The object of research is a tunnel conduit made of star-shaped metal corrugated structures.

The stresses and magnitude of the plastic hinge occurring in the metal corrugated structures of the tunnel conduit were investigated, taking into account the degree of compaction and the height of the soil backfill.

It was established that when the height of the backfill above the tunnel conduit made of precast metal corrugated structures increases and the degree of compaction of the soil backfill decreases, there is an increase in the values of stresses and plastic hinge in metal structures. With the height of the backfill above the conduit equal to 2.75 m and the degree of compaction of the soil backfill RP=80 %, stresses of 235.89 MPa are reached, exceeding the permissible 235 MPa. At the same time, the value of the plastic hinge is 1.03, which exceeds the normative 1.0.

It was established that at embankment heights above the tunnel conduit structures from 1.75 m to 2.0 m, the smallest difference in stresses and magnitude of the plastic hinge is observed. At RP=98 %, the stress difference is 0.66 MPa, and the value of the plastic hinge is 0.008. In the case of the height of the embankment above the conduit from 1.5 m to 1.75 m, the stress increase was 5.5 MPa, and the value of the plastic hinge – 0.031. When the embankment height increases from 2.0 m to 2.25 m, the stress difference is 7.57 MPa, and the value of the plastic hinge is 0.041.

It was determined that when the height of the embankment above the conduit was increased by 1.0 m in the range from 0.75 m to 1.75 m, the stress difference at RP=98 % increased by 27.84 MPa. However, when the height was increased by 1.0 m in the range from 2.75 m to 3.75 m, the stress difference increased by 12.66 MPa. At the same time, the value of the plastic hinge at embankment heights from 0.75 m to 1.75 m increased by 0.139, and at embankment heights from 2.75 m to 3.75 m – by 0.093

Keywords: precast metal corrugated structures, tunnel conduit, stress of metal structures, plastic hinge

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ASSESSING THE STRESSES AND MAGNITUDE OF PLASTIC HINGE IN A TUNNEL CONDUIT MADE OF PRECAST METAL CORRUGATED STRUCTURES TAKING INTO ACCOUNT THE SOIL BACKFILL PARAMETERS

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1. Introduction

Transport structures made of precast metal corrugated structures (PMCS) are an alternative to traditional reinforced concrete structures. They are a system of "soil sealing backfill-metal structures". They are used in the construction of small artificial structures in the road, railroad [1], and other industries.

The load-bearing capacity of facilities made of precast metal corrugated structures is ensured by the normative degree of compaction of the soil sealing backfill around the metal sheets. In the case of an insufficient degree of compaction of the soil fill, the load-bearing capacity of the structures may be compromised.

The strength and spatial rigidity of the shell made of precast elements is generally ensured by the interaction of the metal structure with the compacted soil, in the thickness of which the structure is located. Under the same loads, metal structures are less susceptible to plastic deformations, which are often critical for reinforced concrete structures. The vertical load acting on the structure is transmitted through the side surfaces to the soil located around the PMCS. If the physical and mechanical characteristics of the soil do not allow the load to be adequately elastically perceived, this can lead to a violation of the geometry of PMCS, a partial loss of stability and rigidity of the structure.

From the practice of construction of transport structures made of PMCS, it was established that during the initial period of operation of such structures there were cases of development of residual deformations of the vertical and horizontal diameters of the pipe [2]. This leads to an increase in the values of the plastic hinge and stresses, which may exceed the permissible limit. There are also cases of complete destruction of metal corrugated structures of facilities. In addition, work [3] states that the construction of structures from precast metal corrugated structures in some cases requires an assessment of the degree of risk. This is primarily related to the peculiarities of the construction and operation of facilities with PMCS.

One of the key factors affecting the load-bearing capacity of structures made of PMCS is the degree of compaction and the height of the soil fill above the vault of metal structures. Therefore, studies aimed at establishing the optimal height of the backfill above the vault of metal corrugated structures and the degree of compaction of the soil backfill around the metal structures of the conduit are of practical importance. Thus, evaluating the influence of the degree of compaction of the soil fill and the height of the embankment above the structure with PMCS on the stressed-strained state of such structures is an urgent task of scientific research.

2. Literature review and problem statement

In [4, 5], it was established that facilities made of PMCS could withstand 2.5 times overload. At the same time, the maximum experimental stress values do not exceed 16 % of the yield strength of the steel of the metal structure [6]. However, the cited works did not take into account the degree of compaction of the soil backfill on the stressed-deformed state of the structure made of PMCS.

Work [7] reports the results of dynamic tests of structures made of metal corrugated structures. During the testing of structures with PMCS under the railroad track, it was established that the maximum value of the measured deflection was 0.65 mm, and the maximum accelerations were 1.31 m/s^2. In the case of testing facilities made of PMCS for seismic loads [8], the maximum stresses were 92.3 % of the yield strength of the steel structures of the facility.

The results of studies of the PMCS pipe, which are given in [9, 10], showed that the bearing capacity of the pipe depends on the degree of compaction of the soil backfill. With an insufficient degree of compaction, the load-bearing capacity of facilities decreases. However, the cited works did not investigate the influence of the backfill height on the stressed-strained state of structures.

Work [11] reports the results of studies of the deformed state of structures made of metal corrugated structures of the Multiplate mp 150 type with the dimensions of the corrugated waves of 150*50 mm. However, the cited work does not take into account the complex influence of the degree of compaction and the height of soil filling above the vaults of facilities on the stressed-deformed state of metal corrugated structures.

Study [12] gives the results of the evaluation of the thermally stressed state of metal corrugated structures under the influence of variable climatic temperature changes in the environment. However, the cited work did not take into account the influence of the degree of compaction and the size of the backfill above the structure on the stress state of the structure made of PMCS.

In [13], the results of movements of metal structures depending on the speed of movement of rolling stock are given. It was established that at a rolling stock speed of up to 40 km/h, the difference in the values of the obtained displacements of the shell is up to 4.0 %.

There are also known works on the assessment of the stressed-strained state of transport structures made of metal corrugated structures using the finite element method. Numerical and experimental results of stresses and deformations of structures made of metal corrugated structures were reported in [14]. However, the cited work did not evaluate the influence of the degree of compaction and the height of the embankment above the vault of the structures on the level of stresses and the size of the plastic hinge that develop in metal structures.

In [15, 16], an assessment of the stressed-strained state of arched structures made of metal corrugated structures was carried out. As a result, it was established that the stressed-strained state of such structures depends on the fixing of the arch and the size of the arch span. However, the cited works did not evaluate the stresses and magnitude of the plastic hinge in the arch structures, depending on the physical and mechanical properties of the soil backfill.

In [17], the authors evaluated the stresses and magnitude of the plastic hinge that occur in the metal of the conduit structures, taking into account only the scheme of placing loads above the conduit with constant values of the height of the backfill above the conduit (h) and the degree of compaction (R); their values were taken by the authors to be equal, respectively, to 2.0 m and 97 %. However, the cited work did not evaluate the two-factor influence – the size of the backfill above the structure and the degree of compaction of the soil backfill on the stress and plastic hinge.

Based on the review of studies [4–17], it was established that most works report the results of the assessment of the stressed-strained state of facilities made of metal corrugated structures, which are subjected to the action of variable loads from vehicles. The tasks of assessing the stressed-strained state of structures made of PMCS, taking into account a set of factors, namely the degree of compaction of the soil fill and the height of the embankment above the vault of the structure, remained unsolved. In addition, there were no studies conducted on the strength of the simultaneous influence of the height of the backfill and the degree of compaction on the magnitude of the stresses and the magnitude of the coefficient of the plastic hinge. This could provide a practical opportunity to determine the optimal height of soil filling above the structure, depending on the degree of soil compaction around the metal structures of the conduit, which is very important when designing structures made from PMCS.

3. The aim and objectives of the study

The purpose of our work is to determine the regularities of stress distribution and the plastic hinge of a tunnel conduit made of precast metal corrugated structures when interacting with the soil compacting backfill. This will make it possible to establish the strength characteristics and predict the bearing capacity of the conduit, taking into account the degree of compaction and the height of the soil fill.

To achieve the specified goal, the following tasks must be performed:

– to carry out assessments of the stressed state of the conduit made of precast metal corrugated structures, taking into account the variable two-factor influence: the degree of compaction of the soil fill and the height of the embankment above the conduit;

– to evaluate the size of the plastic hinge in the vault of metal structures, taking into account the variable two-factor influence: the degree of compaction of the soil fill and the height of the embankment above the conduit.

4. The study materials and methods

4. 1. The object of the study

The object of our research is a tunnel conduit made of precast metal corrugated structures.

The hypothesis of the research assumes that the stress and the size of the plastic hinge, which occur in the metal corrugated structures of the conduit, are most dependent on the physical and mechanical parameters of the soil backfill and the size of the backfill above the vault of the metal structures of the conduit.

It is assumed that with an increase in the degree of compaction of the soil backfill, the value of the modulus of elasticity of the soil changes linearly. In the calculation model, the static load acting from motor vehicles on the structure of the conduit is specified, without taking into account the values of variable loads from vehicles.

4. 2. Procedure for estimating stresses and size of plastic hinge in metal conduit structures

To calculate the stressed-strained state of the conduit made of precast metal corrugated structures, it is necessary to calculate the normal forces and bending moment occurring in the conduit structures. These forces arise in the metal structures of the conduit from the action of the surrounding soil of the embankment (q_{st}) and loads from vehicles (p_{tr}). In addition, the magnitude of these forces depends on the cross section of the conduit with diameter D. The magnitude of the normal force from the action of the surrounding soil around the metal structures of the conduit and the action of loads from transport is determined by the formula:

$$N=\frac{(q_{st}+p_{tr})D}{2}. \tag{1}$$

The bending moment that occurs at the top of the metal corrugated structure of the conduit is determined by the formula:

$$M_j=D^3 S_{ar}\frac{(\rho_s h_s+\rho_b h_b)}{D}\left(\frac{R_t}{R_s}\right)^{0.75} f_{cover}, \tag{2}$$

where R_s is the lateral radius of the cross-section of the structure; R_t is the vertical radius of the cross-section of the structure in the vault; h_b – the height of the road surface above the conduit; h_s is the height of the soil fill above the top of the conduit metal structure; ρ_b, ρ_s are the density of the road surface and backfill, respectively. f_{cover} is a coefficient used to determine the bending moment in the vault of a structure made of PMCS; the S_{ar} coefficient takes into account the arching effect of the distribution of soil fill loads on the metal structure.

The bending moment that occurs on the sides of the metal corrugated structure of the conduit is determined by the formula:

$$M_j=-f_{surr}\rho_{cv}D^3, \tag{3}$$

where ρ_{cv} is the average density of soil filling above the top of the structure; f_{surr}, f_{cover} are functions used to determine the bending moment on the sides of structures and on the top [18, 19] to be determined, respectively, by the formulas:

$$f_{surr}=0.0046-0.0010\cdot\log_{10}(\lambda_f), \tag{4}$$

$$f_{cover}=0.018-0.004\cdot\log_{10}(\lambda_f). \tag{5}$$

It can be seen from formulas (4), (5) that the bending moment in the wall of the structure depends on the ratio of the stiffness of the backfill soil and the stiffness of the metal corrugated structure λ_f:

$$\lambda_f=E_{sd}\cdot D^3/(EI)_s, \tag{6}$$

where E_{sd} is the soil deformation modulus of the backfill, which depends on the degree of soil compaction; $(EI)_s$ is the bending stiffness of the structure, which depends on the geometrical and physical-mechanical parameters of corrugated structures.

It should be noted that transport structures made of PMCS work as a “soil fill-structure” system, and at the same time the load-bearing capacity depends on the deformation modulus of the soil fill. Therefore, in this work, the design value of the deformation modulus of soil fill is determined by the formula recommended in [17–19]:

$$E_{s.d}=\frac{1}{\gamma_n\gamma_m}0.42\cdot m\cdot 100\,\text{kPa}\times$$
$$\times k_v\left(\frac{(1-\sin\varphi_k)\cdot\rho\cdot S_{ar}(h_s+H/2)}{100}\right)^{1-\beta}, \tag{7}$$

where γ_n, γ_m are coefficients taking into account the safety class of the structure; m is the modular ratio determined according to [17]; h_s is the height of backfill above the surface of metal structures; RP is the relative degree of compaction of soil fill; k_v is a calculated parameter determined depending on the angle of internal friction of the soil fill φ_k, H is the vertical distance from the top of the structure to its largest horizontal dimension; 100 is the transfer coefficient, kPa.

The formulas for determining the unknown parameters k_v, S_{ar}, φ_k, which are included in formulas (2), (7), are determined according to procedures from [18, 19].

Based on the values of axial forces and bending moments, the maximum stresses occurring in the wall of a metal corrugated structure are calculated according to the Navier equation [18, 19]. At the same time, the calculation is carried out taking into account the coefficient of safe operation of the conduit (ξ):

$$\sigma=\frac{N}{A}+\frac{\xi M}{W}<f_{yd}, \tag{8}$$

where N, M are axial forces and moments of forces in the state of normal operation of the structure; A, W – cross-sectional area and cross-sectional resistance moment per unit length of the structure; f_{yd} is the yield strength of the steel of the metal corrugated structure.

The check of the development of the plastic hinge is carried out on the maximally loaded section of the structure according to the following formula [19]:

$$\left(\frac{N_{d.u}}{\omega f_{yd} A}\right)+\left(\frac{M_{d.u}}{M_u}\right)\leq 1.0, \quad (9)$$

where $N_{d.u}$ is the normal force; $M_{d.u}$ is the moment of forces; M_u is the permissible value of the bending moment per unit length of the structure, at which the yield stress is reached; ω is the bending force at full plasticity of the metal corrugated structure, which is calculated according to the following formula:

$$\omega=\frac{N_{cr}}{A f_{yd}}, \quad (10)$$

where N_{cr} is the critical load calculated by the following formula [20]:

$$N_{cr.}=\frac{3\xi}{\mu}\sqrt{\frac{E_{sd}(EI)_s}{R_t}}, \quad (11)$$

where μ is the parameter taking into account insufficient lateral resistance of the soil, calculated from the condition of reducing the soil shear modulus:

$$\frac{E_{j.red}}{E_j}=\eta_j=1-\left(\frac{1}{1+\kappa}\right)^2, \quad (12)$$

$$\mu=\left(1.22+1.95\left(\frac{(EI)_s}{\eta_j E_{jd} R_t^3}\right)^{0.25}\right)\frac{1}{\sqrt{\eta_j}}. \quad (13)$$

In the case $R_t = D/2$, this dependence is as follows:

$$\mu=\left(1.22+1.95\left(\frac{8}{\eta_j \lambda_f}\right)^{0.25}\right)\frac{1}{\sqrt{\eta_j}}. \quad (14)$$

Parameters ξ and κ are calculated by the formulas:

$$\xi=\sqrt{\kappa}\leq 1.0, \quad (15)$$

$$\kappa=h_s/R_t. \quad (16)$$

The permissible value of the bending moment of forces for the operation of the structure in the limiting state is determined by the following formula [19]:

$$M_u = Z f_{yd}, \quad (17)$$

where Z is the plastic moment of resistance per unit length of the metal corrugated structure, which is determined according to the Peterson procedure [18, 19].

It should be noted that when calculating a plastic hinge, the values of normal forces and bending moment are determined in the maximum possible state of operation of the structures.

The algorithm for calculating stresses and the size of the plastic hinge in the metal structures of the conduit is reduced to the calculation of stresses according to formula (8) and the determination of the size of the plastic hinge according to formula (9).

4. 3. Geometric parameters and materials of the investigated tunnel-type conduit from precast metal corrugated structures

In order to assess the stressed-strained state of precast metal corrugated structures of the tunnel conduit, the conduit in the form of a horizontal ellipse was adopted. The width of the tunnel conduit is 9.36 m, and the height is 7.12 m. The size of the corrugation of the metal structures is as follows: the height of the corrugation wave is 50 mm, the distance between the crests of the corrugation waves is 150 mm, and the thickness of the corrugation sheet is 6 mm. The strength limit of corrugated sheet steel is 235 MPa. The geometric parameters of the conduit are shown in Fig. 1.

Further, based on the geometric model of the tunnel conduit, schemes for loading the conduit with cars were built.

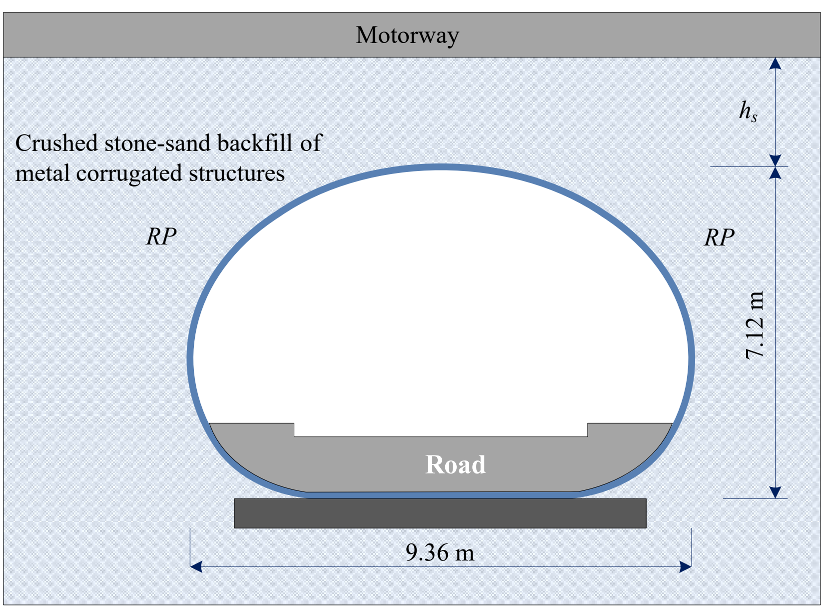

Fig. 1. Geometrical parameters of the studied tunnel conduit made of precast metal corrugated structures: *RP* – degree of compaction of soil backfill; h_s – the height of the embankment above the metal structures of the conduit

4. 4. Scheme of loading the conduit of tunnel type by motor vehicles

To determine the stresses and magnitude of the plastic hinge that occur in the metal corrugated structures of a tunnel conduit, the conduit loading scheme is adopted, shown in Fig. 2. Loading of the conduit was carried out by two cars located on two traffic lanes.

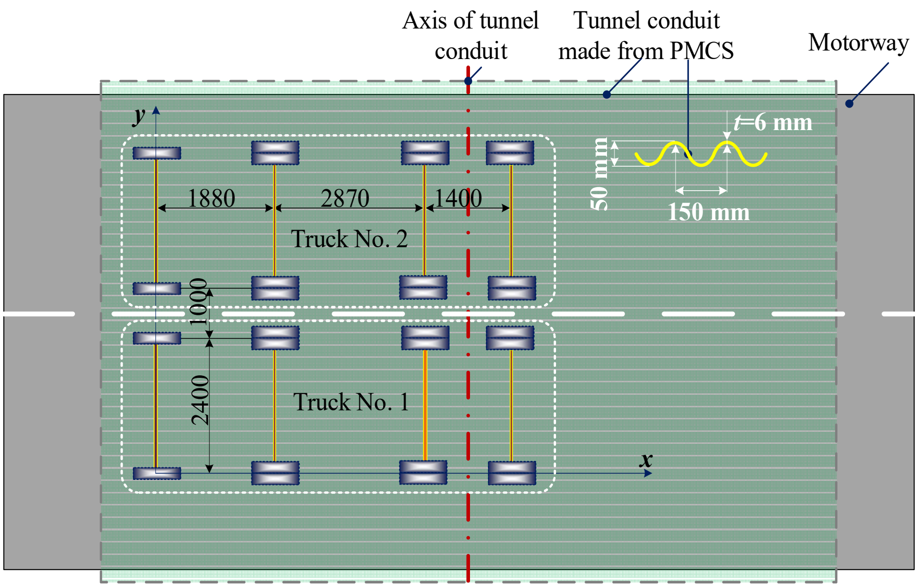

Fig. 2. Diagram of loading tunnel conduit with dump trucks

Conduit loading was carried out by IVECO trucks weighing 38 tons. To estimate the equivalent vertical load acting on the top of the conduit structures from dump trucks, the Boussinesq procedure given in works [21–23] was used.

4. 5. Program for the estimation of stresses and size of plastic hinge

In order to study the influence of the degree of compaction of the backfill (*RP*) and the height of the embankment above the conduit vault (h_s), multivariate calculations of stresses and the magnitude of the plastic hinge were carried out. The program of experimental research provided for the determination of the stresses and magnitude of the plastic hinge at embankment heights above the conduit structures from 0.75 m to 3.25 m in steps of 0.25 m. At each height of the embankment, the stresses and magnitude of the plastic hinge are calculated at variable values of the degree of soil compaction backfills from *RP*=98 % to *RP*=80 %. The backfill material around metal corrugated structures is a crushed stone-sand mixture of fractions to 40 mm.

5. Results of determination of regularities of stress distribution and plastic hinge of tunnel conduit made of metal corrugated structures

5. 1. Stress evaluation of corrugated metal structures of the conduit

The results of the assessment of the stresses that occur in the metal corrugated structures of the tunnel conduit depending on the degree of compaction of the soil fill and the height of the embankment above the structure are given in Table 1 and in Fig. 3. The results of stress calculation are determined by formula (8). At the same time, it should be noted that the magnitude of the stresses is influenced by axial forces and moments of forces, the value of which depends on the geometric parameters of the conduit and the geometric and physical-mechanical parameters of the soil compacting backfill since such structures work together as a "structure-soil backfill" system.

The calculation results showed that with an increase in the height of the backfill h_s above the conduit, the magnitude of the stresses increases. In addition, the degree of compaction of the backfill affects the increase in the amount of stress that occurs in the metal structures of the conduit. From the research results (Table 1), it can be seen that with a height of backfill above the conduit of 2.75 m and a degree of compaction of the soil backfill equal to 80 %, the stresses amount to 235.89 MPa, which exceed the allowable stresses of 235 MPa. In fact, the maximum allowable stresses occur in the case of the influence of two simultaneous factors, the insufficient value of the degree of compaction and the influence of the height of the backfill above the vault of the conduit made of PMCS.

At backfill heights above the conduit of 1.75 m and 2.0 m, approximately the same stress values are observed, which occur in metal structures depending on the degree of compaction of the backfill. In addition, it is observed that the magnitude of stresses at a backfill height of 2.0 m is smaller than at a height of 1.75 m. However, this difference in stresses is not large.

Table 1

Stress calculation results

Backfill height, h, m	Accepted degree of compaction of soil backfill, *RP* %									
	98	96	94	92	90	88	86	84	82	80
	The calculated values of stresses arising in metal corrugated structures of the conduit, MPa									
0.75	54.24	60.87	67.03	72.61	77.47	81.53	84.65	86.76	87.73	87.45
1.0	64.06	73.0	81.78	90.26	98.35	105.96	112.99	119.37	125.01	129.8
1.25	71.01	81.36	91.73	102.01	112.12	121.97	131.48	140.59	149.21	157.29
1.5	76.58	87.86	99.31	110.82	122.3	133.68	144.89	155.87	166.56	176.9
1.75	82.08	94.23	106.65	119.25	131.93	144.62	157.27	169.82	182.21	194.4
2.0	82.74	94.42	106.43	118.67	131.07	143.56	156.11	168.66	181.16	193.59
2.25	89.65	102.54	115.84	129.46	143.31	157.35	171.5	185.74	200.02	214.31
2.5	92.64	105.66	119.13	132.97	147.09	161.46	176.00	190.69	205.49	220.37
2.75	97.88	111.81	126.26	141.14	156.36	171.88	187.64	203.58	219.66	**235.89**
3.0	100.12	114.14	128.72	143.75	159.17	174.93	190.97	207.27	223.78	**240.5**
3.25	102.31	116.41	131.09	146.26	161.85	177.81	194.01	210.66	227.5	**244.58**

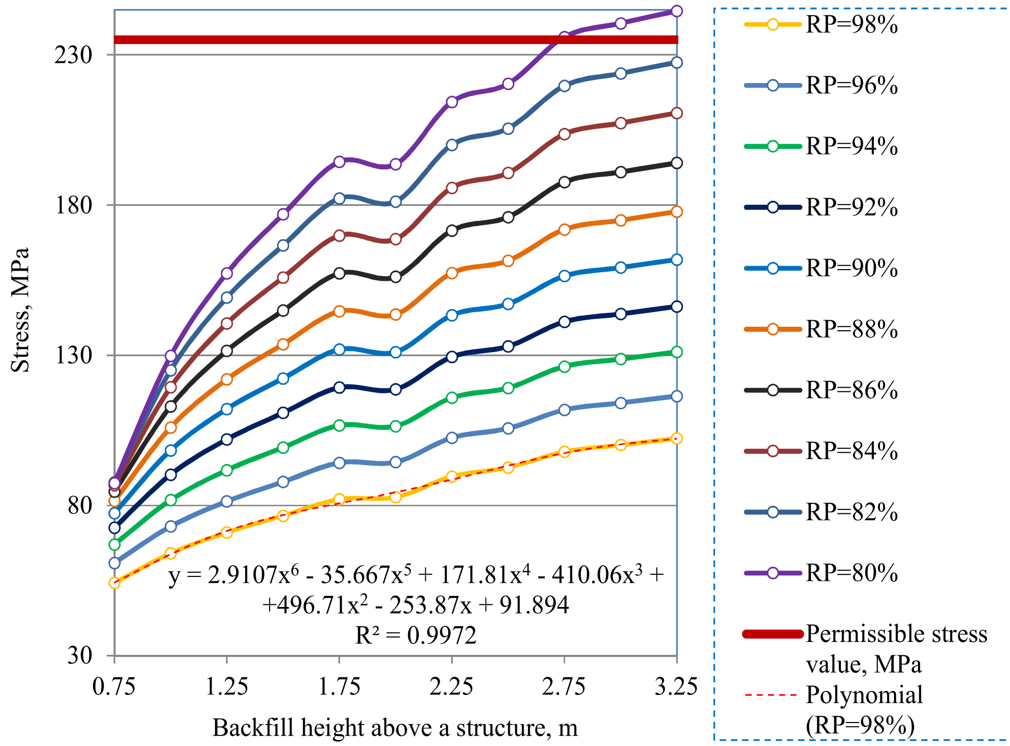

Fig. 3. Graphic dependence of stresses on the height of backfill and the degree of compaction of the soil backfill

The dependence of stresses on the degree of compaction of the soil backfill and the height of the backfill above the vaulting of the metal corrugated structures of the conduit at the normative degree of compaction of the soil backfill R=98 % is described by a polynomial of the 4th power with the approximation probability R^2=0.9972.

When the height of the soil embankment above the conduit was changed by 1.0 m from 0.75 m to 1.75 m, the amount of stress at a degree of compaction of the soil fill of 98 % increased by 27.84 MPa. However, when the height was increased by 1.0 m in the range from 2.75 m to 3.75 m, the stress value increased by 12.66 MPa.

The graphical dependence of stresses depending on the degree of compaction of the soil fill and the height of the embankment above the conduit from 1.5 m to 2.25 m is shown in Fig. 4.

Fig. 3 shows that at embankment heights above the conduit from 1.5 m to 2.25 m, there is a slight increase in stresses depending on the embankment height. When the height changed from 1.5 m to 1.75 m, the increase in stresses at the normative degree of soil backfill compaction of 98 % amounted to 5.5 MPa. However, when the height changed from 1.75 m to 2.0 m, the stress difference was only 0.66 MPa. When the height increases from 2.0 m to 2.25 m, the stress difference is 7.57 MPa.

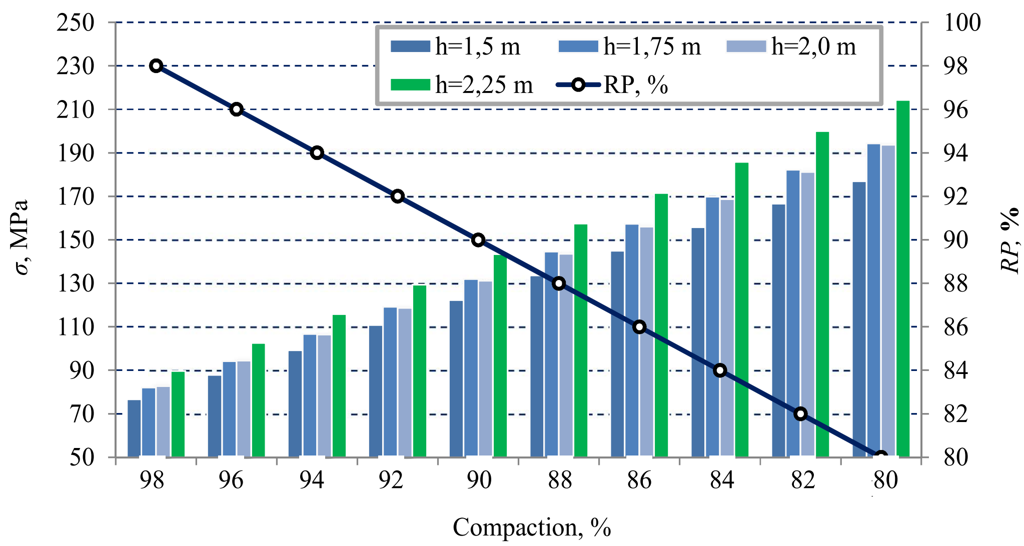

Fig. 4. The dependence of stresses on the degree of compaction of the soil backfill and the amount of backfill above the conduit at: h_s=1.5 m, h=1.75 m, h=2.0 m, h=2.25 m

It should be noted that the feature of the stress distribution depending on the degree of compaction of the soil fill is approximately the same at embankment heights above the conduit from 0.75 m to 1.5 m and at heights from 2.25 m to 3.25 m.

5. 2. Estimation of the size of plastic hinge in metal corrugated conduit structures

The results of calculating the size of the plastic hinge, which arises depending on the degree of compaction of the soil fill and the height of the embankment above the metal structures of the conduit, are given in Table 2 and in Fig. 5. Results of calculating the values of the plastic hinge according to formula (8).

The results of calculating the size of the plastic hinge that occurs in the vault of metal structures showed that their size depends on the height of the embankment above the vault of the conduit made of PMCS and the degree of compaction of the soil backfill. Decreasing the degree of soil backfill compaction and increasing the height of the embankment above the conduit leads to an increase in the size of the plastic hinge. The limit-permissible value of the plastic hinge is observed when the degree of compaction of the soil backfill is equal to 80 % and the height of the embankment above the structure is 2.25. Under the simultaneous influence of these two factors, the value of the plastic hinge exceeds the permissible value of 1.0.

The dependence of the size of the plastic hinge on the degree of compaction of the soil backfill and the height of the backfill above the vaulting of the metal corrugated structures of the conduit at the normative degree of compaction of the soil backfill R=98 % is described by a polynomial of the 6th power with the approximation probability R^2=0.9979.

At embankment heights above the structure of 1.75 m and 2.0 m, the smallest difference in the sizes of the plastic hinge is observed. With a degree of compaction of the soil backfill equal to 98 %, the difference in the size of the plastic hinge is 0.008. However, this difference is higher when the embankment height changes from 0.75 m to 1.25 m and from 2.25 m to 3.25 m.

When the height of the embankment changed from 0.75 m to 1.75 m, the value of the plastic hinge at a degree of compaction of the soil fill of 98 % increased by 0.139. However, in the range from 2.75 m to 3.75 m, the size of the plastic hinge increased by only 0.093.

The graphic dependence of the size of the plastic hinge depending on the degree of compaction of the soil fill and the height of the embankment from 1.5 m to 2.25 m is shown in Fig. 6.

Table 2

The results of calculating the size of the plastic hinge

Backfill height, h, m	Accepted degree of compaction of soil backfill, *RP* %									
	98	96	94	92	90	88	86	84	82	80
	The calculated values of the plastic hinge arising in the metal corrugated structures of the conduit									
0.75	0.161	0.196	0.229	0.26	0.289	0.314	0.336	0.354	0.368	0.378
1.0	0.205	0.251	0.297	0.341	0.385	0.428	0.469	0.508	0.545	0.58
1.25	0.239	0.292	0.345	0.399	0.453	0.506	0.56	0.612	0.665	0.717
1.5	0.269	0.326	0.385	0.445	0.505	0.567	0.629	0.691	0.755	0.819
1.75	0.3	0.362	0.425	0.49	0.557	0.625	0.695	0.766	0.838	0.913
2.0	0.308	0.367	0.429	0.493	0.559	0.626	0.696	0.768	0.841	0.918
2.25	0.349	0.414	0.483	0.553	0.626	0.702	0.78	0.86	0.943	**1.03**
2.5	0.371	0.437	0.506	0.578	0.653	0.73	0.811	0.894	0.98	**1.07**
2.75	0.406	0.476	0.55	0.628	0.708	0.792	0.878	0.968	1.06	1.159
3.0	0.424	0.495	0.57	0.648	0.73	0.815	0.903	0.995	**1.091**	**1.192**
3.25	0.442	0.514	0.589	0.668	0.751	0.837	0.927	**1.021**	**1.119**	**1.221**

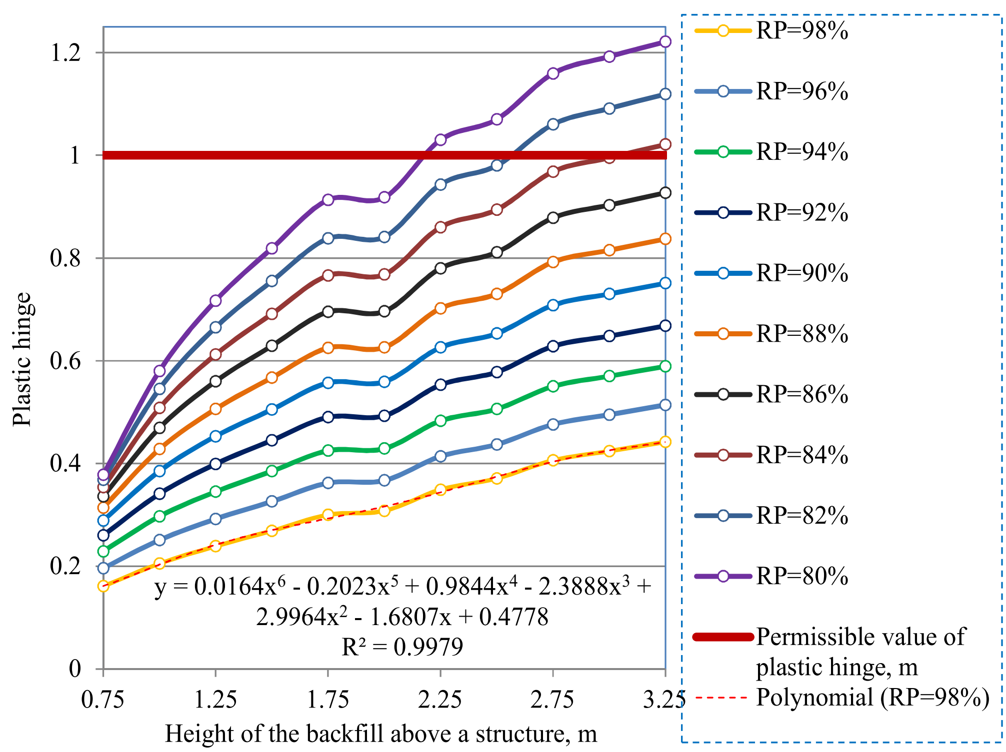

Fig. 5. Graphical dependence of the size of the plastic hinge on the height of the backfill and the degree of compaction of the soil backfill

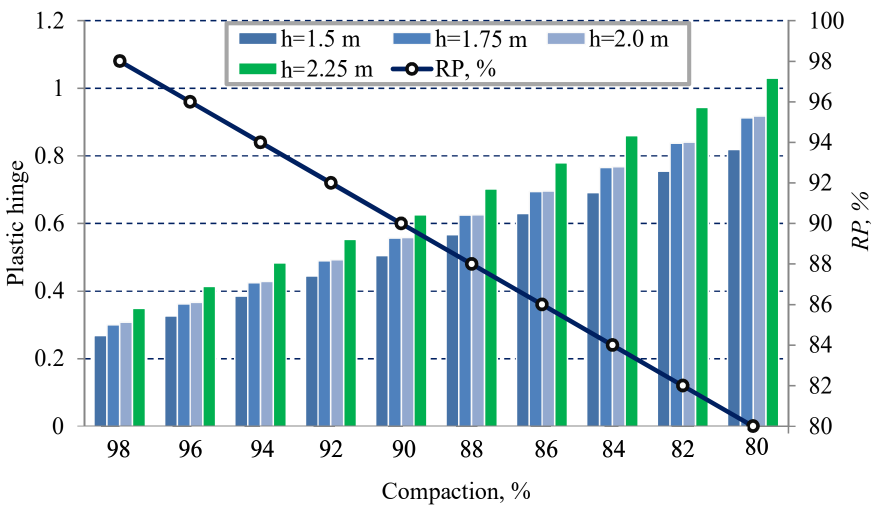

Fig. 6. The dependence of the size of the plastic hinge on the degree of compaction of the soil backfill and the size of the backfill above the structure at: h=1.5 m, h=1.75 m, h=2.0 m, h=2.25 m

When the height of the backfill above the structure is from 1.5 m to 2.25 m, a small increase in the size of the plastic hinge is observed, depending on the height of the backfill. And so, at heights from 1.5 m to 1.75 m, the increase in the value of the plastic hinge at the degree of compaction of the soil backfill was 0.031. However, when the height changed from 1.75 m to 2.0 m, the difference in the size of the plastic hinge was only –0.008. And when the height increases from 2.0 m to 2.25 m, the difference in the size of the plastic hinge is 0.041.

A similar trend of change in the value of the plastic hinge is observed with other degrees of soil backfill compaction from 98 % to 80 %.

Fig. 3, 5 demonstrate that the increase in the height of the backfill above the metal corrugated structures leads to an increase in stresses and the value of the plastic hinge. At the same time, this dependence is non-linear: up to the height of the soil backfill of 1.75 m, the dependence is practically linear, and further from 1.75 m to 2.0 m, a straight section is observed, the stresses are practically the same, and after 2.0 m, a sharp increase in stresses is observed and sizes of the plastic hinge.

It should be noted that the nonlinear pattern is related to the physical and mechanical parameters of the backfill and the features of the distribution of loads in the backfill from the action of vehicles. To explain this, Table 3 gives the results of calculating the deformation modulus of the soil fill depending on the degree of compaction and the height of the fill. Its value is determined by formula (7).

Table 3 demonstrates that the values of the soil fill deformation modulus depend on the degree of compaction R and practically do not depend on the height of the soil fill h. As the compaction of soil fill increases, the value of the soil deformation modulus $E_{s.d}$ increases, and this dependence has a non-linear distribution component. The plot of dependence of the modulus of elasticity of the soil backfill $E_{s.d}$ on the degree of compaction of the backfill R at the height of the backfill h=2.0 m is shown in Fig. 7. It is built based on the results of calculating the modulus of elasticity according to formula (7).

Fig. 7 shows that the dependence of the modulus of elasticity of the backfill on the degree of compaction is described by a polynomial of the 4th power with the approximation probability R^2=1.

Table 3

Results of calculating the soil backfill deformation modulus

Backfill height, h, m	Accepted degree of compaction of soil backfill, RP %									
	98	96	94	92	90	88	86	84	82	80
	Calculated values of the soil backfill deformation modulus, MPa									
0.75	32.08	24.67	19.17	15.04	11.89	9.46	7.57	6.08	4.91	3.98
1.0	32.25	24.8	19.28	15.12	11.95	9.51	7.61	6.12	4.94	3.99
1.25	32.42	24.93	19.38	15.2	12.01	9.56	7.65	6.15	4.96	4.02
1.5	32.57	25.05	19.47	15.27	12.07	9.61	7.68	6.18	4.99	4.04
1.75	32.72	25.17	19.56	15.34	12.13	9.65	7.72	6.21	5.01	4.06
2.0	32.86	25.27	19.64	15.41	12.18	9.69	7.75	6.23	5.03	4.07
2.25	32.99	25.38	19.73	15.47	12.23	9.73	7.78	6.26	5.05	4.09
2.5	33.12	25.48	19.8	15.53	12.28	9.77	7.81	6.28	5.07	4.11
2.75	33.25	25.57	19.88	15.59	12.32	9.8	7.84	6.31	5.09	4.12
3.0	33.37	25.66	19.95	15.64	12.37	9.84	7.87	6.33	5.11	4.14
3.25	33.48	25.75	20.01	15.69	12.41	9.87	7.89	6.35	5.13	4.15

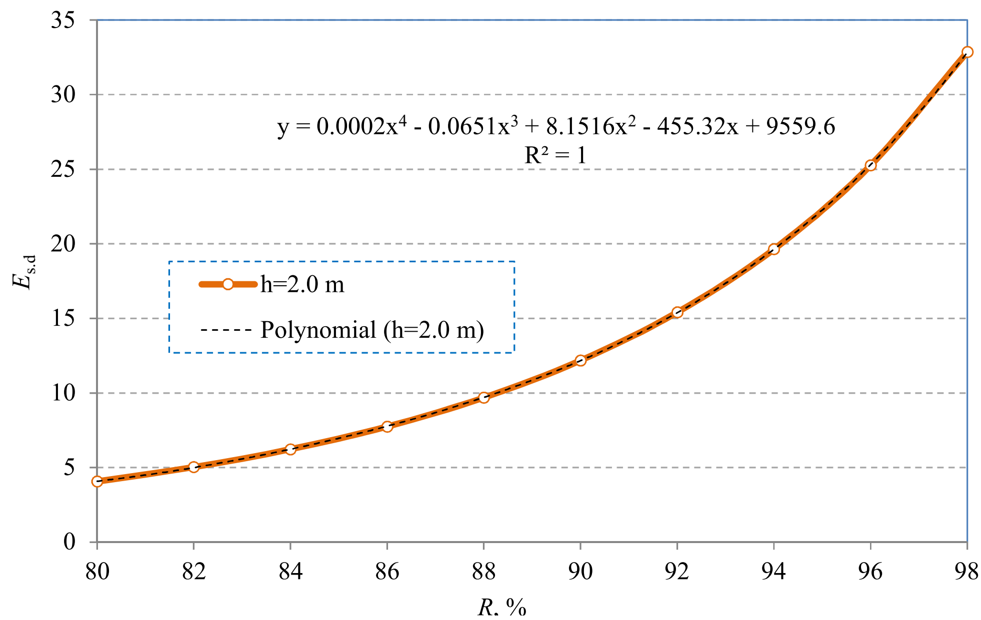

Fig. 7. Dependence of the modulus of elasticity of the soil backfill $E_{s.d}$ on the degree of compaction of the backfill R at h=2.0 m

With an increased degree of soil fill compaction, the value of the deformation modulus increases sharply, at R=80 % the value of $E_{s.d}$ is 4.07 MPa, and at R=98 % the value of $E_{s.d}$ is 32.86 MPa. As a result, such a feature of the change in the physical and mechanical parameters of the backfill depending on the degree of compaction leads to a non-linear distribution of stress values and a plastic hinge, the results of which are shown in Fig. 3, 5.

6. Discussion of results of assessing the stressed-strained state of the reinforced three-layer pipe

The results of the calculation of stresses in the MGC of the conduit showed that with an increase in the height of the backfill above the structure and a decrease in the degree of compaction of the soil backfill, the magnitude of the stresses increases. The maximum allowable stress and coefficient of plastic hinge, which occur in metal corrugated structures of the facility, is observed when the height of the backfill above the facility is equal to 2.75 m and the degree of compaction of the soil backfill is equal to 80 %. At the same time, the estimated stress value of 235.89 MPa exceeds the limit stress of 235 MPa. Also, the value of the plastic hinge coefficient is 1.03 with a permissible value of 1.0. Therefore, stresses exceeding the normative values occur in the case of the influence of two simultaneous factors, an insufficient degree of compaction of the soil backfill and a high backfill above the vault of the structure made of PMCS. This is explained by the fact that the reduction in the compaction of the soil backfill leads to a decrease in the transverse resistance of the soil by horizontal movement. And, taking into account the simultaneous increase in the height of the backfill above the conduit, this leads to an increase in the moment of forces and axial forces, which causes an increase in the values of stresses and plastic hinge.

The results of studying the stresses and magnitude of the plastic hinge established that at embankment heights above the structure of 1.75 m and 2.0 m, there is a minimal difference in stresses and magnitude of the plastic hinge. At a degree of soil backfill compaction of 98 %, the stress difference is 0.66 MPa, and the value of the plastic hinge is 0.008.

When the height of the embankment above the structure was increased by 1.0 m in the range from 0.75 m to 1.75 m, the stress difference at a degree of compaction of the soil backfill equal to 98 % increased by 27.84 MPa. However, when the height was increased by 1.0 m between 2.75 m and 3.75 m, the stress difference increased by 12.66 MPa. At the same time, the value of the plastic hinge at embankment heights from 0.75 m to 1.75 m increased by 0.139, and at embankment heights from 2.75 m to 3.75 m – by 0.093.

Therefore, at lower heights of the embankment, the stress and magnitude of the plastic hinge, which arise in the metal sheets of structures due to the action of vehicles, are higher than at higher embankment heights above the structure. This should be taken into account when designing structures made of precast metal corrugated structures.

Our results make it possible to solve the problem of ensuring the optimal height of the backfill above the vault of metal corrugated structures and the degree of compaction of the soil backfill around the metal structures of the conduit. As a result of the research, the practical aspect was established, which consists in the fact that it is recommended to carry out the backfilling height above the conduit from 1.75 m to 2.0 m. At these heights, the condition of not exceeding the permissible value of stresses and the size of the plastic hinge in the metal of the conduit is met.

In comparison with the available calculation results of structures made of MCS [4–17], our results for the conduit made of MCS take into account a set of factors: the degree of compaction of the soil backfill, the height of the embankment above the conduit vault, and the arrangement of vehicles above the tunnel conduit vault.

It should be noted that in work [17] an assessment of the stresses and magnitude of the plastic hinge occurring in the metal of the conduit constructions was performed, taking into account only the scheme of placement of loads above the conduit. The height of the backfill above the conduit and the degree of compaction are assumed to be constant, 2.0 m and 97 %, respectively. In contrast to [17], in our work a comprehensive assessment of the stresses and magnitude of the plastic hinge was performed, taking into account the two-factor influence, namely, the height of the backfill above the structures and the magnitude of the degree of soil compaction. In addition, work [17] adopted four schemes for loading the structure with automobile loads. The value of stresses obtained in [17] is 71.59 MPa, and in the current work it is 82.74 MPa. The stress difference of 11.15 MPa is explained by the different geometric cross-sections of structures made of PMCS and the different size of the corrugated profile of metal structures.

The dependence of the stresses and the value of the plastic hinge on the height of the backfill above the conduit made from PMCS and the degree of compaction of the soil backfill around the metal corrugated structures of the conduit was established.

One of the limitations of our studies of stresses and magnitudes of the plastic hinge, which occur in metal corrugated constructions of transport facilities, is the consideration of the three-factor influence on their magnitudes. Only the influence of the degree of compaction of soil filling, the height of the embankment above the structure and the load from vehicles are taken into account.

Among the shortcomings of our study into the stressed-deformed state of the tunnel conduit made of prefab metal corrugated structures is the failure to take into account the values of variable loads from vehicles and their different positions above the structure.

Therefore, the further continuation of research work is to study the stressed-strained state of transport structures made of metal corrugated structures, taking into account multifactorial influences, namely: variable loads from vehicles, various schemes for the location of vehicles above the structure.

7. Conclusions

1. The results of the calculation of stresses that arise in metal corrugated structures showed that with an increase in the height of the backfill above the structure, the magnitude of the stresses increases. The degree of compaction of the backfill also affects the increase in the amount of stress that occurs in metal structures. When the height of the backfill above the facility made from PMCS is 2.75 m and the value of RP=80 %, a stress of 235.89 MPa is reached, which exceeds the permissible 235 MPa.

The results of our research showed that with embankment heights above the structure of 1.75 m and 2.0 m and a degree of compaction of the soil backfill of 98 %, a minimal stress difference is observed. It is 0.66 MPa. In comparison, with an increase in the height of the embankment above the structure from 1.5 m to 1.75 m, the increase in stresses was 5.5 MPa, and with an increase in the height of the embankment from 2.0 m to 2.25 m – 7.57 MPa.

When the height of the embankment above the structure was increased by 1.0 m at heights from 0.75 m to 1.75 m, the stress value at *RP*=98 % increased by 27.84 MPa. However, at heights from 2.75 m to 3.75 m, the stress value increased by 12.66 MPa.

2. The results of calculating the size of the plastic hinge that occurs in the vault of metal corrugated structures showed that their size depends on the height of the embankment above the vault of structures made of PMCS and the degree of compaction of the soil backfill. The limit-permissible value of the plastic hinge is observed at *RP*=80 % and the height of the embankment above the structure is 2.25 m. Under the simultaneous influence of these two factors, the value of the plastic hinge exceeds the permissible value of 1.0.

At embankment heights above the structure of 1.75 m and 2.0 m, the smallest difference in the sizes of the plastic hinge is observed. At *RP*=98 %, the difference in the size of the plastic hinge is 0.008. However, this difference is higher at other heights. And so, at heights from 1.5 m to 1.75 m, the increase in the size of the plastic hinge at *RP*=98 % was 0.031, and when the height changed from 2.0 m to 2.25 m, the difference in the size of the plastic hinge was 0.041.

When the embankment height changed from 0.75 m to 1.75 m, the value of the plastic hinge at *RP*=98 % increased by 0.139. However, in the range from 2.75 m to 3.75 m, the size of the plastic hinge increased by 0.093.

Conflicts of interest

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

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Data availability

The manuscript contains data included as additional electronic material.

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