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STUDY OF THE STRESS-STRAIN STATE IN DEFECTIVE RAILWAY REINFORCED-CONCRETE PIPES RESTORED WITH CORRUGATED METAL STRUCTURES

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Розроблено перспективні технології ремонту дефектних залізобетонних труб із використанням металевих гофрованих конструкцій. Наведено методику розрахунку величин сил тиску на вершину залізобетонної труби, яка підсилена металевою гофрованою трубою, при статичних та динамічних навантаженнях у залежності від висоти засипки. За результатами статичних та динамічних сил тиску, методом скінченних елементів розраховується напружено-деформований стан труби при взаємодії із ґрунтом засипки

Ключові слова: залізобетонна труба, металева гофрована конструкція, дефект, статичне і динамічне навантаження, напруження, деформації

Разработаны перспективные технологии ремонта дефектных железобетонных труб с использованием металлических гофрированных конструкций. Приведена методика расчета величин сил давления на вершину железобетонной трубы, усиленной металлической гофрированной трубой, при статических и динамических нагрузках в зависимости от высоты засыпки. По результатам статических и динамических сил давления, методом конечных элементов рассчитывается напряженно-деформированное состояние трубы при взаимодействии с почвой засыпки

Ключевые слова: железобетонная труба, металлическая гофрированная конструкция, дефект, статическая и динамическая нагрузка, напряжение, деформации

1. Introduction

One of the main lines of the state economic policy is improvement of effectiveness of all national economy branches. Solution of this problem in the field of capital construction of transport facilities is associated with a rational use of allocated capital investments. Improvement of effectiveness of capital investments largely depends on validity of the decisions made at the stage of design and repair of objects. This is achieved by introduction of advanced building structures and materials.

In construction of new railways and highways, a large number of reinforced concrete culvert aqueduct pipes (more than 50 % of all transport facilities) are built. Therefore, the choice of economically feasible pipe designs provides an efficient investment and ensures prolongation of pipe service life which in turn will enable the state to save money on their repairs.

The conducted studies were directed on development of promising technologies for repairing defective reinforced-concrete pipes with the use of corrugated metal structures as the state of reinforced-concrete culvert aqueducts (including those constructed according to standard designs) has been markedly deteriorating recently. This is caused by ambient effects, physical wear and ageing of materials and structures, growth of rail and motor transportation volumes, increased axle loads and transport means speed. The defects arising in operation of reinforced-concrete pipes necessitate taking repair measures to these pipes. Thus, according to the State Administration of Railway Transport of Ukraine (Ukrzaliznytsia), of 10.940 culvert aqueduct pipes operated by railways, 259 are defective. According to the Ukrainian Highway Service (Ukravtodor), there are 129.053 culverts in operation of which 37.425 are defective [1]. If only pipes are taken into consideration, there is on the average one (more precisely, 0.8) pipe per each of 169.739 kilometers of the public highway network and 29 % of these pipes require repair activities [2]. Given that repairs were carried out not to the full in the last 5 years, percentage of pipes requiring repair has increased even higher [1].

Since under conditions of economic development of the state it is absolutely necessary to ensure continuity of transport flows, development and introduction of new technologies for repair of existing defective reinforced-concrete pipes is a relevant task. This is feasible on condition that advanced repair technologies are applied.

The available advanced repair technologies and the results of research work will enable engineers to repair defective concrete structures with no resort to stopping railway or automobile traffic. This issue is particularly relevant for the transport routes which connect Ukraine with the European Union countries, so one of the ways to extend service life of defective reinforced-concrete pipes is the use of corrugated metal structures.

2. Literature review and problem statement

The first knowledge on the use of composite culverts incorporating corrugated metal structures in Russian transport construction dates back to 1875 and although their construction ceased since 1914, the studies of their operation continued, which is evidenced by well-known scientific works [3, 4]. It was only at the end of 1970s when production of corrugated metal pipes was restored [5]. Design of such structures came from the use of commercially produced elements of the standard 2.0 m and 3.0 m diameter round pipes from corrugated 2.5 mm thick metal sheets with wave dimensions of 130×32.5 mm [5]. Comparison with similar foreign 1.5–3.0 m ID pipes [6] but with undulation wave measuring 150×50 mm showed that domestic pipes with a minimum wall thicknesses of 2.7–3.0 mm had 1.49–1.75 times smaller moment of resistance [7]. In this regard, a conclusion was made that the use of pipes made from corrugated 2.5 mm thick elements with undulation wave measuring 130×32.5 mm requires additional studies. It is noted in [8] that smaller areas of the wall arch cross section in corrugated metal pipes are simultaneously an indicator of metal consumption efficiency. In comparison with corrugated metal pipes with undulation wave measuring 150×50 mm, they may be 1.14 to 3.0 times smaller which makes these structures more promising transport structures from an economic point of view [9].

A vast experience of the use of corrugated metal structures has been accumulated in the USA [10], Canada, Western Europe [11], and in Japan.

In Ukraine, structures fabricated from corrugated metal sheets were introduced only in the 1990's [1, 2]. The available normative document VNH V.2.3-218-198:2007 [12] concerns only calculation and design of corrugated metal pipes with a clear opening up to 3 m and recommendations ODM 218.2.001-2009 [13] are relevant to the design of pipes with a clear opening up to 6 m. There are no normative data on the design of composite pipes at all. Therefore, this problem is relevant and requires studies concerning operation of corrugated metal structures in interaction with the backfill soil and the existing documents have to be supplemented.

It follows from this analysis that behavior and magnitude of the arch deformation and the filling soil pressure on the arch are insufficiently studied and there is no analysis of bearing capacity of composite pipes (reinforced-concrete pipes strengthened with corrugated metal pipes).

It was also established that along with their positive properties, the structures under consideration possess relatively low reliability and short service life. During their operation, numerous cases of inadmissible growth of deformations are observed, that is, an increase in horizontal and a decrease in vertical pipe dimensions. To exclude inadmissible deformations, improvements in the methods for calculation of corrugated metal structures, which work jointly with the backfill soil, should be implemented. This will make it possible to predict strength and longevity of corrugated metal structures.

3. The aim and objectives of the study

This study objective was to develop advanced technologies for repair of defective culvert aqueduct reinforced-concrete pipes by their shelling with corrugated metal structures to prolong their service life on railways and highways with determining the structure strength using a finite element method.

To achieve this goal, the following tasks had to be solved:

– to develop a technology for restoration of defective reinforced-concrete pipes operated on the railways using corrugated metal structures;

– to calculate vertical and horizontal forces acting on the pipe from the railway rolling stock;

– to estimate the stress-strain state in restored reinforced-concrete pipes by the finite element method.

4. Technology for repair of defective reinforced-concrete pipes using corrugated metal structures

The shelling method was proposed to repair defective reinforced-concrete pipes. Its essence is in the following. A structure of corrugated metal sheet is inserted in the interior of the existing defective reinforced-concrete pipe. Next, the space between the existing pipe and the wall of the inserted structure or a pipe made from a corrugated metal sheet is filled with concrete (Fig. 1). This technology ensures full and effective filling of this space [12–17] for repair of the existing object without stopping traffic and resort to the object disassembly.

As a result of this operation, a multilayered structure is obtained with a difficult to describe calculation model, partially because of a joint work of the elements that differ significantly in their physical and mechanical characteristics.

The technology of repair by the shelling method involves a sequence of operations as shown in Fig. 2. It includes two main stages, namely design and construction. At the design stage, it is necessary to conduct surveying, select diameter of the structure and calculate its lifetime.

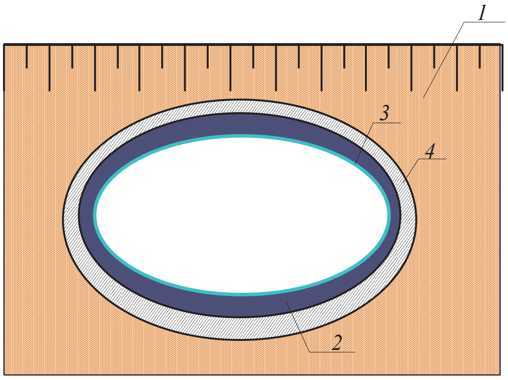

Fig. 1. Schematic view of repair of reinforced-concrete pipes by the shelling method: the railroad embankment (1); the space filled with concrete (2); the corrugated metal structure (3); the defective reinforced-concrete pipe (4)

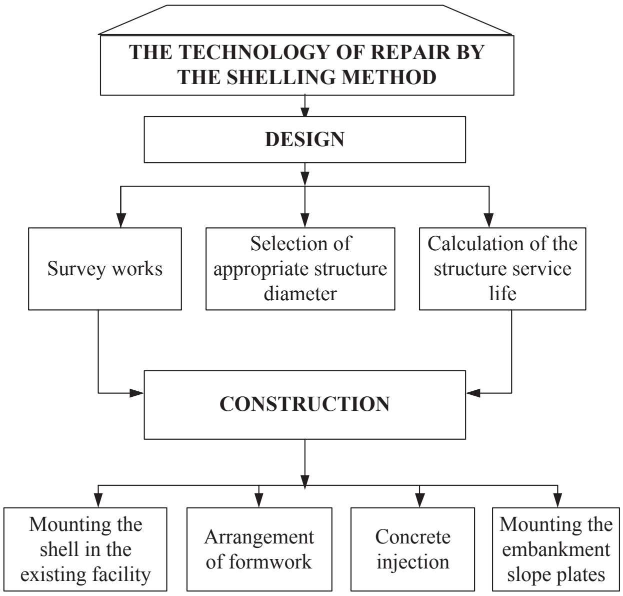

Fig. 2. Stage sequence in repair of defective reinforced-concrete culvert aqueduct pipes by the shelling method

When choosing shape of the structure of corrugated metal, it is necessary to bear in mind two main criteria: the repaired structure shape and the required clear opening of the object after repair. Since the repaired pipe will have a smaller clear opening for water passage, the design stage should provide selection of appropriate materials for the corrugated metal structure with a small roughness factor. In some cases, reduction of the pipe clear opening does not necessarily result in a constraint of the hydraulic properties of the strengthened structure. This follows from the relatively low magnitude of the Manning roughness index ‘n’ which is within the range of n=0.013–0.033 for corrugated pipes. Therefore, introduction of corrugated metal structures with a roughness factor lower than that of the repaired facility will improve hydraulic characteristics of the repaired culvert aqueduct pipes.

Mostly, the following cross section shapes of structures or corrugated metal pipes are used in repair of engineering facilities by the shelling method: flat-base sections, round sections, and arch sections. During designing, engineers have to select cross-section shape of the corrugated metal structure which would be as much as possible adapted to the shape of the existing facility. However, it often happens that the structure intended for strengthening of the existing facility is designed individually, so it can differ from the shape of the existing facility to be repaired.

At the construction stage, the shell (corrugated metal pipe) is inserted into existing facility, formwork is installed and then concrete mixture is injected. When concrete gains its design strength, the formwork is dismantled and the slope plates of the embankment are mounted.

During installation, it is necessary to arrange (before filling) restraints that will prevent displacement of the structure during concrete compaction. The space that is to be filled with concrete does not need additional reinforcement but if such a decision is made, the concrete reinforcement should be attached to the arch of the existing facility.

Galvanized corrugated metal structures are most often embedded in two ways [12, 13]. The first method is installation of a pipe the total length of which corresponds to the length of the repaired structure or is larger if it is necessary to extend the existing culvert aqueduct pipe. The second method involves sequential joining of the pipe sections during their installation inside the defective reinforced-concrete pipe.

Taking into account that the cross sections of defective pipes being repaired differ in shape and size, different materials and methods of filling the free space between the repaired pipe and the corrugated metal structure are used. Cast concrete and sand mixtures are often used as fillers. The filling material must ensure joint work of the repaired facility and the corrugated metal structure, so it is important to provide a proper, dense filling of the free spaces without formation of air cavities. The space between the existing facility and the inserted pipe must be filled with a concrete mixture of a wet consistency at a pressure of 0.6 MPa such that the mixture fills the entire space between the structures. It is recommended [12] to use C12/15 class concrete with a maximum diameter of the filler grains 16 mm. The concrete frost resistance should meet requirements to the structures operated in an aquatic environment of the particular geographic region [12, 13]. Concrete mixtures must be compacted with immersion vibrators. However, they should be used with care to prevent damaging the corrugated metal structures. Use of self-expanding and self-compacting concretes is also permitted.

It is recommended to leave at least 100 mm of free space between the outer contour of the corrugated metal structure and the existing object. Filling with concrete mixture should be symmetrical on both sides of the pipe previously protected from its forcing out or displacement by the buoyancy force of the liquid concrete. To that purpose, it is recommended to ballast the pipe, e.g. with sandbags, use spacers or provide filling with concrete in stages [12, 13]. In order that the concrete mixture could freely fill the space between the inserted pipe and the existing structure, it is necessary to arrange air-bleed channels in a quantity and location corresponding to the length and dimensions of the object. It is important to properly remove air from the space to be filled through the openings at the top of this space (Fig. 3, 4). These openings can also serve as inspection openings to control the filling level. The concrete mixture can be injected in four ways: from the face of the wall (formwork) which restricts leakage of the mixture (Fig. 3, *a*); through the holes drilled in the roadbed and passing through the structure of the existing object (Fig. 3, *b*); through the holes drilled in the embankment body and passing through the structure of the existing object and through the working holes of the structure or the pipe made of corrugated sheets (Fig. 4).

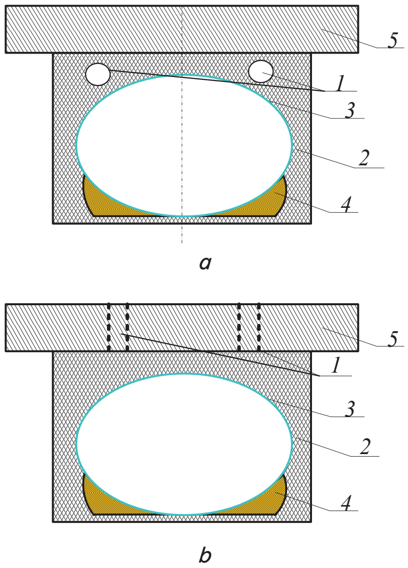

Fig. 3. Concrete injection holes:
a – in the formwork face; *b* – holes in the plate of the existing object: holes for filling (or inspection) (1); formwork (2); corrugated metal structure (3); a pillow of sand or granulated slag (4); plate of the object under repair (5)

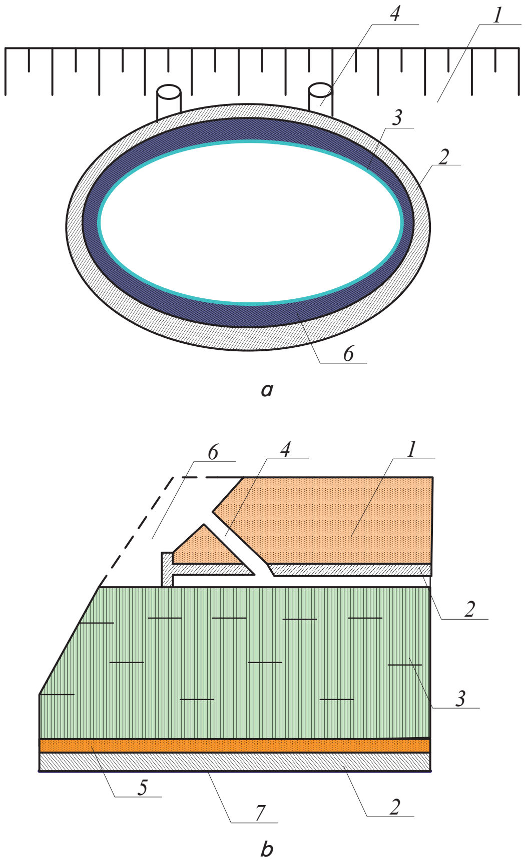

Fig. 4. Concrete feeding holes in the embankment:
a – view from the face of concrete feed; *b* – longitudinal section of the object; embankment (1); the object being repaired (2); the structure of corrugated metal (3); the holes for concrete feed or inspection (4); the pillow of sand or gravel from the embankment broadening (5); the formwork, geotextile or geomesh (6)

Before starting injection of concrete mixture, it is necessary to arrange a formwork (Fig. 4) at the ends of the object under repair and the newly installed structure. Instead of a wooden formwork, a wall of brick or stone may be used and then removed after concrete setting.

In the case of injection of concrete mixture from the face, a stepped change of the feed level can be applied. However, this technique is used to the objects with diameter of the pipe clear opening more than 3.5 m and a larger filling space (the distance to the wall of the existing object greater than 1.0 m). Diameter of the holes for injection of concrete mixture should ensure free passage of the feed hose and be not less than 25 cm.

The space is filled with a sandy gravel or a sand of a heterogeneous granularity with grain size less than 4.5 mm. The gravel mixture should be well compacted (compacting factor of 0.98 to 1.0 is recommended) in 0.2 to 0.3 m thick layers.

There are cases when strengthening of objects should be performed along with their extension. In this case, it is necessary to widen the embankment at the location of elongated corrugated metal structures or pipes. Such a decision is very practical since it enables extension of an object after removal of the embankment over the inlet and outlet ends of the object being repaired. This elongation is accomplished by joining next sections to the existing structure and re-filling of the embankment.

5. Study of horizontal and vertical pressures acting on the pipe from the railway rolling stock

Pipes are calculated for constant loads from the weight of the embankment soil and a temporary moving vertical load on the embankment. Both of these loads transmitted through the embankment bring about vertical and horizontal pressures on the pipe sections. Pipe loading diagrams and design diagrams are shown in Fig. 5 [10].

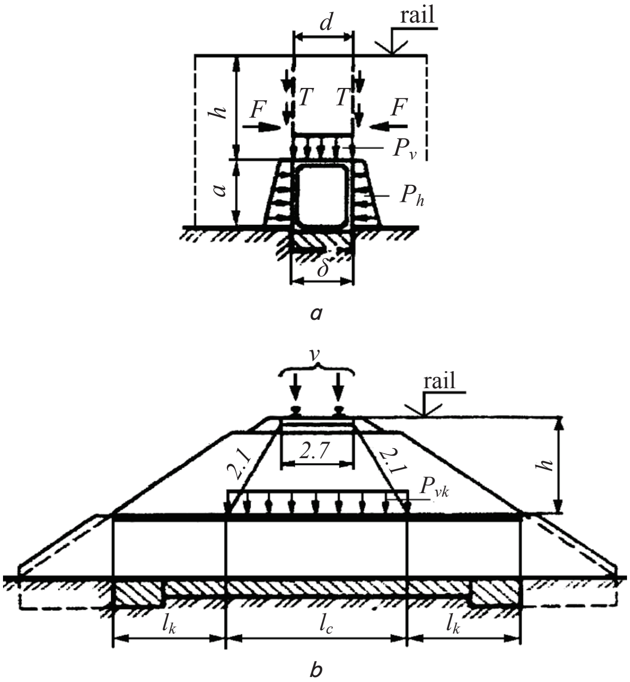

Fig. 5. Diagram of loads acting on the pipe:
a – pressure from the proper weight of the embankment;
b – pressure from the temporary moving load

Vertical pressure on the pipe from the constant load is determined taking into account the frictional forces acting on the vertical planes limiting the column of the embankment soil under the pipe (Fig. 5). These friction forces arise from the fact that subsidence of the embankment soil occurring in the first period after its filling over the pipe is less than on the pipe sides. The difference in subsidence reaches the maximum value at the level of the pipe top and is much smaller at the train level, especially in high embankments.

The friction forces F acting on the column of the embankment soil over the pipe are directed downward since the embankment soil on the sides of the pipe next to the column under consideration will come down. The magnitude of friction forces can be determined by multiplying the forces of normal pressure by the boundary areas and the coefficient of internal friction of the embankment soil. Therefore, the pressure of the embankment soil on the pipe appears to be larger than the weight of the soil column above the pipe.

The value of the vertical uniformly distributed pressure on the pipe (in MPa) is determined by the formula:

$$P = C\gamma_n H, \tag{1}$$

where $C > 1$ is the dimensionless coefficient taking into account friction forces; γ_n is volume weight of the embankment soil, t/m^3; H is the height of the soil column from the top of the pipe to the sleeper bottom or to the top of the road pavement, m.

Coefficient C is determined from the following considerations. The friction force on one of the planes attributed to 1 m^2 of the horizontal pipe projection with width D is equal to:

$$F = \frac{E}{D}\operatorname{tg}(\varphi_n), \tag{2}$$

where $E = 1/2\gamma_n H^2\mu$ is active soil pressure on 1 running meter of the length of the plane limiting the soil column above the pipe;

$$\mu = \operatorname{tg}^2(45 - \varphi_n/2),$$

where φ_n is the normative angle of internal friction of the soil.

The values of γ_n and φ_n are usually taken based on laboratory tests of the soil intended for filling the structure. In standardized design, when characteristic soil pressure is determined, it is supposed to take the filling soil density $\gamma_n = 17.7$ kN/m^3 (1.80 t-f/m^3), the characteristic angles of internal friction φ_n should be taken as follows: $\varphi_n = 35°$ for riser pipes when filling with sandy soil (drainage); $\varphi_n = 30°$ for the pipe sections in the embankment; $\varphi_n = 25°$ for the culvert head.

The sum of the friction forces in two planes over the pipe will be equal:

$$2F = \frac{2E}{D}\operatorname{tg}\varphi_n = \frac{\gamma_i}{D}H^2\mu\operatorname{tg}\varphi_n. \tag{3}$$

Therefore, determine coefficient C for a low embankment using formula (3):

$$N = 1 + \frac{H}{D}\mu\operatorname{tg}\varphi_n = 1 + A\mu\operatorname{tg}\varphi_n. \tag{4}$$

For high embankments where the soil subsidence at a certain height above the pipe and on the sides of the pipe equalizes, a refined value of the following quantity can be obtained based on similar considerations

$$A = \frac{Sh}{H}\left(2 - \frac{SDn}{H^2}\right), \tag{5}$$

where h is the pipe height, m; s is the base stiffness factor equal to 15 for rock or pile base, 10 for the base of dense sand, solid and tight plastic clays and loam soils and 5 for the base of red sands, soft plastic loams and clays.

At a good compaction of embankment during its filling, vertical pressure on the pipe decreases because subsidence gets smaller. In this case, for the pipes under highways, coefficient c can be reduced by 30 %. When $Sh/H = H/D$, it is necessary to take $A = H/D$.

The horizontal constant pressure (MPa) on the pipe from the embankment soil is determined by the formula:

$$e_p = \mu\gamma_n H', \tag{6}$$

where $H' = H$ for round pipes and $H' = H + h/2$ for rectangular pipes.

In its turn, the temporary vertical load on the embankment brings about vertical and horizontal pressure of the soil on the pipe (Fig. 1). It is distributed in the embankment at an angle equal to arctg1/2 to the vertical. Admitting that the load from the railway rolling stock is equal to $2K$ (for the load of C14 to 28 t per running meter of the track) and that the length of the sleepers through which the load is distributed across the track axis is equal to 2.7 m, the vertical pressure on the pipe (t/m^2) is obtained as follows:

$$q = \frac{2K}{2.7 + H} = \frac{28}{2.7 + H}. \tag{7}$$

For the pipes under highways, pressure (1 t/m^2) from the moving load NK-80 can be determined by the formula

$$q = \frac{19}{H + 3}. \tag{8}$$

If the filling height above the pipe is less than 1 m, consider the actual pressure on the pipe from the wheels of load NK-100 or NK-80 taking into account its distribution by pavement and embankment.

Horizontal pressure is also determined by multiplying vertical pressure by μ:

$$e_q = \mu q, \tag{9}$$

where q is determined for the height $H' = H$ for round pipes and $H' = H + h/2$ for rectangular pipes.

Deviation of the load from the normative value is taken into account by multiplying pressure values p, e_p, q, e_q by overload factors while deviation from the normative angle of internal friction is taken into account accepting it 5° higher or lower than the normative value to a side disadvantageous for calculation of the pipe design.

Sections of round pipes are calculated as rings working in conditions of uneven radial compression. The highest design bending moments in such a ring in the vertical and horizontal sections (without taking into account normal and transverse forces) are determined by formula:

$$M=\pm\nu r^2\left(n_p P+n_t q\right)\left(1-\mu\right). \qquad (10)$$

Here, effect of constant pressures p and e_p and temporal pressures P and e_q is taken into account; n_p and n_t denote overload factor; μ is the standard angle of internal friction ±5°; r is the pipe ring radius to the middle of the section thickness; $\nu\geq 0.2$ is the coefficient accounting conditions of the section resting: $\nu=0.22$ for the sections resting on a foundation; $\nu=0.25$ for the sections resting on a soil base.

By these values of bending moments, thickness of the ring is determined when it is designed proceeding from the condition of preventing crack formation in concrete.

To study the values of horizontal and vertical pressures on the pipe, the following source data were selected: the filling height varying from 1 m to 3 m, the pipe diameter: 2 m; the filling soil density $\gamma_n=17.7$ kN/m^3; the angle of internal friction of soil $\varphi_h=30°$; coefficient of the relative base stiffness $S=1.0$. To take into account dynamic properties of the railway rolling stock, a load from the railway rolling stock was taken equal to $2K$ (for a load C14 it is 28 t/m of the track) with the length of sleepers through which the load is distributed across the track axis equal to 2.7 m.

To calculate the pressure forces acting on the pipe, a program was developed in the software package Mathcad 14. The results of calculation of horizontal and vertical soil pressures from the constant loading of the backfill soil are given in Fig. 6 and the data for the railway rolling stock are given in Fig. 7.

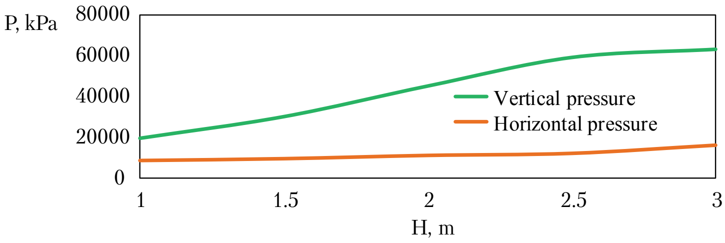

Fig. 6. Values of vertical and horizontal pressure on the pipe from a static load of the railways rolling stock

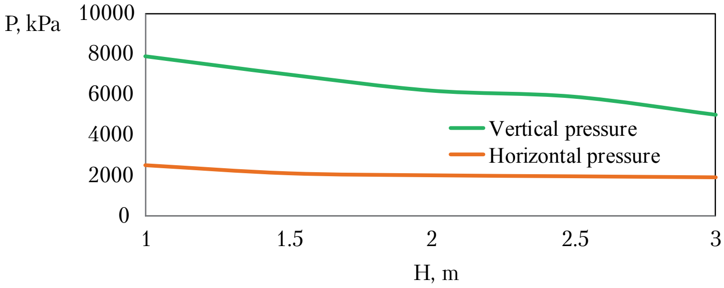

Fig. 7. The values of vertical and horizontal pressures on the pipe from dynamic load of the railway rolling stock

As it can be seen from Fig. 6, the magnitude of both vertical and horizontal pressures on a reinforced-concrete pipe strengthened with a corrugated metal pipe increases with an increase in the height of soil filling above it. For example, for the filling height 1 m above the pipe, the value of vertical pressure from the constant loading of soil is 17.7 kPa and that of horizontal pressure is 5.9 kPa. For the filling height 2 m, vertical soil pressure is 45.62 kPa, horizontal soil pressure 11.8 kPa. For the filling height 3 m, vertical soil pressure is 65.21 and horizontal pressure is 17.7 kPa.

It is evident from Fig. 7 that the magnitude of both vertical and horizontal pressures on a reinforced-concrete pipe arising from the action of rolling stock decreases with an increase in the filling height which is explained by energy dissipation in the depth of soil.

For the filling height above the pipe 1 m, the value of vertical pressure from the load C14 is 7.568 kPa and horizontal pressure is 2.523 kPa. The respective figures of vertical and horizontal pressures are 5.957 kPa and 1.986 kPa for the filling height 2 m and 4.912 kPa and 1.637 kPa for the filling height 3 m.

6. The stress-strain state in a reinforced-concrete pipe strengthened with a corrugated metal structure

Next, numerical studies of the stress-strain state were carried out at the following geometric parameters of a reinforced-concrete pipe: diameter: 2.000 mm; wall thickness: variable from 150 mm to 200 mm; ambient temperature: 20 °C. Physical and mechanical characteristics of the inserted pipe were taken as follows. For steel St3: $E_1=2.1\cdot 10^5$ MPa, $\nu_1=0.3$; $\alpha_1=1.25\cdot 10^{-5}$ 1/°C. For C25/30 concrete: $E_2=3.6\cdot 10^4$ MPa; $\nu_2=0.25$; $\alpha_2=1.0^{-5}$ 1/°C.

The boundary conditions in this calculation problem were as follows. The lower surface $x=0$ was rigidly fixed and the left and the right surfaces were free to move along coordinate y.

The stress-strain state of the reinforced-concrete pipe was calculated by the finite element method [15, 17] using the FEMAP licensed program with MSC NASTRAN.

In this problem, the tube section was modeled as a curvilinear rod (one-dimensional element) and the reinforced concrete was modeled as flat elements.

The advantage of this approach is a rapid preparation of the model and a relatively small number of finite elements. Its disadvantage is impossibility of taking into account the pipe undulation waves and correct application of loads from the rolling stock.

An element of BEAM type was selected as a one-dimensional element, and an element of PLATE type (quadrinodal tetragon) was chosen as a two-dimensional finite element.

15.874 nodes of the finite-element network formed 7.551 elements.

The results for stresses and strains arising from the given constant and temporal vertical and horizontal pressures are shown in Fig. 8, 9, respectively.

The results of calculation of the stress-strain state in a reinforced-concrete pipe strengthened with a corrugated metal structure showed that the maximum stress value arose in the pipe vault and was equal to 0.024 MPa. Strains made up $9.3\cdot 10^{-4}$ mm.

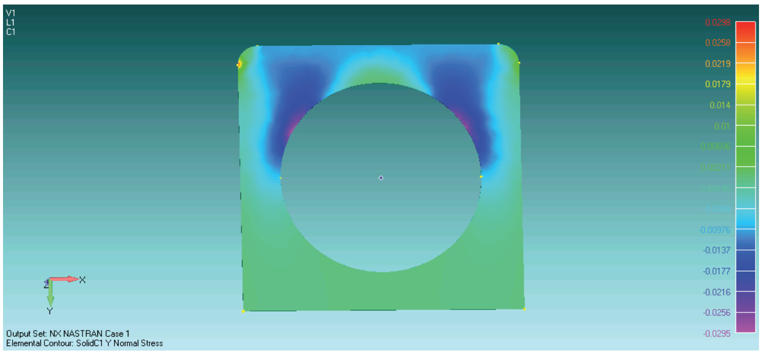

Fig. 8. Stresses in the pipe

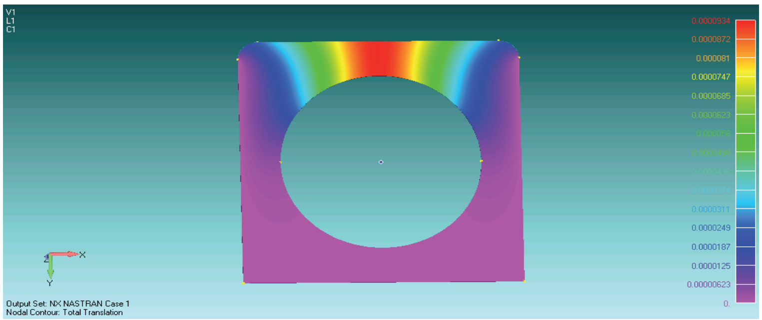

Fig. 9. Strains in the pipe

7. Discussion of the results obtained in the study performed to assess strength of the corrugated metal structure elements under railway conditions

The use of pipes made from corrugated metal sheet for major repairs (rebuilding) of railway and highway facilities in Ukraine will cut costs for their reconstruction and further operation. In this regard, scientific researches aimed at the choice of rational and reliable designs of culverts with the use of corrugated metal products are relevant and timely for Ukraine. Moreover, relevance of these researches grows over time.

The results of calculation of the pressure forces acting on the pipe vault showed that at the filling height 1 meter above the pipe, the value of vertical pressure from the constant soil load was 17.7 kPa and horizontal pressure was 5.9 kPa. The respective figures for vertical and horizontal pressures were 45.62 kPa and 11.8 kPa for 2 meters and 65.21 kPa and 17.7 kPa for 3 meters. The results of calculation of the stress-strain state in a reinforced-concrete pipe strengthened with an corrugated metal structure showed that the maximum stress value appeared in the upper part of the pipe and measured 0.024 MPa while the strain was $9.3 \cdot 10^{-4}$ mm.

Analysis of the bearing capacity of the corrugated metal structures made by the mentioned method has ensured evaluation of performance of corrugated metal structures depending on dimensions of the undulation waves and physical and mechanical characteristics of the soil filling. Also, application of this technique has allowed us to determine at which geometrical, power and speed parameters of the rolling stock the loss of bearing capacity of the corrugated metal structures is possible.

The results obtained for the bearing capacity of the corrugated metal structures can be used by engineers of bridge-testing stations of Ukrzaliznytsya and Ukravtodor and design institutions in their further designs of corrugated metal structures.

The determined stress-strain state in the corrugated metal structures provides the scopes of formation of a normative base for determining reliability of railway facilities taking into account the complex of initial factors influencing their bearing capacity.

One of the disadvantages of the conducted studies is that a two-dimensional finite-element model of calculation was used in the study of the bearing capacity of a defective reinforced-concrete pipe strengthened with a corrugated metal structure. Therefore, further scientific research works should use the finite element method in a three-dimensional formulation for assessment of the pipe bearing capacity.

8. Conclusions

1. The use of corrugated metal pipes in major repairs of reinforced-concrete pipes will eliminate the need for stopping movement of railroad and motor transport. This will enable repair of defective pipes in short terms and reduce costs for reconstruction and further operation of transport facilities.

2. The value of both vertical and horizontal pressure on a reinforced-concrete pipe from the action of rolling stock decreases with an increase in the filling height which is a result of energy dissipation in the depth of the soil. At a filling height 1 meter above the pipe, the value of vertical pressure from a constant soil load was 17.7 kPa, and horizontal pressure was 5.9 kPa. The respective figures for vertical and horizontal pressures were 45.62 kPa and 11.8 kPa for 2 meters and 65.21 kPa and 17.7 kPa for 3 meters.

3. The maximum value of stresses in a composite pipe was in the vault of the pipe and measured 0.024 MPa which is less than the permissible normative stresses.

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