УДК 624.21:625.745.2
DOI: 10.15587/1729-4061.2018.123002

ESTIMATION OF CARRYING CAPACITY OF METALLIC CORRUGATED STRUCTURES OF THE TYPE MULTIPLATE MP 150 DURING INTERACTION WITH BACKFILL SOIL

V. Kovalchuk
PhD
Department of rolling stock and track
Lviv branch of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan
I. Blazhkevych str., 12a, Lviv, Ukraine, 79052
E-mail: kovalchuk.diit@gmail.com

Yu. Kovalchuk
Assistant*
E-mail: tzov.lviv.bud@gmail.com

M. Sysyn
PhD, Associate Professor
Department of Planning and design of railway infrastructure
Dresden University of Technology
Hettnerstraße str, 3/353, Dresden, Germany, D-01069
E-mail: mykola.sysyn@tu-dresden.de

V. Stankevich
PhD, Associate Professor
Department of Computational mechanics of deformable systems
Pidstryhach Institute for Applied Problems of Mechanics and Mathematics National Academy of Sciences of Ukraine
Naukova str., 3-b, Lviv, Ukraine, 79060
E-mail: stan_volodja@yahoo.com

O. Petrenko
PhD, Associate Professor*
E-mail: olexapetrenko@gmail.com
*Department of construction industry
Lviv Polytechnic National University
S. Bandery str., 12, Lviv, Ukraine, 79013

Проведено оцінку напруженого стану залізничної конструкції типу Multiplate MP 150 із врахуванням ступеню ущільнення ґрунтової засипки. Встановлено, що у початковий період експлуатації металева гофрована конструкція є нестійкою проти утворення пластичного шарніра, коли ґрунтова засипка ще не досягла нормативного ступеню ущільнення. З метою недопущення розвитку залишкових деформацій металевої гофрованої труби необхідний технічний нагляд за трубою протягом року експлуатації

Ключові слова: залишкова деформація, несуча здатність, гофрована конструкція, модуль пружності, нерівність на залізничній колії

Проведена оценка напряженного состояния железнодорожной конструкции типа Multiplate MP 150 с учетом степени уплотнения грунтовой засыпки. Установлено, что в начальный период эксплуатации металлическая гофрированная конструкция является неустойчивой против образования пластического шарнира, когда грунтовая засыпка еще не достигла нормативного степени уплотнения. С целью недопущения развития остаточных деформаций металлической гофрированной трубы необходим технический надзор за трубой в течение года эксплуатации

Ключевые слова: остаточная деформация, несущая способность, гофрированная конструкция, модуль упругости, неравенство на железнодорожном пути

1. Introduction

It is accepted at present to assess performance of corrugated metal pipes for residual deformations by applying the criterion of relative vertical and horizontal deformations, relative to the diameter of the pipe. As indicated in refs [1, 2], residual vertical deformation of pipes must not exceed 3.0 % over operation time.

Technical observations of relative deformations of metal pipe at the section from Vadul-Siret to the state border on the Lviv railroad (Ukraine) [3] showed that relative deformations of the pipe are accumulated during initial period of pipe operation. However, the residual deformations decreased in one year of pipe operation. This is connected to the self-compaction of soil under its own weight and the weight of the railroad load.

In order to determine the actual location of the rail track in the profile, over the pipe and adjacent structures, and to control the position of pipe design, instrumental measurements were performed that involved geodetic instruments and tools, according to the program of specialized observations [4]. Position of the rail track and the inspection points in structures in the profile was determined applying a method of leveling from the temporary reference point. To determine the record of subsidence under the motion of a track measurement railroad car, we shall consider the estimated schematic of subsidence recording (Fig. 1). Subsidence recording implies the difference in displacements of journal boxes of wheelsets of a single railroad car, measured relative to the car base.

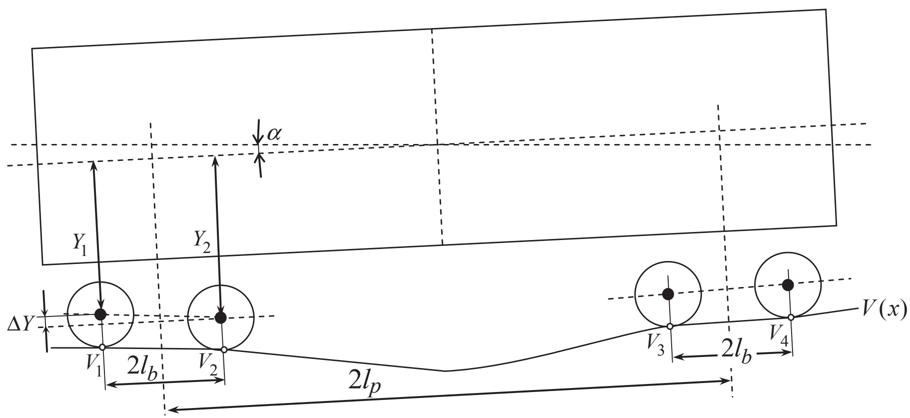

Fig. 1. Schematic of subsidence recording executed by a track measurement railroad car when passing over a track irregularity

In Fig. 1, the following designations are used: $V(x)$ is the mark function of the rail head; V_1, V_2, V_3, V_4 are the marks of the rail head under the wheels of a track measurement car; Y_1, Y_2 are the distances from the journal boxes of wheels of the track measurement car to the longitudinal axis of the railroad car; ΔY is the subsidence recording in the same position of the railroad car; $2l_p$ is the length of the railroad car base, 17 m; $2l_b$ is the length of base of the railroad car bogie, 2.7 m.

The subsidence, which is recorded by a track measurement car, as shown in Fig. 1, is calculated using formula:

$$\Delta Y = Y_2 - Y_1. \quad (1)$$

When values for marks of the rail head under the wheels of a track measurement car are V_1, V_2, V_3, V_4, and the longitudinal inclination of the car axis is α, formula for calculating the subsidence will take the form:

$$\Delta Y = V_2 - V_1 - 2l_b \cdot \alpha. \quad (2)$$

When the longitudinal inclination of the car axis α is expressed via marks, the formula for calculating the subsidence will take the following form:

$$\Delta Y = V_2 - V_1 - \left(\frac{V_2 + V_1}{2} - \frac{V_4 + V_3}{2} \right) \frac{2l_p}{2l_b}. \quad (3)$$

Values for marks V_1, V_2, V_3, V_4 are derived from the following expressions:

$$V_1 = V(x),$$
$$V_2 = V(x + 2l_b),$$
$$V_3 = V(x + 2l_b + 2l_p),$$
$$V_4 = V(x + 4l_b + 4l_p). \quad (4)$$

The initial data on levelling a track profile and results of establishing the track subsidence derived from a record by the track measurement car are shown in Fig. 2.

Fig. 2 shows that in the longitudinal direction (in the profile) a rail track over the pipe, at the section with a length of 60 m, exhibits a broken profile with a saddle along the axis of the pipe.

Estimation of bearing capacity of the metal corrugated structure that has residual deformations of vertical diameter is an important task. This is explained by the fact that the railroads of Ukraine lack established procedures for such estimation, while the constructed structure is the first one put into operation within a framework of the experiment on the Ukrainian railroads.

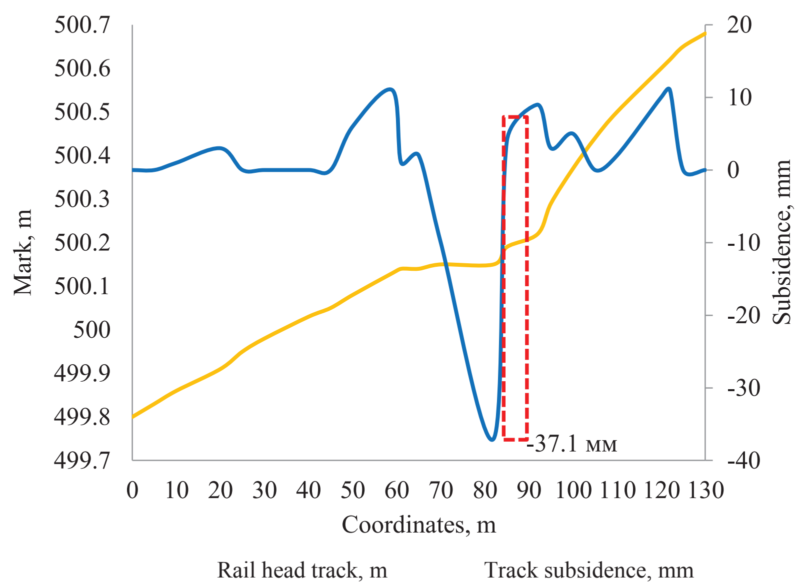

Fig. 2. Results of the leveling of a track profile, and a record of the track measurement car's pass over a track subsidence over the pipe

2. Literature review and problem statement

Metallic corrugated structures (MCS) have been utilized in transportation construction from the end of XIX century for erecting the artificial structures on automobile and rail roads, along with reinforced concrete structures. Facilities made of metallic corrugated structures have a number of advantages, which is why their implementation in transport construction is a promising and necessary direction for Ukraine, and for the world in general.

The main objective when designing metallic corrugated structures (thereafter MCS) is to take into consideration their joint performance with the backfill soil, one of the basic parameters of which is a module of deformation (modulus of elasticity). Thus, an important task on estimating MCS is to assign the module of the overall deformation of backfill soil E_0 [5].

The issues on creation and improvement of methods for calculating metallic corrugated structures in the soil environment were first tackled in parallel with their implementation in the practice of construction engineering [6]. Since the diagram «stress-deformation» at loading the non-rocky soils demonstrates a nonlinear character, soil in the first approximation can be characterized by four elastic characteristics [7]: initial module of elasticity $E_y^{(0)}=\mathrm{tg}\alpha_y$, conditional plastic module $E_{pl}=\mathrm{tg}\alpha_{pl}$, a module of the overall deformation $E_0=\mathrm{tg}\alpha_0$, and a module of elasticity at unloading $E_y=\mathrm{tg}\alpha_p$. The task is complicated by the fact that the specified characteristics largely depend on the stressed state, specifically static pressure in the soil. For this reason, the modules of soil deformation significantly increase with depth.

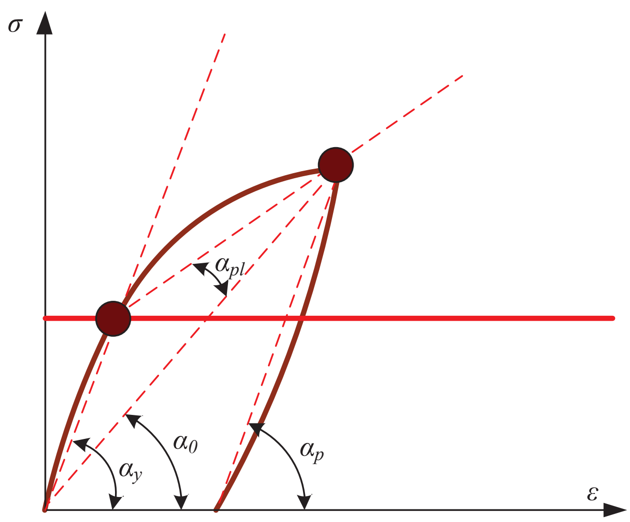

Fig. 3. Characteristic diagram «σ–ε» for soil

Despite such a complex character of soil work, most calculations are limited to modeling it as an elastic body with hysteresis [8, 9]. The main and the only characteristic of soil elasticity in our rules [1] is a module of the overall soil deformation E_0. However, the very value of deformation module E_0 significantly depends on the stressed state of soil [10, 11].

Authors of paper [12] show that an increase in soil deformation module of the backfill decreases the impact of bending moments on the stressed-strained state of a metallic corrugated structure. That is why the procedure considers two phases in the structure work:

1) the phase of installation when the filling has reached the top of the pipe;

2) the final phase when the filling has reached designed height.

The authors accepted as the feasibility criterion the prevention of the onset of plastic deformations in the walls of the pipe. This is achieved by introducing an appropriate margin factor to their calculations. Attention is emphasized on the compaction of backfill.

In paper [13], authors established the effect of soil friction on the magnitude of a compressing force that occurs in the metal of a pipe. They concluded as a result that the compaction of soil filling exerts a direct influence on the bearing capacity of a structure in general.

One of the newest techniques being used globally is the Pettersson-Sundquist design method [14]. It is based on the experience acquired from the conducted experiments on destroying the structures and employs analytical approaches of the elasticity theory and geoengineering. Underlying the technique is a prerequisite on that the different deformativeness of the structure and the lateral prisms of soil that surround it leads to a non-uniform subsidence of the ground located above. As a consequence, there occurs the state of boundary equilibrium of the backfill, which is located above the pipe. The friction forces that emerge along the sliding planes are directed in such a way that they decrease vertical pressure on the pipe in flexible pipes. To estimate bearing capacity, it is required to take into consideration an axial force and a bending moment, the angle of internal friction of a backfill, and the dynamic load caused by a moving vehicle.

As noted in paper [15], a metallic corrugated pipe, together with the surrounding backfill soil, forms a uniform structure that accepts the loads acting on the structure. In this case, the pipe accepts mostly the tensile stresses and, due to the presence of corrugation, eliminates bending moments. The soil massif accepts compressing stresses. Thus, it is allowed to apply the estimation procedures that take into consideration the work of pipe for compression only, and to disregard small magnitudes of bending moments when investigating a metallic corrugated pipe and the soil massif together.

Comparing international [16, 17] and Ukrainian [18] design standards, we established significant differences in the boundary heights of backfill above the metallic corrugated pipe (thereafter MCP) at a similar thickness of the corrugation wall. It turned out that pipes in international projects can withstand the weight of backfills that are much higher. This fact gave rise to the problem related to the development of new types of MCS. The actual reason was the fundamental differences in standards for estimating MCS. In Ukraine, the culverts with a diameter of up to 3 m are calculated according to rules specified in ref. [18]. According to them, the first boundary state is defined by the boundary static equilibrium during interaction of the system «structure – soil» and which can be applied to derive bearing capacity of the pipe. The recommended formula includes several empirical coefficients, though it lacks direct strength characteristics of the metal of a pipe. However, it is this condition that sets the limit in most cases.

It is accepted in international practice [17, 19] to assess the strength and resistance of the corrugation wall when the pipe vault is exposed to weight of the column of soil and pressure on the temporary load at the level of a pipe top. The joint work of MCS with soil at a sufficient height of backfill above the vault is accounted for through the introduction of a reducing coefficient to the sum of temporary and constant loads, which depends on the degree of compaction of soil prism around the structure. A similar test of strength and stability of the pipe wall is included in the standards in Russia, though it almost never sets a limit. Thus, estimation of the pipe beyond the boundary static equilibrium during interaction of the system «structure – soil» is the critical issue that limits the scope of application of structures.

Residual deformations of metallic corrugated pipes, which exceed permissible deformations, are observed in the process of operation. This is related primarily to the fact that builders and designers for a long time underestimated, at the design stage, the role of soil backfill in the work of MCS. The opportunities for a correct analysis of the interaction between MCS and soil backfill under static and dynamic loads have appeared only in recent years.

The scientific literature indicates that, as the experience of maintaining and operating MCS reveals, their technical resource is almost never used in full as it is required by the design estimation. One of the reasons is the specificity of MCS work, which is defined by the character of interaction between a metal shell and the backfill soil. The value for the elasticity module of backfill soil directly depends on the degree of soil compaction in the course of construction of the structure. Therefore, it is a promising task to study the carrying capacity of MCS taking into consideration reliable values for the elasticity module of backfill soil. They would allow designers to employ reliable values for the elasticity module of backfill soil at the design stage of metallic corrugated structures. It is also necessary to account for the effect of dynamic load of the railroad rolling stock, as well as residual deformations of vertical diameter of a metallic pipe.

3. The aim and objectives of the study

The aim of present study is to estimate bearing capacity of the metallic corrugated structure of type Multiplate MP 150, which is under operation on a railroad track, depending on the module of elasticity of soil backfill and the degree of compaction.

To accomplish the set aim, the following tasks must be solved:

– to establish the physical-mechanical characteristics of backfill soil depending on the degree of compaction;

– to estimate equivalent stresses in a metallic corrugated pipe as a result of the design state of the track and operational irregularity;

– to establish a mechanism that causes deformations in a railroad track and a metallic pipe;

– to compute the percentage impact of multivariate factors on the development of plastic deformations in the metal of a corrugated pipe and the accumulation of vertical irregularities on a railroad track.

4. Materials and methods of research

4. 1. Procedure for estimating the modulus of elasticity of backfill soil

The relationship between magnitude E_0 and the value of vertical compression σ_z is based on the ratio between volumetric deformation ε_v and the sum of main stresses [15] $\theta=\sigma_x+\sigma_y+\sigma_z=\sigma_1+\sigma_2+\sigma_3$:

$$\varepsilon_v = \frac{(1-2\nu)\theta}{E}, \tag{5}$$

where ν is the Poisson's ratio of soil.

Under condition of all-round compression:

$$\theta = \sigma_z (1+2\xi), \tag{6}$$

where

$$\zeta = \frac{\sigma_x}{\sigma_z} = \frac{\sigma_y}{\sigma_z} = \frac{1+\nu}{1-\nu}. \tag{7}$$

We shall obtain with respect to equation (5):

$$E = \frac{(1-2\nu)(1+\nu)\sigma_z}{\varepsilon_v (1-\nu)}. \tag{8}$$

Volumetric deformation is proportional to a change in the volume of pores ΔV_{por}:

$$\varepsilon_v = \frac{\Delta V_{por}}{V_{por}+V_{ck}} = \frac{\Delta e}{1+e}, \tag{9}$$

where V_{ck} is the volume of soil skeleton; $e=V_{por}/V_{ck}$ is the porosity of soil $0<e<\infty$; Δe is a change in porosity relative to porosity e in the state of static equilibrium.

The magnitude of compression σ_z caused by a change in porosity Δe, is a gain in stresses relative to the stresses of static equilibrium σ. There is a logarithmic dependence [1] between a change in porosity and the change in stresses, which is written in the form:

$$\Delta e = -a \lg \frac{\sigma+\sigma_z}{\sigma} = -a \lg\left(1+\frac{\sigma_z}{\sigma}\right) \approx a\left(2.3\frac{\sigma_z}{\sigma}\right). \tag{10}$$

Substituting the resulting expression (10) in formula (9) to calculate the value of ε_v, and the value obtained in formula (8) for determining E, we obtain:

$$E = \frac{(1-2\nu)(1+\nu)}{(1-\nu)} 2.3\frac{1+e}{a}\sigma = 2.3\beta\,\frac{1+e}{a}\sigma. \tag{11}$$

Static pressure of soil thickness increases with depth:

$$\sigma = \gamma z. \tag{12}$$

The rated value E_0 refers to soil at depths from 2 m to 3 m. In certain cases that require operations with soil thickness, it is recommended that modulus of deformation and modulus of elasticity should increase with depth. In accordance with equation (12), in order to account for a change in the modulus of deformation at depth z, it is necessary to apply formula:

$$E = 2.3\cdot\gamma\cdot h\cdot\frac{1+e}{a}\beta, \tag{13}$$

where γ is the volumetric weight of soil; e is the coefficient of porosity, which is for the material of backfill is equal to 0.6; a is the coefficient of compression, which is equal to 0.04 for the newly laid compacted soil, and to 0.02 for soil after 2–3 years of operation; β is the factor, which is determined depending on the coefficient of lateral expansion ν:

$$\beta = \frac{(1-2\nu)(1+\nu)}{1-\nu}. \tag{14}$$

When one knows a coefficient of soil expansion, it is possible using formula (13) to calculate the modulus of soil deformation at any depth of the soil massif.

4. 2. Methods for modeling a corrugated shell

At present, there are three approaches in the scientific literature to the modeling of a corrugated shell. The first approach is based on replacing the corrugated isotropic shell with a smooth orthotropic shell [20–23].

The isotropic material of a corrugated shell (Young modulus E, Poisson ratio ν) are replaced with the orthotropic material that possesses mechanical characteristics E_x, E_y, ν_x, ν_y, and in this case:

$$E_x = E\frac{A_a}{ah},\quad E_y = E\left(\frac{t}{h}\right)^3,\quad \nu_x = \nu,\quad \nu_y = \nu\frac{E_y}{E_x},$$

$$h = \sqrt{12\left(1-\nu_x^2\right)\frac{I_a}{A_a}}. \tag{15}$$

Here I_a, A_a are, respectively, the moment of inertia and the cross-sectional area of the pipe, related to wavelength a of the corrugation; t is the height of the corrugation; h is the accepted thickness of the orthotropic shell; R is the radius of curvature of the inside surface.

The second approach implies the replacement of shell with a grid of rod elements at imposing certain kinematic conditions [21]. The rods are located along the circular coordinate and along the generatrix of the cylinder, with the geometrical characteristics of their cross sections are determined by ratios:

$$A_x = \frac{A_0}{a}a_y,\quad I_x = \frac{I_a}{a}a_y,$$

$$A_y = \frac{a_x a_y}{\pi R^3}\left(\frac{t}{R}\right)^3,\quad I_y = \frac{a_x a_y}{12\pi r^3}r^3. \tag{16}$$

The two described approaches yield overestimated results of the stressed-deformed state of the shell [22].

The third approach involves the construction of a corrugated shell followed by the finite-difference partitioning [24]. Numerical results obtained by the third approach are the most probable and maximally close to field tests. At the same time, preparing the model requires a large amount of time, advanced skills of researcher, and significant computational resources.

5. Results of research of the stressed-deformed state of metallic corrugated structures of the type Multiplate MP 150

We conducted a series of multivariant calculations to assess the impact of physical and mechanical properties of soil and residual deformations of pipe on bearing capacity of the pipe. We studied a metallic pipe of length 12.69 m, vertical diameter 6.2 m, and horizontal diameter 6.57 m (Fig. 4). Metallic sheets of the pipe were made from corrugated structures of the type Multiplate MP 150 with a length of wave corrugation of 150 mm, a height of the corrugation wave of 50 mm, and a thickness of the metallic steel of 6 mm. Modulus of elasticity of steel of the pipe is $E=2.1\cdot10^5$ MPa; a Poisson ratio of the structure's material is $\nu=0.25$.

The structure has soil backfill with soil specific weight $\gamma=20$ kN/m^3.

Estimation of carrying capacity of the metallic pipe was performed using a method of finite elements executed by the software FEMAP with MSC NASTRAN.

Plastic behavior of material of the corrugated pipe is defined according to the criterion of plasticity by von Mises.

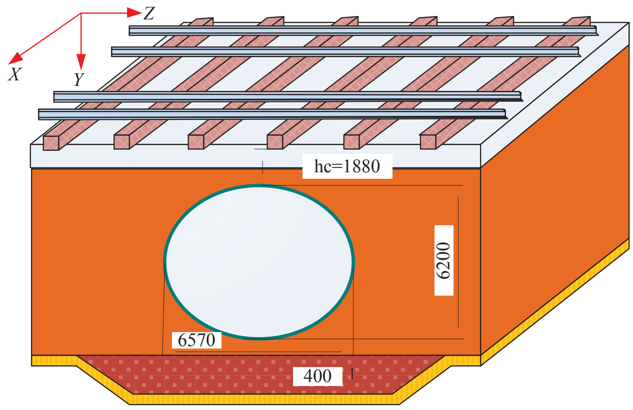

Fig. 4. Estimated model of the problem

The relationship between stresses and deformations in the isotropic material will be written in the following matrix form of the Hooke's law:

$$\{\sigma\}=[D]\{\varepsilon\}, \tag{17}$$

where $[D]$ is the elasticity matrix.

Stresses are derived from formula:

$$\{\sigma\}=\left[\sigma_{xx}\ \sigma_{yy}\ \sigma_{zz}\ \sigma_{xy}\ \sigma_{yz}\ \sigma_{zx}\right]. \tag{18}$$

Deformations are calculated by formula:

$$\{\varepsilon\}^T=\left[\varepsilon_{xx}\ \varepsilon_{yy}\ \varepsilon_{zz}\ \varepsilon_{xy}\ \varepsilon_{yz}\ \varepsilon_{zx}\right]. \tag{19}$$

Plastic behavior of the material of backfill and the material of a ballast layer is determined by the Mohr-Coulomb criterion of plasticity.

It is believed that fluidity starts when stresses correspond to plasticity criteria:

$$F\left(\{\sigma\},x\right)=0, \tag{20}$$

where x is a parameter of strengthening.

If $F(\{\sigma\},x)=0$, then the material behaves elastically, otherwise there is a gain in plastic deformations with components normal to the fluidity surface, which is determined by the function of plastic potential Q.

Because of the danger of occurrence of plastic deformations in the metal of pipe during calculations, we assign a von Mises criterion.

Therefore, we add to the parameters of module of elasticity, Poisson's coefficient, and density coefficient (E, ν, ρ) the value for yield limit σ_m.

In the calculations, we accept a perfect-plastic model of soil of the Mohr-Coulomb and Drucker-Prager type. For this purpose, we assign six characteristics of the backfill soil. Two elastic characteristics are a module of deformation E (similar to the Young modulus) and Poisson's ratio ν, and density ρ of the backfill soil. And three characteristics for the plasticity of soil – angle of internal friction φ, coefficient of adhesion c, and angle of dilatation ψ.

Note that there are many models of soil, with specialized types of finite elements created for some of them.

A metallic pipe is modeled using flat 2-D finite elements of the type Plate; the space of soil in the axils of corrugations is filled with tetrahedra; next, the soil further from the shell is modeled by hexahedra. A diagram of finite-element spatial model of the railroad track structure with a metallic corrugated pipe is shown in Fig. 5.

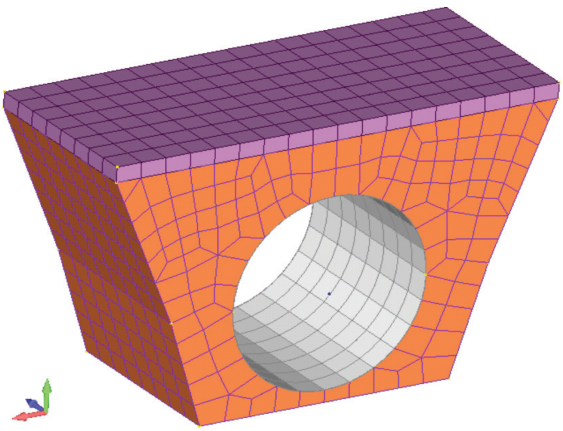

Fig. 5. Diagram of finite-element spatial model of the railroad track structure with a metallic corrugated pipe

The influence of compaction degree of the ballast layer material and the backfill material was determined in line with the Peterson procedure [25] and tabular dependences of physical and mechanical characteristics on porosity coefficient, known from the literature on standards. Results of estimations of physical and mechanical parameters of soil are given in Table 1.

Table 1

Estimated characteristics of soil at different degrees of compaction

Compaction degree of soil backfill *RP*, %	Soil characteristics		
	Porosity coefficient, *e*	Internal friction angle γ, degrees	Soil deformation modulus *E*, MPa
85	0.425	36	6.584
90	0.40	38	11.54
95	0.329	40	21.089
97	0.30	40.8	27.27

Visualization of results of estimations of stresses and deformations using a finite element method is shown in Fig. 6, 7.

The process of changing the degree of compaction and the remaining irregularity over time is not known, which is why we perform the multi-variant calculation taking into consideration a series of possible values of the initial compression degree and parameters of a railroad track irregularity. To analyze the reasons for occurrence of deformations, we select the most unfavorable case in the combination of these two factors.

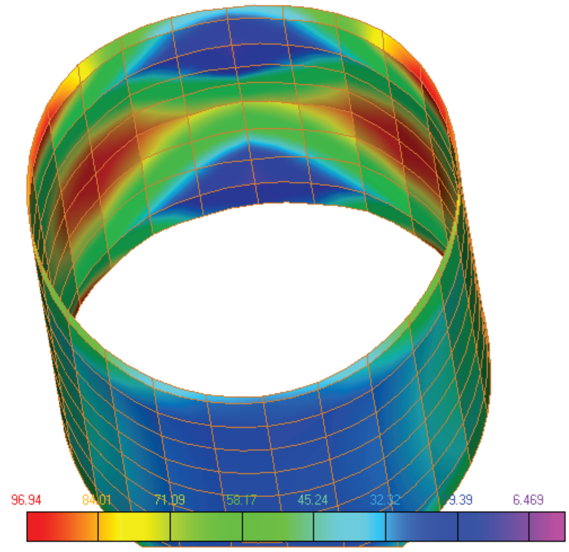

Fig. 6. Distribution of stresses in a metallic corrugated structure

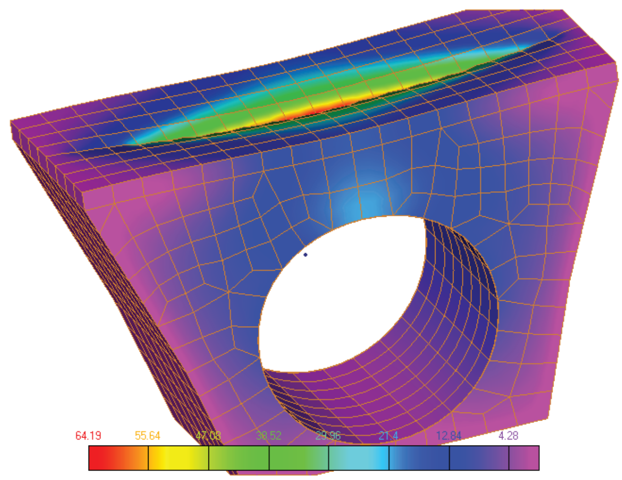

Fig. 7. Distribution of deformations in a metallic corrugated structure

An analysis of the obtained numerical results reveals that the greatest deformations and stresses (equivalent, in line with the von Mises hypothesis) occur in the walls of the metallic corrugated shell in the middle of its deflection (Fig. 8, 9).

The results of research we conducted show that an increase in the degree of compaction of soil backfill leads to an almost twofold decrease in stresses in the metallic pipe. The stresses grow much faster with an increase in the railroad track irregularity.

Numerical calculations have shown that the equivalent stresses exceed permissible magnitude of 235 MPa at compaction degree of the soil backfill below 90 % and at development of operational irregularity of the track. There is a threat that the metal of a corrugated pipe may enter a plastic state.

The mechanism of origin of deformation in a railroad track and a metallic pipe is shown in Fig. 10. A given mechanism takes into consideration the impact of human and technological factors, which, when combined, could cause residual deformations of the metallic pipe.

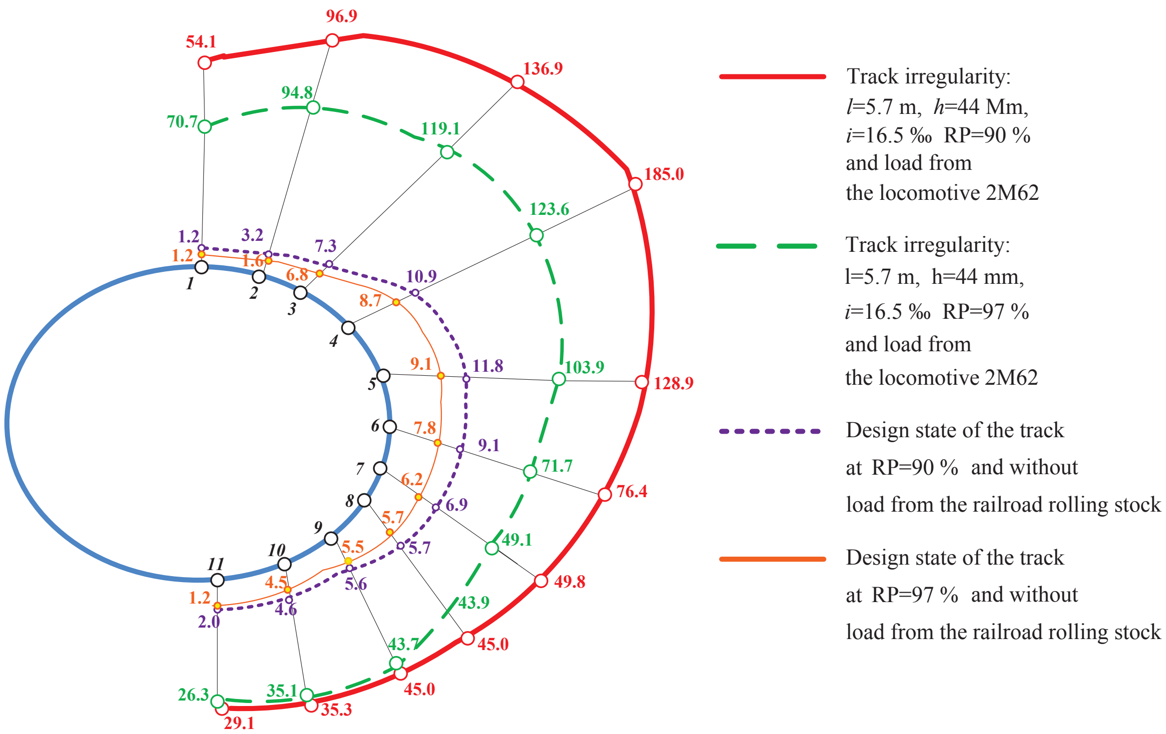

Fig. 8. Equivalent stresses in the metallic corrugated pipe as a result of the design state of the track and the operational irregularity and a degree of compaction of soil filling of 90 % and 97 %

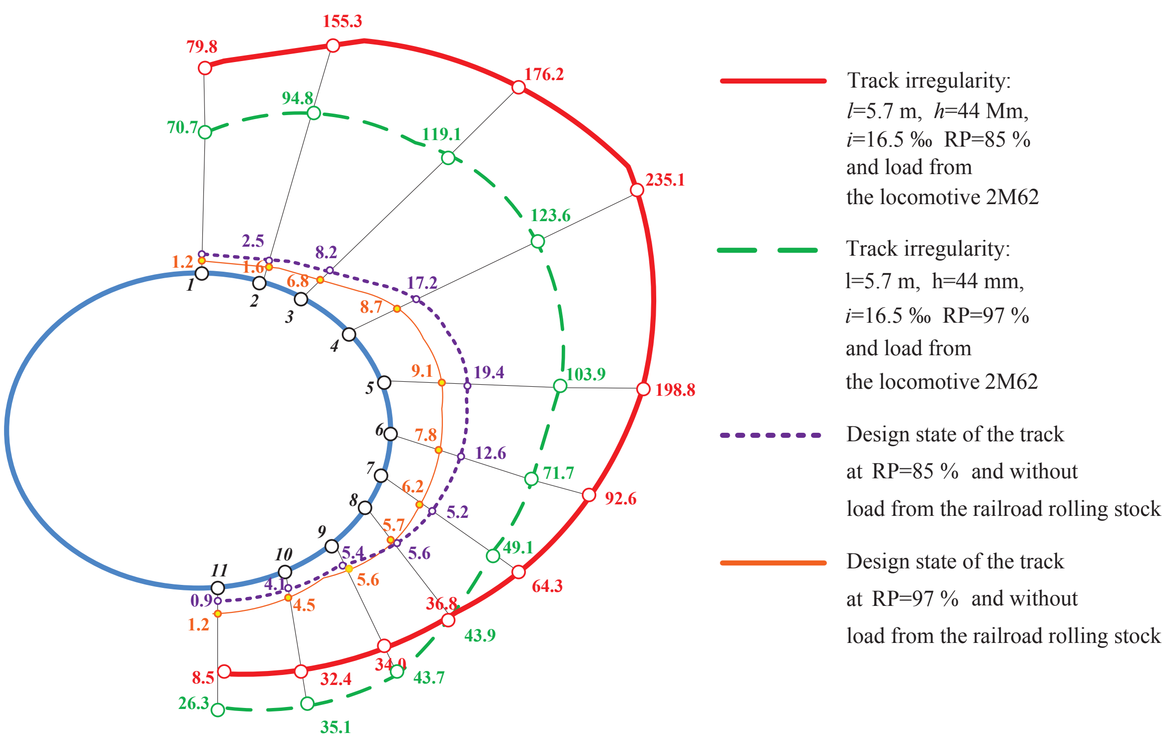

Fig. 9. Equivalent stresses in the metallic corrugated pipe as a result of the design state of the track and the operational irregularity and a degree of compaction of soil filling of 85 % and 97 %

Compaction of backfill soil starts at the time of construction of a metallic corrugated structure and motion of trains. As a consequence, there occurs uneven subsidence of the upper structure of the track, which manifests itself in the emergence of vertical irregularities in the geometry of the track with a simultaneous growth of vertical irregularities at the top of the pipe.

This leads to an increase in the dynamic load from the rolling stock on a railroad track and, as a result, on the entire structure.

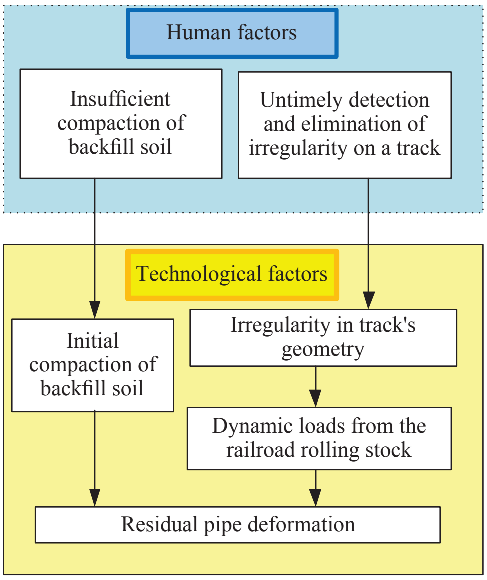

Fig. 10. Mechanism of occurrence of railroad track deformation and metallic pipe deformation

6. Discussion of results of the study into carrying capacity of a metallic corrugated pipe of the type Multiplate MP 150

The experience of building metallic corrugated structures demonstrates that it is impossible to ensure perfect symmetry of the structure's model, soil compaction, and the character of loading during operation. The structures considered are very sensitive to asymmetrical loads, which is why during operation one may expect asymmetrical deformation. Given this, it should be recommended that special attention during construction of such structures be paid to the homogeneity of the backfill soil and a symmetrical compression degree.

When the designed backfill soil compaction of 97 % by Proctor criterion is fulfilled, the strength criterion and permissible vertical deformations of a metallic corrugated structure are ensured. This is due to the fact that the side walls of a metallic pipe demonstrate a sufficient resistance against horizontal deformations. However, when the backfill soil compaction is below 90 %, test for the formation of a plastic hinge in a metallic pipe is not effective.

As regards the influence of a track irregularity and a degree of compaction on the bearing capacity of a metallic corrugated structure, it can be stated that both factors exert a significant impact. The lowest value for bearing capacity is characteristic for the initial period of operation, immediately after construction. However, provided a timely elimination of an irregularity on the railroad track, even at insufficient compaction of backfill soil, the reserve of carrying capacity is 58 %. Whereas at a normal degree of compaction, the margin factor is about 80 %. If an irregularity in the railroad track upper structure exceeds the normative values, it leads to a rapid growth in the dynamic load from the rolling stock and, consequently, to a decrease in carrying capacity. It should be noted that even when an irregularity exceeds the standards, it is possible to ensure stable work of the pipe if backfill soil has a sufficient degree of compaction.

At the same time, a significant shortcoming in the criterion of relative deformations is the influence of design diameter of the pipe, since a given criterion is unified for all possible ranges of metallic corrugated pipes. Therefore, the absolute value of pipe deformations can be different in each particular case. Thus, relative deformation is not applicable when estimating position of the track. Along with it, absolute deformations must be accounted for. Therefore, in the further research it is necessary to estimate the stressed-strained state taking into considerations the absolute deformations of a metallic pipe. This is due to the fact that the horizontal deformations of the pipe's cross section have no influence on the horizontal deformations of the track upper structure and on the dynamic loads from the rolling stock.

5. Conclusions

1. At the initial stage of operation of a metallic corrugated pipe it is necessary to improve the level of technological control over a change in the vertical and horizontal diameters of the pipe because the backfill soil has not yet reached the standard degree of compaction of 97 %. With an increase in the degree of backfill soil compaction *RP* from 85 % to 97 %, the modulus of deformation of backfill soil increases threefold.

2. The study conducted shows that carrying capacity of a structure depends on two interconnected factors, specifically the magnitude of an irregularity on the railroad track and the degree of compaction of backfill soil. An increase in the degree of compaction of backfill soil leads to a decrease in the stresses in a metallic pipe by almost half. The stresses grow much faster with an increase in the irregularity on the railroad track. Numerical computations have shown that the equivalent stresses exceed the permissible magnitude of 235 MPa when the degree of compaction of backfill soil is below 90 % and the development of operational irregularity on the track. It poses a threat of the metal of a corrugated pipe entering a plastic state. In the combined effect of both reasons, more important is the degree of compaction of backfill soil whose share accounts for 42 %, with the proportion of an irregularity development making up 22 %.

3. The examined metallic structure under standard operation conditions has a large reserve of carrying capacity, which amounts to 80 %. However, these structures, despite their high initial strength margin, are sensitive to an increase in external dynamic loads due to the emergence of an irregularity on the railroad track.

References

1. Posibnyk do VBN V.2.3-218-198:2007. Sporudy transportu. Proektuvannia ta budivnytstvo sporud iz metalevykh hofrovanykh konstruktsiyi na avtomobilnykh dorohakh zahalnoho korystuvannia: Rekomendovano naukovo-tekhnichnoiu radoiu DerzhdorNDI vid 17 lystopada 2006 r. No. 14. Kyiv, 2007. 122 p.
2. Koval P. M., Babiak I. P., Sitdykova T. M. Normuvannia pry proektuvanni i budivnytstvi sporud z metalevykh hofrovanykh konstruktsiyi // Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu. 2010. Issue 39. P. 114–117.

3. Luchko Y. Y., Kovalchuk V. V., Nabochenko O. S. Study of carrying capacity of a corrugated metal construction by criterion of yield hinge development // Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport. 2015. Issue 5 (59). P. 180–194. doi: 10.15802/stp2015/55340
4. Die Tragfähigkeit von Eisenbahndurchlässen in Abhängigkeit von der Bauausführung und der Instandhaltung / Sysyn M., Kowaltschuk W., Nabotschenko O., Gerber U. // ETR – Eisenbahntechnische Rundschau. 2016. P. 39–44.
5. Luchko Y. Y. Gruntoznavstvo, mekhanika gruntiv, osnovy ta fundamenty. Lviv: Kameniar, 2013. 320 p.
6. Research and analysis of the stressed-strained state of metal corrugated structures of railroad tracks / Kovalchuk V., Luchko J., Bondarenko I., Markul R., Parneta B. // Eastern-European Journal of Enterprise Technologies. 2016. Vol. 6, Issue 7 (84). P. 4–9. doi: 10.15587/1729-4061.2016.84236
7. Wysokowski A., Janusz L. Mostowe konstrukcje gruntowo – powlokowe. Laboratoryjne badania niszczace. Awarie w czasie budowy i eksploatacji // XXIII konferencja naukowo-techniczna. Szczecin, 2007. P. 541–550.
8. Esmaeili M., Zakeri J. A., Abdulrazagh P. H. Minimum depth of soil cover above long-span soil-steel railway bridges // International Journal of Advanced Structural Engineering. 2013. Vol. 5, Issue 1. P. 7. doi: 10.1186/2008-6695-5-7
9. Modeling the Dynamic Failure of Railroad Tank Cars Using a Physically Motivated Internal State Variable Plasticity/Damage Nonlocal Model / Ahad F. R., Enakoutsa K., Solanki K. N., Tjiptowidjojo Y., Bammann D. J. // Modelling and Simulation in Engineering. 2013. Vol. 2013. P. 1–11. doi: 10.1155/2013/815158
10. Novodzinskiy A. L., Kleveko V. I. Uchet vliyaniya tolshchiny gofrorovannogo elementa na prochnost' i ustoychivost' metallicheskoy vodopropusknoy truby // Vestnik PNIPU. Stroitel'stvo i arhitektura. 2014. Issue 1. P. 81–94.
11. Saat M. R., Barkan C. P. L. Generalized railway tank car safety design optimization for hazardous materials transport: Addressing the trade-off between transportation efficiency and safety // Journal of Hazardous Materials. 2011. Vol. 189, Issue 1-2. P. 62–68. doi: 10.1016/j.jhazmat.2011.01.136
12. AASHTO: Standart Specifications for Highway Bridges. American Association of State Highway and Transportation Officials, 444 N. Capitol St., N. W., Ste. 249, Washington, D. C., 2001.
13. Handbook of steel drainage and highway construction products. American Iron and Steel Institute. Canada, 2002.
14. Waster M. RORBROAR. Verifiering av nyutvecklat dimensioneringsprogram samt vidareutveckling for jernvagstrafik. Orebro University, Sweden, 2008. 143 p.
15. Machelski C. Modelowanie mostowych konstrukcji gruntowo-powlokowych. Dolno-slaskie Wydawnictwo Edukacyjne, 2008. 208 p.
16. ODM 218.2.001-2009. Rekomendacii po proektirovaniyu vodopropusnyh metallicheskih gofrirovannyh trub: Rasporyazhenie Federal'nogo dorozhnogo agentstva ot 21 iyulya 2009 g. No. 252-r.
17. Pettersson L., Sundquist H. Design of soil steel composite bridges. Structural Desing and Bridges, Stockholm, 2007. 84 p.
18. Posibnyk do VBN V.2.3-218-198:2007. Sporudy transportu. Proektuvannia ta budivnytstvo sporud iz metalevykh hofrovanykh konstruktsiyi na avtomobilnykh dorohakh zahalnoho korystuvannia. Kyiv, 2007. 122 p.
19. Mechelski C. Vodelowanie mostowych konstrukcji gruntowo-powlokowych. Wrozlaw, 2008. 205 p.
20. El-Sawy K. M. Three-dimensional modeling of soil-steel culverts under the effect of truckloads // Thin-Walled Structures. 2003. Vol. 41, Issue 8. P. 747–768. doi: 10.1016/s0263-8231(03)00022-3
21. Machelski C. Kinematic method for determining influence function of internal forces in the steel shell of soil-steel bridge. Studia Geotechnica et Mechanica. 2010. Vol. XXXII, Issue 3. P. 28–40.
22. Elshimi T. M. Three-dimensional nonlinear analysis of deep-corrugated steel culverts. Queen's University Publ., 2011. 738 p.
23. Barbato M., Bowman M., Herbin A. Performance evaluation of buried pipe installation. Louisiana State University Publ., 2010. 123 p.
24. Kovalchuk V. V. The effect of corrugated elements thickness on the deflected mode of corrugated metal structures // Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport. 2015. Issue 3 (57). P. 199–207. doi: 10.15802/stp2015/46079
25. Pettersson L., Leander J., Hansing L. Fatigue design of soil steel composite bridges // Archives of institute of civil engineering. 2002. Issue 12. P. 237–242.