Проведено дослідження та аналіз несучої здатності металевих гофрованих конструкцій залізничної колії. Виконано розрахунок еквівалентних сил, які виникають від рухомого складу залізниць. Встановлено, що накопичення залишкових деформацій склепіння труби у часі може вплинути на появу текучості матеріалу металевих гофрованих конструкцій, а це, у свою чергу, може призвести до утворення пластичного шарніру металу труби

Ключові слова: металева гофрована конструкція, товщина металевої гофрованої труби, еквівалентні сили, динамічне навантаження, напруження

Проведено исследование и анализ несущей способности металлических гофрированных конструкций железнодорожного пути. Выполнен расчет эквивалентных сил, возникающих от подвижного состава железных дорог. Установлено, что накопление остаточных деформаций свода трубы во времени может повлиять на появление текучести материала металлических гофрированных конструкций, а это, в свою очередь, может привести к образованию пластического шарнира металла трубы

Ключевые слова: металлическая гофрированная конструкция, толщина металлической гофрированной трубы, эквивалентные силы, динамическая нагрузка, напряжение

UDC 624.014.27-422.12.13
DOI: 10.15587/1729-4061.2016.84236

RESEARCH AND ANALYSIS OF THE STRESSED-STRAINED STATE OF METAL CORRUGATED STRUCTURES OF RAILROAD TRACKS

V. Kovalchuk
PhD*
E-mail: kovalchuk.diit@mail.ru
J. Luchko
Doctor of Technical Sciences, Professor*
E-mail: luchko.diit@mail.ru
I. Bondarenko
PhD, Associate Professor**
E-mail: irina_bondarenko@ua.fm
R. Markul
PhD**
E-mail: guaranga_mr@mail.ru
B. Parneta
PhD
Department "Construction industry"
National University Lviv Polytechnic
S. Bandera str., 12, Lviv, Ukraine, 79013
E-mail: f_termit@yahoo.com
*Department "The rolling stock and track"
Lviv branch of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan
I. Blazhkevych str., 12 a, Lviv, Ukraine, 79052
**Department "Track and track facilities"
Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan
Lazaryan str., 2, Dnipro, Ukraine, 49010

1. Introduction

In the process of operation of metal corrugated structures (MCS), the following defects were registered: sagging of a pipe arch, excessive deformations of vertical and horizontal diameters of pipe, metal spalling around bolt connections, corrosion of pipe's metal, etc.

When observing behaviour of a metal corrugated pipe in the process of operation [1, 2], it turned out that they are undamped in character. Thus, an analysis of the intensity of accumulation of excessive deformations over one year of operation of a metal corrugated pipe revealed that relative deformations of pipe do not increase, gradually decreasing instead.

The research we conducted aimed at establishing the causes of occurrence of such defects are necessary and relevant at present. An appropriate monitoring will make it possible to make timely engineering decisions to increase bearing capacity of MCS.

2. Literature review and problem statement

World practice of designing and operation of metal corrugated structures demonstrates that a decisive influence on the stressed-strained state of MCS is exerted by the degree of compaction of soil backfill [1–3]. Recommended compaction should reach the degree of 0.95–0.97. However, paper [1] indicated that the reduction of soil compaction even from 0.95 to 0.8 leads to the reduction of soil deformation module by 4 times, which, in turn, is the cause of significant growth of stresses and strains in the walls of the structure.

Conducting a long-term monitoring of more than 900 objects from corrugated pipes, constructed from 1951 to 1965 in the state of Ohio (USA) [4, 5] made it possible to draw the following conclusion: in all cases, for the designs that did not experience destruction, large deformations accounted for 22–34 %; for the structures that suffered damage, such deformations reached 45–55 %. These studies unequivocally proved that the cause of excessive deformations was the insufficient soil compaction, or the use of inappropriate type of material for the backfill. According to [6–8], if deformations are within 15–20 % and height of the layer above the pipe is larger than 1.8 m, then the structure does not require additional measures for its strengthening.

Extending the scope of application of MCS has not enough scientific and regulatory provision. Existing regulation documents [3, 9, 10] refer only to round pipes with diameter up to 3 m and are based on a calculation analysis of the deformation of pipes at simplified hypothesizes on soil pressure on the pipe.

Thus, the practice of applying MCS in the soil environment convincingly demonstrated that the examined structures, with regard to their positive properties, are characterized by relatively low reliability and durability. In the course of their operation, a growth of unacceptable deformations is observed in many cases, namely an increase in horizontal and a decrease in vertical diameters of the pipe. To exclude unacceptable deformations of pipes, it is necessary in future to develop methods for the calculation of MCS that work together with soil backfill, allowing the prediction of strength and durability of MCS.

When calculating MCS, there are a number of techniques. The known methods for the valuation of bearing capacity of pipe include a technique of the interaction between pipes and soil, which was proposed by Duncan and Drawsky [11]. The method was developed based on many years of research into engineering structures carried out on the models of observation and performed numerical calculations using the method of finite elements. In this method they considered both the effect of squeezing forces and bending moments on the structure's wall, as well as nonlinear stresses and deformations of soil. It was demonstrated that an increase in soil hardness (deformation module) reduces the effect of bending moments on the stressed-strained state of the structure. That is why the method took into account two phases of the structure's performance:

1) the phase of installation when the backfill reached the top of the pipe;

2) the final phase when the backfill reached design height.

As a criterion of working efficiency they accepted early prevention of the start of plastic deformations in the walls of the pipe. This is achieved by the introduction to calculations of the corresponding assurance factor. However, in this method the calculations are performed for pipes of small diameter, up to 3 m only.

The Vaslestad method [12] is proposed for the structures of large cross sections. It application makes it possible to estimate the bearing capacity of the pipe walls by compression strength and deformation of the top of structure during placement and compaction of the backfill and the effect of soil friction on the magnitude of squeezing force. This technique describes the occurrence of phenomenon of the structure's spreading under the influence of the upper soil layer above the pipe. However, it takes into account the action of axial forces only, it is accepted that much of the stress is taken by the soil.

The methods of OHBDC (Ontario Highway Bridge Design Code) and CHBDC (Canadian Highway Bridge Design Code) [13] were developed based on the American and Canadian standards for designing the bridges. They are based on the assumption about dominant role of axial forces in the pipe walls. The methods take into account a case of pipes with open cross section and a phenomenon of the structure's spreading and influence of the degree of soil compaction on the magnitude of module of its deformation. They also take into account pliability of a structure that allows for the design of structures with box section. These methods ignore the influence of bending moments and consider only axial forces.

The technique of AASHTO (American Association of State Highway and Transportation Officials) [14]. The American technique was developed in accordance with norms for the design of bridges by the American Association of Highway and Transportation Officials. Similar to the methods of OHBDC, it neglects the influence of bending moments and takes into account axial forces only. Calculations of strength of the seams are presented, as well as bulging (loss of stability) of a structure's walls, assembling hardness; a possibility of occurrence of plastic deformations in the pipe walls is considered. It provides for the possibility to explore structures with the frame-type section and to take into account dynamic coefficients for a case of variable loads.

One of the newest methods is the Sundquist-Petterson technique [15, 16]. It is based on the above described methods and experience, gained in the conducted experiments on destroying the structures, it uses analytical approaches of elasticity theory and geotechnology. To assess bearing capacity, it takes into account axial force and bending moment, the angle of internal friction of the backfill and dynamic load from movable transportation vehicle. It is characterized by sufficient universality and takes into account pliability of structures from corrugated metal sheets.

Conducted literary analysis demonstrates that the estimation of bearing capacity of metal corrugated structures was performed only for pipes of small diameter to 6 m. Pipes of large diameters at the boundary load from the railroad rolling stock have not been examined by the stressed-strained state. These papers also lack analysis of the bearing capacity of metal corrugated pipes depending on the type of corrugation, characteristics of the soil and the degree of soil compaction during construction and operation of pipes.

3. The aim and tasks of the study

The aim of this work is to conduct research and analysis of bearing capacity of corrugated metal structures, which are used in railways tracks.

To achieve the set aim, the following tasks are to be solved:

– to carry out calculation of equivalent forces of railroad rolling stock, at which a metal corrugated pipe is used;

– to conduct multivariate calculations of the stressed-strained state of pipe using the Peterson method, taking into account the following criteria: a degree of compaction of the soil backfill, dimensions of the type of corrugation and equivalent load from the railroad rolling stock;

– to test the condition of occurrence of plastic hinge in the top of a metal corrugated pipe.

4. Materials and methods of research into the influence of rolling stock on the stressed-strained state of MCS under conditions of operating railroad tracks at industrial enterprises

4. 1. Formation of source data to describe the stress-strained state of MCS

Papers [2, 3] indicated that for the optimal design of MCS, it is necessary to consider the effect of thickness of a corrugated metal sheet on the strength and stability of the whole structure. As a result of the conducted research into the strength of MCS of arch type depending on thickness of a metal corrugated sheet, it is established that the thickness of a metal sheet exerts the largest influence on the strained state of a structure and vertical deformations of MCS. As an object of study, we chose a structure of the horizontal ellipse type (Fig. 1).

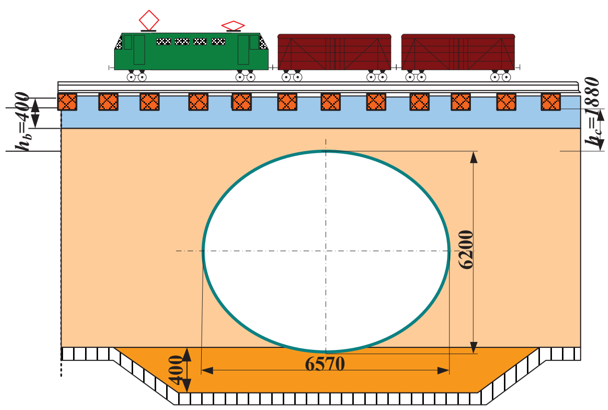

Fig. 1. Calculation scheme for calculating the strength of corrugated metal structures with the cross section of the horizontal ellipse type

The basic parameters that affect the bearing capacity of a structure are: module of deformation of the soil backfill, standard dimension of corrugation, stages of construction. We selected three types of corrugation for the calculation: 150×50×6 mm, 200×55×6 mm, 380×140×6 mm when filling over the top of the metal corrugated pipe 1.88 m at the module of deformation of soil backfill 33 MPa, module of elasticity of steel is $E=2{,}1\cdot 10^5$ MPa; Poisson ratio of structure's material is $\nu=0{,}3$.

The load on MCS was changed as follows: the load of the pipe's own weight, the backfill, layer of gravel and rail-sleeper grid was left unchanged; the indicator of RP (a degree of soil backfill compaction) was accepted equal to 1.0; 0.95; 0.9. Dynamic load on the sleepers from the rolling stock was increased proportionately and the corresponding strains in the points of contour of the pipe's cross section were recalculated. Distribution of loads by the sleepers along the track was received from the calculations of the track by strength [17].

4. 2. Determining normal forces on MCS

The calculations implied that the maximum normal force and moment are calculated. Bearing capacity is tested from the point of view of normal force, as well as of combination of the normal force and the moment by the Peterson technique [15, 16]. Calculations of the stressed-strained state of a metal corrugated structure were conducted using the Peterson method [15, 16].

Normal forces in the walls of the pipe as a result of $p_{traffik}$ are calculated as follows:

at $h_{c.red}/D \le 0.25$;

$$N_t = p_{traffik} + (D/2)q, \tag{1}$$

at $0.25 < h_{c.red}/D \le 0.75$;

$$N_t = (1.25 - h_{c.red}/D)p_{traffik} + (D/2)q, \tag{2}$$

at $0.75 < h_{c.red}/D$;

$$N_t = 0.5p_{traffik} + (D/2)q, \tag{3}$$

where q is the distributed load from the rolling stock, road bed's own weight and the elements of superstructure; D is the diameter of the pipe.

Normal force from the surrounding soil is determined by formula

$$N_j = 0{,}2\frac{H}{D}\rho_1 D^2 + S_{ar}\left(0{,}9\frac{h_{c.red}}{D} - 0{,}5\frac{h_{c.red}}{D}\frac{H}{D}\right)\rho_{cv} D^2, \tag{4}$$

where ρ_1 is the mean specific weight of material of the backfill (to the top of the pipe); ρ_{cv} is the mean specific weight of material of the backfill (above the top of the pipe to height $h_{c.red}$).

Coefficient S_{ar} takes into account the arch effect of distribution of loads in the soil above the culvert pipe, which occurs at a large height of the backfill:

$$S_{ar} = \frac{1 - e^{-k}}{k},$$

$$k = 2S_v\frac{h_c}{D},$$

$$S_v = \frac{0{,}8\tan\varphi_{cv.d}}{\left(\sqrt{1+\tan^2\varphi_{cv.d}} + 0{,}45\tan\varphi_{cv.d}\right)^2}, \tag{5}$$

where $\varphi_{cv.d}$ is the projected angle of internal friction of soil for the metal part of the pipe by formula, based on the parameters of reserve γ_n, γ_m and the natural angle of internal friction of soil.

$$\tan\varphi_{cv.d} = \frac{\tan\varphi_{cv.k}}{\gamma_n\gamma_m}. \tag{6}$$

In formula (6), the value of γ_m is usually equal to 1.3. The angle of internal friction, which is used in the formula, is related to the soil above the top of the pipe.

Projected normal forces under normal operation are determined by formulas:

$$N_{d.s} = (\psi\gamma)_{j.s}\cdot N_j + (\psi\gamma)_{t.s}\cdot N_t; \tag{7}$$

in the maximum possible state:

$$N_{d.u} = (\psi\gamma)_{j.u}\cdot N_j + (\psi\gamma)_{t.u}\cdot N_t; \tag{8}$$

in the state of long-term fatigue loads:

$$N_{d.f} = (\psi\gamma)_{t.f} \cdot N_t, \tag{9}$$

where $\psi\gamma_{j.s}$, $\psi\gamma_{j.u}$, $\psi\gamma_{t.f}$ are the safety coefficients that are chosen in accordance with the standard for the corresponding boundary conditions.

4. 3. Determining the bending moments on MCS

Bending moment in the wall of the pipe depends on the ratio between soil hardness and rigidity of the pipe. This ratio is denoted through λ_f, and is determined by formula:

$$\lambda_f = E_{jd} \cdot D^3 / (EI)_s, \tag{10}$$

where E_{jd} is the shear modulus for soil; EI_s is the bending rigidity of pipe.

Shear modulus for material of the soil depends on the prevailing distribution of stresses in the soil. For the design of culverts with different materials of the soil at height (hc+H/2), mean value of E_{jd} is used in the calculation of λ_f. In the simplified calculations, one needs only the value of degree of compaction. It can be determined using the test methods of soils: a standard Proctor method [16] – RP^{std} or the modified Proctor method – RP^{mod}. The ratio between the results by the standard Proctor method and the modified method for unconnected materials is accepted as follows:

$$RP^{std} = RP^{mod} + 5\ \%. \tag{11}$$

Bending moment in the pipe from the surrounding soil, caused by the load of soil, for the limit of boundary state of the working capacity and in the boundary state is expressed by formula:

$$\frac{M_j}{\rho_1 D^3} = -f_1 f_3 f_{2,surr} + S_{ar} \frac{\rho_{cv}}{\rho_1} \frac{h_c}{D} \left(\frac{R_t}{R_s}\right)^{0.75} f_1 f_{2,cover}. \tag{12}$$

Equation (12) is based on experimental observations: during reverse filling, the compaction occurs around elastic structure of pipe, it is compressed to the middle on the sides and on the top of the pipe there is a negative bending moment. This moment reaches a maximum when the filling level reaches level of the top of the pipe, which is represented by the first term in the right side of the equation (12). When the filling continues, above the level of the top of the pipe, the structure of the pipe is squeezed down and negative moment is reduced. If the height of the backfill is large enough, then at this time the moment at the top of the pipe can change the sign and become positive.

In the case of profile at which $R_t/R_s \geq 1$, the moment in the lateral walls of the pipe is calculated as 2/3 of the moment calculated by formula (12).

Bending moment that arises from the action of rolling stock through the equivalent linear evenly distributed load $p_{traffik}$, is calculated as follows:

$$M_t = f_4^I f_4^{II} f_4^{III} f_4^{IV} D p_{trafic} + S_{ar} \left(\frac{R_t}{R_s}\right)^{0.75} f_1 f_{2,cover} q D^2, \tag{20}$$

where f_1, $f_{2,surr}$, $f_{2,cover}$, f_3, f_4^I, f_4^{II}, f_4^{III}, f_4^{IV}, are the coefficients calculated depending on the geometrical and physical characteristics of the soil backfill and are calculated by the Peterson method [16, 17].

In the case of transversal profile of the pipe, when $R_t/R_s \geq 1$, bending moment in the lateral sides of the pipe is calculated as 1/3 of the moment calculated by formula (12).

Projected bending moments in the pipe from the soil and load from the action of rolling stock have different directions in different points of the cross-section. Therefore, to establish maximum variant of superposition of the loads, it is necessary to perform the check in accordance with the following formula. Projected moments of forces in the state of normal operation are determined according to formula:

$$M_{d.s} = M_{jd.s} + M_{td.s}. \tag{21}$$

Projected moments of forces from the action of rolling stock in the maximum possible condition are determined according to formulas:

$$\begin{cases} M_{td.s}^{max} = (\psi j)_{t.s}^{max} M_t; \\ M_{td.s}^{min} = (\psi j)_{t.s}^{min} (-M_t / 2). \end{cases} \tag{22}$$

In the maximum possible state, projected moments are calculated according to formula:

$$M_{d.u} = M_{jd.s} + M_{td.u}. \tag{23}$$

In the state of long-term fatigue loads, a range of moments is calculated by formula:

$$\Delta M_{d.f} = (\psi\gamma)_{t.f} \cdot M_t \cdot 1.5. \tag{24}$$

Consequently, by the above presented Peterson algorithm we will calculate the stressed-strained condition of a metal corrugated structure of a railroad track.

5. Results of research into the stressed-strained state of MCS

Results of equivalent forces obtained from the locomotive 2M62 are displayed in Fig. 2. Numerical calculations of equivalent forces demonstrated that maximum forces amount to the value of up to 450 kN, at the following parameters of irregularity: length – 5.7 m, height – 44.7 mm and slope – 16.5 %.

A method of estimation of the stressed-strained state of MCS was as follows: by the obtained values of equivalent forces, we calculate maximum stresses in the wall of the pipe, using the Navier equation:

$$\sigma = \frac{N_{d.s}}{A} + \frac{M_{d.s}}{W} < f_{yd}, \tag{25}$$

where $N_{d.s}$, $M_{d.s}$ are the forces and moments of forces under normal operation; A is the cross-sectional area and moment of resistance of the cross section per unit length of pipe; f_{yd} is the boundary fluidity of pipe's steel; W is the moment of resistance per unit length of pipe.

Relative changes in vertical and horizontal diameters of a metal corrugated pipe are determined by formula:

$$\varsigma = \frac{\frac{\gamma(h+R)}{E}}{\frac{\delta}{R} + \frac{E_0}{E}(1-\nu^2)}, \tag{26}$$

where R is the radius of the facility; E_0 is the module of deformation of the soil backfill; E is the modulus of elasticity of steel; δ is the thickness of a metal corrugated pipe; v=0,25 is the Poisson coefficient of material of the facility; γ is the specific weight of material of the facility; h is the height of backfill over the top of a metal corrugated pipe if calculated from the sole of the sleepers (Fig. 1).

Results of calculations of stresses and magnitude of plastic hinge of MCS are represented in Table 1.

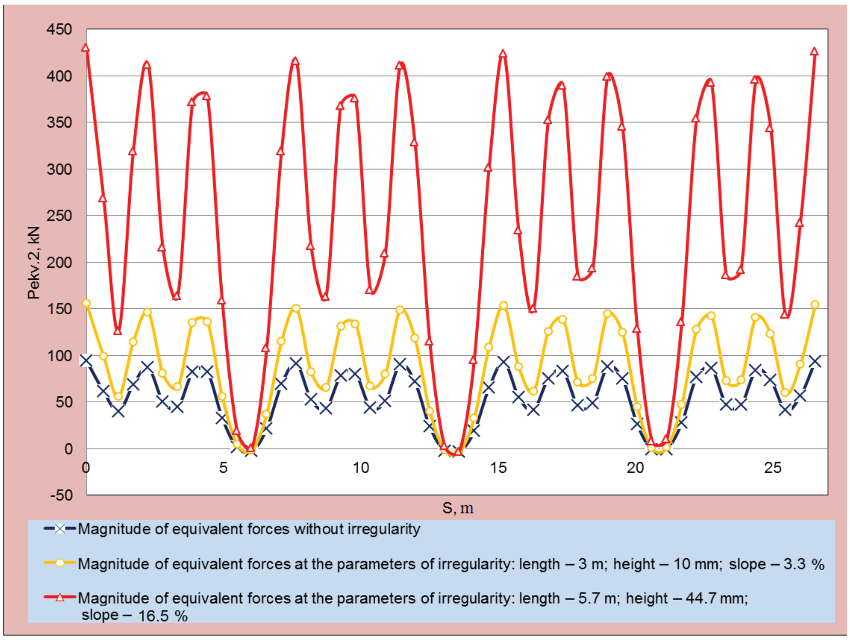

Fig. 2. Magnitude of equivalent forces from the locomotive 2M62 at the value of module of elasticity of the under-rail base of 92.1 MPa

Table 1

Results of calculation of normal stresses and relative deformations of MCS

No. of entry	Examined parameters		Degree of compaction	Dimensions of corrugation type 150×50×6	200×55×6	380×140×6
1	Stresses, MPa		0,9	235,815	256,756	232,592
			0,95	175,196	191,722	200,526
			1,0	117,744	130,048	169,709
2	Longitudinal forces, kN/m	At the MCS top, kN/m	0,9	138,483	138,541	141,618
			0,95	146,497	146,551	149,427
			1,0	154,595	154,644	157,269
		On the sides of MCS, kN/m	0,9	71,268	71,268	71,268
			0,95	75,227	75,227	75,227
			1,0	79,186	79,186	79,186
3	Bending moments, kNm/m	At the MCS top, kNm/m	0,9	4,405	4,407	8,384
			0,95	4,662	4,662	7,291
			1,0	4,918	4,919	5,868
		On the sides of MCS, kNm/m	0,9	–8,273	–8,273	–14,605
			0,95	–8,732	–8,732	–12,876
			1,0	–9,192	–9,192	–10,605
4	Magnitude of plastic hinge		0,9	1,045	1,141	1,074
			0,95	0,742	0,827	0.892
			1,0	0,463	0,534	0,716

Results of the stresses we obtained demonstrated (Table 1) that the strength of the MCS elements, which is made from the corrugated structure Multiplate MR150 with thickness of corrugated sheet 6 mm with dimensions of the corrugation waves at 150×50 mm and 380×140 mm, is provided at the degrees of compaction of the soil backfill from 0.9 to 1.0. However, in a metal corrugated structure that is made from corrugated sheets of size 200×55 mm, at the degree of compaction of the soil backfill of 0.9, there occur stresses that exceed the permissible, which leads to plastic hinge formation, the magnitude of which equals 1.141.

6. Discussion of results of research to form evaluation of condition of strength of the MCS elements under conditions of operation of railroad tracks

We conducted analytical studies of the stressed-strained state, magnitude of plastic hinge, longitudinal forces and bending moments, relative deformations of MCS in the interaction with the backfill soil, taking into account a set of factors – a degree of compaction of the soil backfill material, magnitude of dynamic load from the rolling stock, influence of superstructure design and varying thickness of a metal corrugated pipe. At the projected soil backfill compaction, which is 97 % by the Proctor method, criterion of strength and permissible vertical deformations of MCS are provided. This is due to the fact that the side walls of the metal pipe have sufficient resistance against the horizontal deformations. However, at the soil backfill compaction below 90 %, the test of plastic hinge formation of a metal pipe is not provided.

An analysis of the MCS bearing capacity by the presented methodology makes it possible to assess working efficiency of MCS depending on the standard dimensions of corrugations of pipe and physical and mechanical characteristics of the soil backfill. The use of this technique allows us to determine which geometric, power and speed parameters of the rolling stock may cause a loss of bearing capacity of metal corrugated structures.

Therefore, the results we obtained confirm that in the course of designing MCS, it is necessary to ensure the coefficient of soil backfill compaction not lower than 95 %. Results of the MCS bearing capacity may be applied by engineers at the bridge-testing stations of Ukrainian Railroads and Ukravtodor and by design organizations for the consequent design of corrugated metal structures.

A defined stressed-strained state of MCS provides for the limits of formation of normative document base on reliability of the transportation facilities of railroads with regard to a set of source factors that influence their bearing capacity.

One of shortcomings of the conducted studies is the fact we used a two-dimensional model to explore the MCS bearing capacity. Therefore, further research into the MCS bearing capacity evaluation will be performed by the method of finite elements to form evaluating criteria on reliability and functional safety of the transport constructions of a railroad track.

7. Conclusions

1. Numerical calculations of equivalent forces demonstrated that the maximum forces from the locomotive 2M62 reach values up to 450 kN at the following parameters of irregularity of a railroad track: length – 5.7 m, height – 44.7 mm and slope – 16.5 %.

2. The strength of the MCS elements, which is made from the corrugated structure Multiplate MR150 at thickness of corrugated sheet 6 mm, is provided at the degrees of compaction of the soil backfill from 0.9 to 1.0. In a metal corrugated pipe that is made from corrugated sheets of size 200×55 mm, at the degree of compaction of the soil backfill 0.9, there develop stresses that exceed the permissible. Consequently, with residual stresses accumulation, it may affect the occurrence of fluidity of the MCS material, which in turn may lead to the formation of plastic hinge.

3. An analysis of multi-choice calculations of checking a condition of occurrence of plastic hinge at the top of the pipe connection revealed that the origin of the plastic hinge, which takes place in the MCS connection, happens only under condition of adverse impact of two factors (causes): existence of development of irregularity of the track beyond the permissible values (the first cause) and reduction in the degree of compaction of the backfill soil below 90 % (the second cause). When one cause is absent, the emergence of plastic hinge will not take place.

References

1. Kovalchuk, V. V. The effect of corrugated elements thickness on the deflected mode of corrugated metal structures [Text] / V. V. Kovalchuk // Bulletin of Dnipropetrovsk National University of Railway Transport. – 2015. – Issue 3 (57). – P. 199–207. doi: 10.15802/stp2015/46079
2. Luchko, Y. Y. Study of carrying capacity of a corrugated metal construction by criterion of yield hinge development [Text] / Y. Y. Luchko, V. V. Kovalchuk, O. S. Nabochenko // Bulletin of Dnipropetrovsk National University of Railway Transport. – 2015. – Issue 5 (59). – P. 180–194. doi: 10.15802/stp2015/55340
3. Koval, P. M. Normuvannia pry proektuvanni i budivnytstvi sporud z metalevykh hofrovanykh konstruktsii [Text] / P. M. Koval, I. P. Babiak, T. M. Sitdykova // Visnyk Dnipropetr. nats. un-tu zal. transp. im. ak. V. Lazariana. – 2010. – Issue 39. – P. 114–117.
4. Novodzinskij, A. L. Uchet vlijanija tolshhiny gofrorovannogo jelementa na prochnost' i ustojchivost' metallicheskoj vodopropusknoj truby [Text] / A. L. Novodzinskij, V. I. Kleveko // Vestnik PNIPU. Stroitel'stvo i arhitektura. – 2012. – Issue 1. – P. 81–94.
5. Wysokowski, A. Mostowe konstrukcje gruntowo – powlokowe. Laboratoryjne badania niszczace. Awarie w czasie budowy i eksploatacji [Text] / A. Wysokowski, L. Janusz // XXIII konferencja naukowo-techniczna. – Szczecin, 2007. – P. 541–550.
6. Esmaeili, M. Minimum depth of soil cover above long-span soil-steel railway bridges [Text] / M. Esmaeili, J. A. Zakeri, P. H. Abdulrazagh // International Journal of Advanced Structural Engineering. – 2013. – Vol. 5, Issue 1. – P. 7. doi: 10.1186/2008-6695-5-7
7. Ahad, F. R. Modeling the Dynamic Failure of Railroad tank cars using a physically motivated internal state variable plasticity /damage nonlocal model [Text] / F. R. Ahad, K. Enakoutsa, K. N. Solanki, Y. Tjiptowidjojo, D. J. Bammann // Modelling and Simulation in Engineering. – 2013. – P. 1–11. doi: 10.1155/2013/815158
8. Saat, M. R. Generalized railway tank car safety design optimization for hazardous materials transport: Addressing the trade-off between transportation efficiency and safety [Text] / M. R. Saat, C. P. L. Barkan // Journal of Hazardous Materials. – 2011. – Vol. 189, Issue 1-2. – P. 62–68. doi: 10.1016/j.jhazmat.2011.01.136
9. DBN V.2.3-14: 2006. Sporudy transportu. Mosty ta truby. Pravyla proektuvannia [Text]. – Kyiv, 2006. – 359 p.
10. VBN V.2.3-218-198:2007. Sporudy transportu. Proektuvannia ta budivnytstvo sporud iz metalevykh hofrovanykh konstruktsii na avtomobilnykh dorohakh zahalnoho korystuvannia [Text]: posibnyk. – Kyiv, 2007. – 122 p.
11. Duncan, J. M. Design Procedures for Flexible Metal Culvert Structures. Reports No. UCB/GT/83-02 [Text] / J. M. Duncan, R. H. Drawsky. – Berkeley, 1983.
12. Vaslestad, J. Long-term behaviour of flexible large-span culverts. Publication No. 74 [Text] / J. Vaslestad. – Oslo, 1994. – P. 38–56.
13. Handbook of steel drainage and highway construction products, American Iron and Steel Institute [Text]. – 2-ed ed. – Canada, 2002. – 482 p.
14. AASHTO: Standart Specifications for Highway Bridges. American Association of State Highway and Transportation Officials [Text]. – Washington, D. C., 2001.
15. Waster, M. Verifiering av nyutvecklat dimensioneringsprogram samt vidareutveckling for jernvagstrafik [Text] / M. Waster. – Sweden, 2008. – 143 p.
16. Pettersson, L. Design of soil steel composite bridges [Text] / L. Pettersson, H. Sundquist. – Stockholm, 2007. – 84 p.
17. Danilenko, E. I. Pravyla rozrakhunkiv zaliznychnoi kolii na mitsnist i stiikist. TsP-0117 [Text] / E. I. Danilenko, V. V. Rybkin. – Kyiv: Transport Ukrainy, 2006. – 168 p.