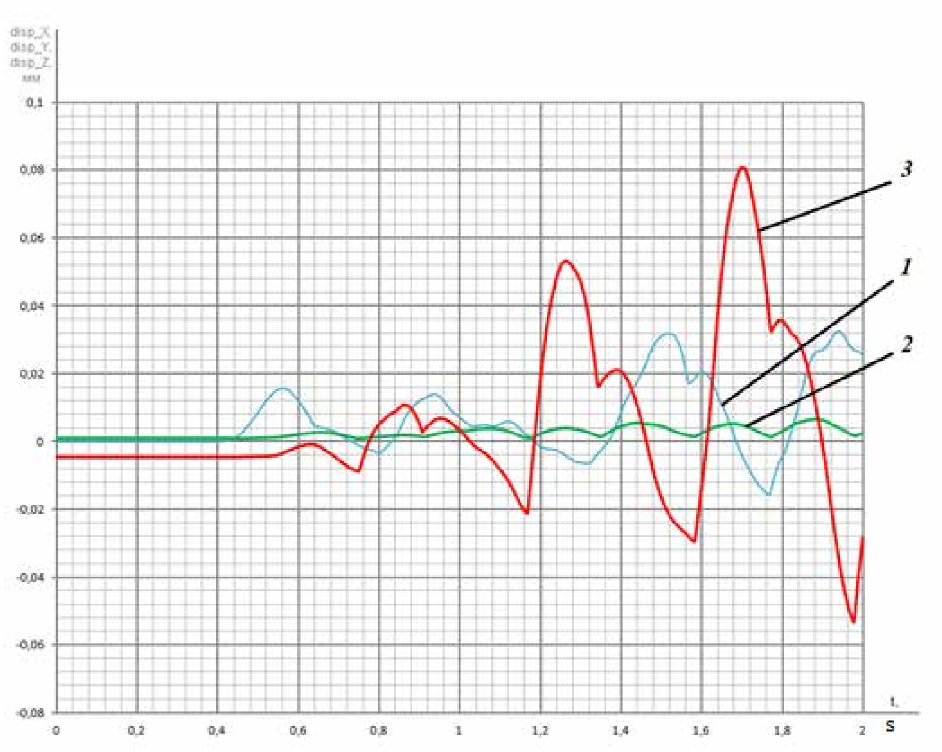
Site	Axis X		Axis Y		Axis Z	
	behaviour in tension	behaviour in compression	behaviour in tension	behaviour in compression	behaviour in tension	behaviour in compression
Fermskoye Highway	752	-890	2535	-2488	525	-1126
Yuzhnoye Highway	904	-1303	5489	-5499	1347	-1708
Obvodny Canal	3212	-3702	3398	-3358	2840	-3989



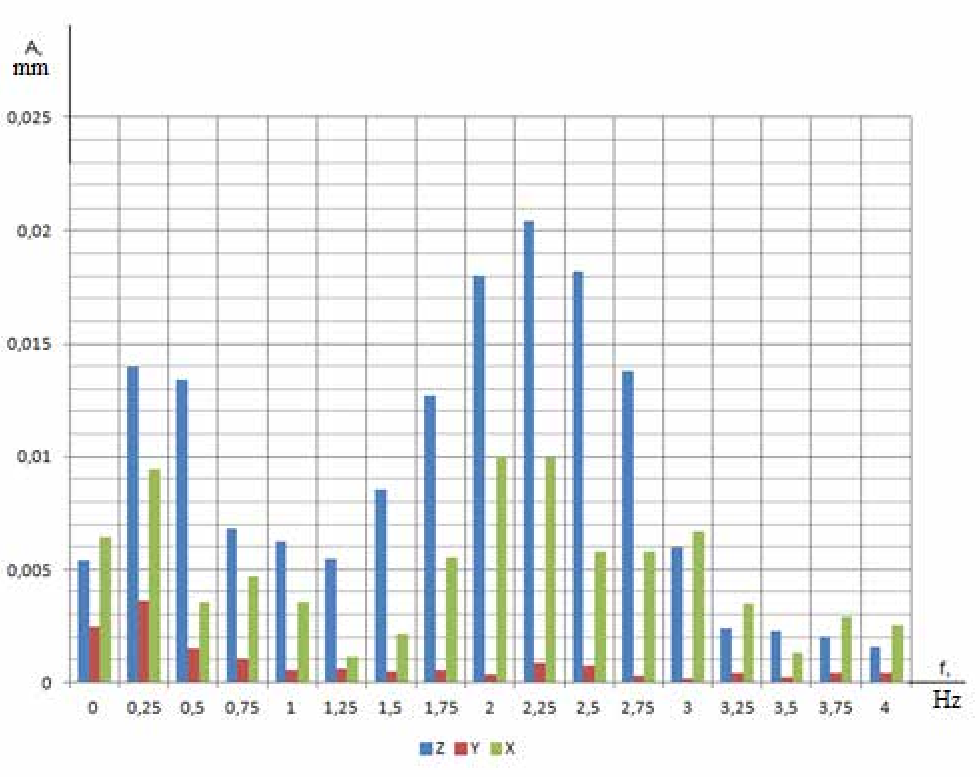
Pic. 3. The result of calculation of deformations of the ballast, sewer and rail track. The values of rail deformations are significantly increased compared to the real ones for the sake of clarity [16] [performed by the authors].



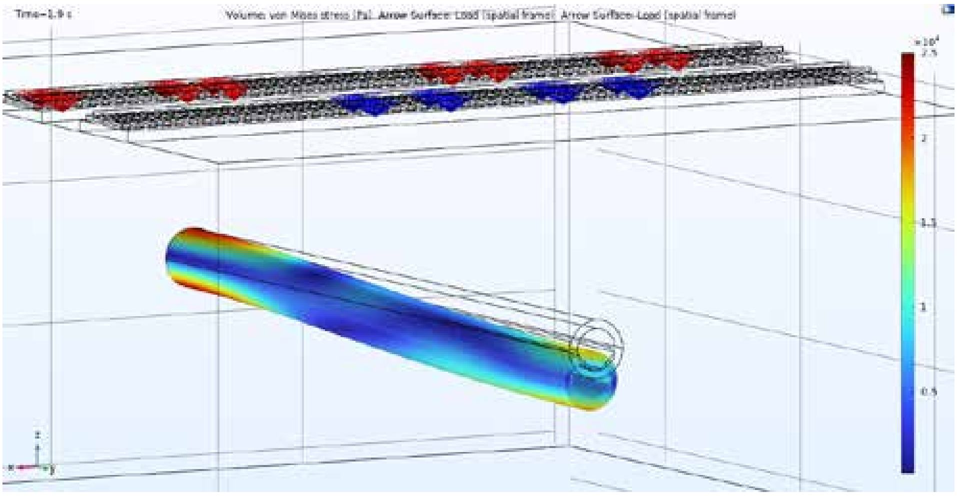
Pic. 4. The results of calculating the maximum values of stresses in the concrete of the sewer along the X, Y and Z axes when the train moves along the side track at a speed of 55 m/s:
1 – behaviour in tension along the X axis; 2 – the same, but behaviour in compression;
3 – behaviour in tension along the Y axis; 4 – the same, but behaviour in compression;
5 – behaviour in tension along the Z axis; 6 – the same, but behaviour in compression [performed by the authors].



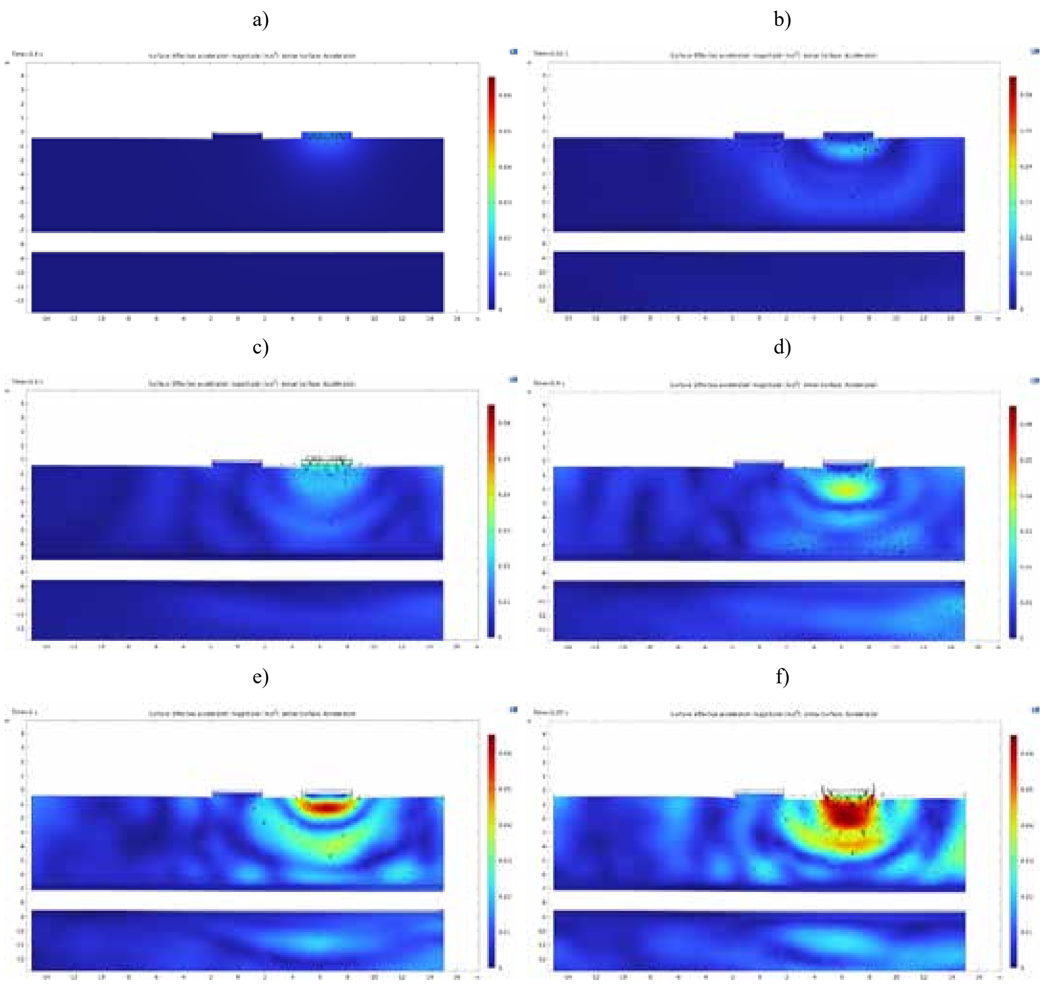
Pic. 5. The result of calculation of deformations of the sewer (displacement along the X axis), calculated on the outer surface of the sewer in the area near Yuzhnoye Highway [performed by the authors].



Pic. 6. The results of the spectral analysis of the time dependences of the deformation of the outer surface of the sewer in the area near Yuzhnoye Highway along the X, Y and Z axes [performed by the authors].

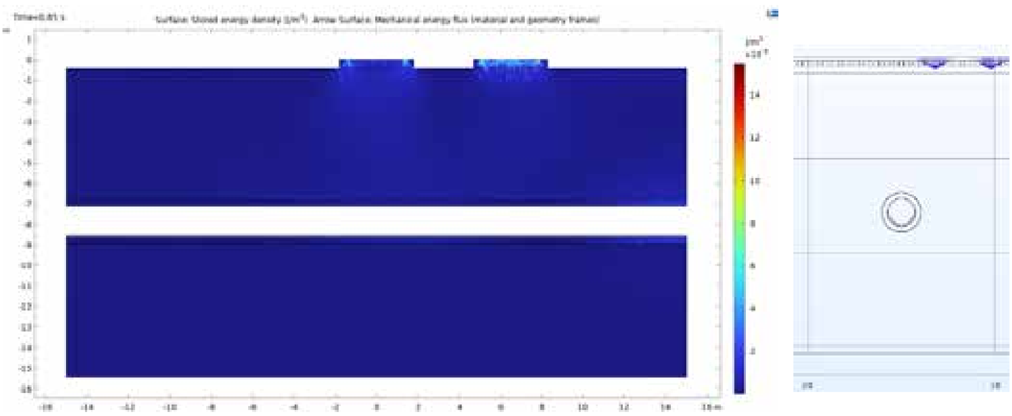


Pic. 7. The stress-strain state (according to Mises) of the sewer in the area near Yuzhnoye Highway at the time (1,9 s) corresponding to the maximum deformation. The scale of deformation is greatly enlarged for the purpose of clarity. The load from a train at rest is shown by red arrows, form a moving one by blue arrows [performed by the authors].

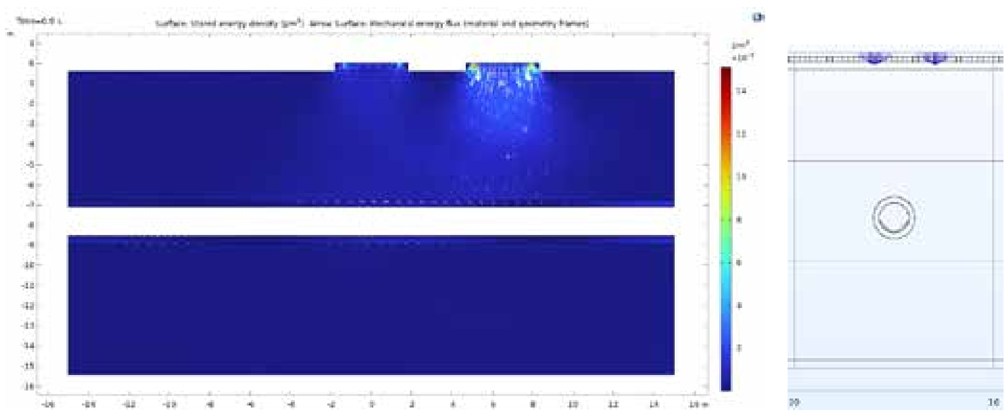


Pic. 8. Phases of the field of distribution of accelerations in the thickness of the soil: a – at the moment of time 0,4 s; b – at the moment of time 0,51 s; c – at the moment of time 0,6 s; d – at the moment of time 0,9 s; e – at the moment of time 1 s; e – at the moment of time 1,07 s. For clarity, the scale of soil deformation is increased by 2000 times [performed by the authors].

a)



b)



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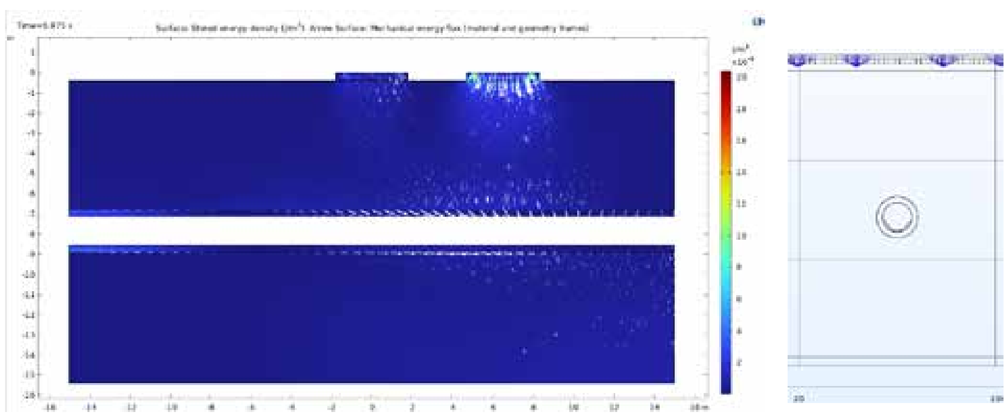

Pic. 9. Phases of the field of distribution of energy density in the thickness of the soil during the passage of the second bogie of the head wagon: a – at the moment of time 0,85 s; b – at the moment of time 0,9 s; c – at the moment of time 0,975 s. White arrows and lines show the direction of energy flows [performed by the authors].

indicate, among other things, the presence of resonant phenomena. This circumstance requires performing a frequency analysis and determining the natural frequencies of the structure.

The spectral analysis of the time dependences of the deformation of the outer surface of the sewer was performed along the *X*, *Y*, and *Z* axes (Pic. 6).

Table 2

A summary table of values of mass fractions involved in the oscillatory process at resonant frequencies, the corresponding amplitude values of displacements (μm), and the components of the tensile/compression stresses on the tunnel surface, (MPa) [performed by the authors]

Localisation	Parameter	X	Y	Z
Near Obvodny Canal	Mass participation coefficient, m_{f_X}, r.u. at a frequency of **1,9493** Hz	8,59E-10	0,000566	0,79543
	Mass participation coefficient, m_{f_Y}, r.u. at a frequency of **2,2184** Hz	0,556368	3,2E-10	1,08E-10
	Mass participation coefficient, m_{f_Z}, r.u. at a frequency of **2,3156** Hz	3,79E-10	0,507095	8,24E-05
	Total value of mass participation, $\sum m_f$	0,644884	0,618909	0,81044
	Amplitude values of displacements at resonant frequencies (μm)	46,7	46,7	45,3
	Tensile/compressive stress components on the tunnel surface, (MPa)	0,042/–0,037	0,024/–0,024	0,037/–0,047
Near Yuzhnoye Highway	Mass participation coefficient, m_{f_X}, r.u. at a frequency of **1,937** Hz	1,46E-10	0,000765	0,794426
	Mass participation coefficient, m_{f_X}, r.u. at a frequency of **2,213** Hz	0,551516	7,7E-11	5,57E-11
	Mass participation coefficient, m_{f_X}, r.u. at a frequency of **2,30** Hz	1,78E-10	0,504217	9,24E-05
	Total value of mass participation, $\sum m_f$	0,6474	0,6241	0,8103
	Amplitude values of displacements at resonant frequencies (μm)	45,3	46,7	45,3
	Tensile/compressive stress components on the tunnel surface, (MPa)	0,017/–0,009	0,027/–0,027	0,012/–0,011
Near Fermerskoye Highway	Mass participation coefficient, m_{f_X}, r.u. at a frequency of **1,9314** Hz	4,52E-10	0,000356	0,800222
	Mass participation coefficient, m_{f_X}, r.u. at a frequency of **2,2158** Hz	0,551564	5,38E-10	5,64E-11
	Mass participation coefficient, m_{f_X}, r.u. at a frequency of **2,3651** Hz	7,46E-10	0,460332	0,0001
	Total value of mass participation, $\sum m_f$	0,650512	0,611397	0,812321
	Amplitude values of displacements at resonant frequencies (μm)	45,3	48,3	45,3
	Tensile/compressive stress components on the tunnel surface, (MPa)	0,011/–0,017	0,016/ –0,011	0,009/–0,013

The resulting spectrum contains two resonant peaks at frequencies of the order of 0,25 and 2,25 Hz in directions *Y* and *Z*, and in direction *X*, in addition to those indicated, two additional peaks were detected at frequencies of 3 and 3,75 Hz.

The deformed state of the sewer, corresponding to the moment of reaching the maximum deformation (1,9 s), is shown in Pic. 7.

In general, the results of the calculation show that the obtained values of deformations of the sewer's section, due to the action of train loads, are insignificant and cannot have a significant impact on the state of the structure.

The initial stage of the oscillatory process of the soil under the influence of displacements of the track superstructure, corresponding to the passage of the first bogie over the sewer, is shown in Pic. 8.

The wave nature of the distribution of accelerations in the thickness of the soil is revealed. The acceleration value decays significantly as the distance from the railway track increases. The maximum values of accelerations in the thickness of the soil were found near the roadbed at the moments of time corresponding to the passage of the wheel over the axis of symmetry of the sewer.

The result of calculating the distribution of the specific energy of the system is shown in Pic. 9, that considers the process that accompanies the passage of the wheel over the axis of symmetry of the sewer. The position of the load on the rail relative to the sewer axis is shown on the right.

The following moments of time are considered: 0,85 s – approach of the wheelset of the second bogie of the head wagon; 0,9 s – the axis of symmetry of the second bogie is located above the axis of symmetry of the sewer; 0,975 s – approach of the bogie of the second wagon; 1,015 s – the axis of the wheelset of the first bogie of the second wagon is above the axis of symmetry of the sewer; 1,04 s – the axis of symmetry of the first bogie of the second wagon is located above the axis of symmetry of the sewer; 1,1 s – distancing of the first bogie of the second wagon from the sewer's symmetry axis.

Based on the results of studying the distribution of the specific energy of the system, it can be concluded that there is a tendency for a sharp decrease in the intensity of energy processes for a depth level within 5–7 m. Thus, the effect of dynamic train loads and vibration of the track superstructure on the object under consideration is insignificant.

Calculation of Natural Frequencies of Oscillatory Processes of Sewer's Sections

To assess the dependability of a structure, the distribution of modal (effective) mass fractions of the structure involved in the oscillatory process at resonant frequencies is sufficiently informative. The calculation is made in the Comsol environment using the Eigenfrequency tool. As a result of the calculation, the masses involved in the oscillatory process in directions X, Y and Z, m_{fX}, m_{fY}, m_{fZ}, respectively, were determined. The obtained values were correlated with the total mass of the oscillatory system under consideration.

The total values of the components of the coefficient of mass participation of structural elements of the structure according to the directions of the basis vector (X, Y, Z) show the achievement of resonant frequencies within the seventh iteration (more than 50–60 % of the mass participation of the structure is involved in the oscillatory process [7]), which allows us to consider the resonant frequencies achieved, and the results of the dynamic study reliable.

The relative values of the mass fractions involved in the oscillatory process for the corresponding values of the modal frequency values are presented in the summary Table 2.

CONCLUSIONS

Modelling the stress-strain state of the sewer under the action of static and dynamic loads from the train load (with an axial load of 25 tons) made it possible to establish the wave nature of distribution of deformations and accelerations in the soil with pronounced harmonic components. The frequency spectrum of the oscillatory process is generally identical for all sections of the sewer and contains two resonant peaks at frequencies of the order of 0,25 and 2,25 Hz along directions Y and Z, while along direction X (along the axis of the tunnel), in addition to those indicated, two additional peaks were detected at frequencies 3 and 3,75 Hz. The frequency of the perturbing forces is close to the resonant one, however, due to the smallness of the oscillation amplitudes, this phenomenon is not dangerous.

The sections of the sewer with a significant lining thickness are characterised by higher values of the stress tensor components along the Y axis (within 45 kPa), which confirms the fact that the sewer's structure is subject mainly to bending. A structure with a smaller wall thickness and a larger tunnel diameter (respectively, a lower bending resistance moment) is characterised by relatively high longitudinal and vertical loads (components along the X and Z axes).

As a result of the study of the process of distribution of the specific energy of the system over the massif, a tendency was revealed for a sharp decrease in the intensity of energy processes within the depths of 5–7 m.

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Article received 22.02.2023, approved 27.12.2023, accepted 27.12.2023.

Editorial note. ***The paper that presents from the authors' perspective a new approach to the statement and solution of the considered problem, caused several questions from behalf of the reviewers. The authors have suggested feedback and clarifications to some questions and counterarguments to others. The editorial board, understanding debatable contents of the article, novelty and and complexity of the problem stated within the topic under consideration, deemed possible to suggest the article for readers' consideration as a step towards wider discussion.***

Positively highlighting practical and scientific value of the authors' conclusions on the wave character of distribution of deformations and accelerations within the soil massif with pronounced harmonic components, the reviewers have noted a logical inconsistency between statement of the problem as that of assessment of rate of influence of oscillatory impact of high-speed rolling stock on the bearing elements of buried tunnel-type culvert, problem as assessment of operational dependability of the structure, the objective as analysis of strain-stress state of bearing elements of buried structures and the conclusions. Editorial board notes also certain inconsistency between the declared objective and sufficiently substantiated particular conclusion.

The authors from their part note absence of discrepancy outlined by reviewers between stated analysis of dynamic impact and static analysis described in the article. The authors are well aware that with the increase in speed of rolling stock dynamic impact on track and infrastructure also increases. That with that purpose that the static calculation of tunnel structure was performed along with dynamic calculation regarding movement of high-speed train. According to authors' opinion, the results described in the paper demonstrate just the character of changes in stress and strain deformations in tunnel structure in dynamic mode, and that is testified by time dependencies of changes in tensor components and maximum values of deformations; tensor's components in static mode are quoted for comparison; it was clearly revealed that loads in dynamic mode are higher than in static one.

In any case, in editorial board's opinion, only further discussion can help to reconciliate controversial opinions that arose during preparation of the article for publication.