

*This paper has analyzed the use of fiberglass pipes in the body of the railroad embankment by a method of pushing them through the subgrade.*

*A flat rod model has been improved for assessing the deformed state of the transport structure "embankment-fiberglass pipe" by a method of forces when replacing the cross-section of the pipe with a polygonal one.*

*The analytical model accounts for the interaction between the pipe and soil of the railroad embankment. To this end, radial and tangential elastic ligaments are introduced into the estimation scheme, which make it possible to simulate elastic soil pressure, as well as friction forces that occur when the soil comes into contact with the pipe.*

*The deformed state of the transport structure "embankment-fiberglass pipe" was calculated by the method of forces and by a finite-element method under the action of load from the railroad rolling stock, taking into consideration the different cross-sections of the pipe.*

*It has been established that with an increase in the diameter of the fiberglass pipe, the value of deformations of the subgrade and fiberglass pipe increases. With a pipe diameter of 1.0 m, the deformation value in the vaulted pipe is 2.12 mm, and with a pipe diameter of 3.6 m – 4.16 mm. At the same time, the value of deformations of the subgrade under the sleeper is 5.2 mm and 6.0 mm, respectively.*

*It was determined that the maximum deformations of the subgrade, which occur above the pipe, with a pipe diameter of 3.6 m, are 4.46 mm. At the same time, the maximum vertical deformations of a fiberglass pipe arise in the pipe vault and, with a pipe diameter of 3.6 m, are 4.16 mm.*

*It has been established that the maximum horizontal deformations of the subgrade occur at points of horizontal diameter of the fiberglass pipe while the minimal horizontal deformations of the subgrade occur at points lying on the vertical diameter of the pipe*

*Keywords: subgrade, fiberglass pipe, railroad track, horizontal and vertical deformations, equivalent load*

# INVESTIGATING THE INFLUENCE OF THE DIAMETER OF A FIBERGLASS PIPE ON THE DEFORMED STATE OF RAILROAD TRANSPORTATION STRUCTURE "EMBANKMENT-PIPE"

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## 1. Introduction

Improving the reliability and uninterrupted operation of transportation infrastructure is the main guarantee of

creating conditions for safe and stable operation of rail and road transport in general. Particular attention should be paid to the introduction of modern advanced and economic structures that should ensure uptime during the warranty period

of their life cycle. At the design stages of repair of sections of roads or tracks, it is necessary to make informed decisions on the choice of promising structures of transportation structures. That should allow for increasing the bearing capacity of roads and making it safer to pass transport units.

Water culverts are important structural elements of highways and railroads. They account for about 25 % of the total number of all artificial road structures. Therefore, the general condition of roads and traffic safety depend on the proper functioning of the pipes.

Stopping train traffic causes significant economic losses for the railroad industry due to the downtime of freight and passenger trains. To prevent downtime and restore the operation of railroad under conditions of flooding the track, the current scientific work proposes using promising fiberglass reinforced pipes Hobas GRP (hereinafter, fiberglass pipes).

Note that such structures should be used on oversaturated sections of the railroad track. Oversaturation leads to a loss of strength and stability of the railroad subgrade, which adversely affects the carrying capacity of the railroad section.

Hobas GRP pipes consist of fiberglass reinforced plastic and are manufactured by centrifugal casting [1]. Such structures in the countries of the European Union are laid in the railroad embankment by a pushing method. The general view of fiberglass pipes used on a railroad is shown in Fig. 1.

It should be noted that at present there is no accumulated experience in the use of fiberglass pipes on railroads. Therefore, research on the substantiation of the possibility of applying fiberglass pipes in the body of a railroad embankment used for the rolling stock traffic requires a study on determining the deformed state of the transportation structures “embankment-fiberglass pipe”. Such studies should be carried out taking into consideration the specificity of loads from railroad rolling stock and constant loads from soil backfill and elements of the upper structure of the track.



Fig. 1. The operation process of fiberglass pipes in the body of a railroad embankment [1]

## 2. Literature review and problem statement

Work [1] states that Hobas GRP fiberglass pipes are embedded in the body of the mound of subgrade by pushing without stopping the movement of trains. The maximum diameter of the pipes, which can be installed by pushing, is 3600 mm [1].

The main materials of water culverts at present are reinforced concrete and corrugated steel [2]. During the reconstruction and replacement of defective small bridges and water culverts, metal corrugated structures are used (hereinafter referred to as MCS) [3]. Transportation facilities made of metal corrugated structures have been widely used in the countries of the European Union [4] and are also implemented on motorways and railroads [5] in the form of water culverts, overpasses, small bridges, etc. [6].

However, the studies into the influence of soil backfill on the deformation of a metal pipe reported in work [4] do not take into consideration the friction forces that occur in the contact of the pipe with the ground filler.

In [5], research was carried out only to determine the temperature stresses and deformations of metal corrugated structures. Work [6] provides a model for calculating the deformations of pipes such as Multiplate MP 150 and reports a study of their deformation depending on the density of soil backfill. However, the model does not take into consideration the friction forces that occur in the contact of the pipe with the ground filling and the action of the railroad rolling stock.

It should be noted that one of the disadvantages of reinforced concrete pipes is the limited size of the cross-section, limited length, and, as a result, a large number of joining seams. This requires careful waterproofing. In addition, such pipes are subject to active corrosion processes in the form of leaching, which leads to the destruction of pipes.

As regards steel pipes, they have less weight compared to reinforced concrete ones. However, during construction, a lot of time is spent on the installation of structures since steel water culverts are arranged from separate links using a bolt connection. The use of galvanized corrugated pipes does not warrant the durability of structures due to the fact that during operation there is an abrasion of the protective coating and, subsequently, there is catastrophically rapid corrosion of the base metal.

In addition, work [7] found that with an increase in the cross-sections of structures made of metal corrugated structures [7], there remains low operational reliability due to operational and technical factors of influence [8]. This feature is due to the fact that the operation of structures made from MCS is associated with the interaction of a metal shell with soil backfill [9]. And only with a high-quality degree of the compaction it is possible to achieve the necessary bearing capacity of transportation facilities made from MCS [10].

With abnormal compaction of soil filling, uneven subsidence of the embankment over MCS, deformation of the strengthening of the slopes of the embankment and the most dangerous, residual deformations of the vertical and horizontal cross-sections of MCS [11], may occur.

In work [12], it is established that under the action of dynamic load of railroad rolling stock, crushed rubble is compacted, which causes the formation of irregularities on the track. Therefore, for effective compaction, it takes time to adjust the crushed rubble ballast. And in the case of the use of metal corrugated structures, which, in the initial period of work, are capable of the formation of residual deformations of the cross-section, a prerequisite for their operation is to achieve a normative degree of compaction of soil filling [13].

For the repair and construction of water supply facilities on highways, polymer pipes of large diameters are widely used [14]. The first road construction projects using corrugated polyethylene pipes are known in the United States [15]; design calculations are reported in [16].

Work [17] established the relative efficiency of polyethylene pipes in comparison with pipes from other materials. Tests of various pipes under similar conditions showed that polyethylene pipes with a profiled wall are stronger in performance than “smooth” pipes made of more rigid materials.

However, in the cited studies [14–17], the issues of assessing the deformed state of polyethylene pipes under the action of vehicles were not resolved.

Australia and New Zealand issued a number of joint regulatory documents, including TNZ F/2 [18], TNZ F/3 [19], on the design of water culverts made of polymeric materials on highways [20]. In this case, the structure of water pipes must comply with the Auckland Transport Code [21].

Work [22] established that an important factor in the operation of plastic pipes is the impact of transport load through the soil embankment. In [23], it is proven that the minimum thickness of the soil embankment above a pipe should be taken in the range from 0.9 m to 1.2 m. It should also be noted that in some countries the height of the embankment above the pipe is more than 15 m [24].

Fiberglass pipes are widely used in different countries. In the 1980s, they were applied at micro tunneling in Hamburg, their outer diameter was 752 mm. Later, they began to be successfully used in the United States, with a diameter of 400 mm to 2200 mm. After 1999, such structures have been effectively used in Poland and other countries.

Paper [24] describes methods for examining the mechanical properties of fiberglass using samples cut from pipe fragments. It is established that in all samples the destruction of fiberglass evolved with the formation of a crack at an angle of about 45° from the surface of the pipe, opposite to the surface of load application. When saturating fiberglass with moisture, the nature of the destruction did not change. However, there remained unresolved issues related to the assessment of the deformed state of fiberglass pipes under the action of railroad rolling stock.

Our review of the above studies revealed that there was no theoretical research into the deformed state of transportation structures “embankment-fiberglass pipe” under the action of railroad rolling stock; the cited authors confined themselves to assessing the results of the practical application of structures of this type. Therefore, the topic of our work is important for designing water culvert structures for roads for various purposes and forecasting their strength and reliability.

### 3. The aim and objectives of the study

The aim of our work is to determine the impact of the diameter of a fiberglass pipe on the deformed state of the transportation structure “embankment-pipe” of the railroad track under the action of railroad rolling stock. This will make it possible to obtain reasonable data on the deformed state of fiberglass pipes under the action of the railroad rolling stock.

To accomplish the aim, the following tasks have been set:

- to improve the analytical model for assessing the deformed state of fiberglass pipes;
- to conduct a study of the deformed state of railroad track subgrade by a finite-element method, taking into consideration the different cross-sections of the pipe;
- to investigate the deformed state of fiberglass pipes at different values of the cross-section of the pipe by a finite-element method and by the method of forces.

### 4. The study materials and methods

#### 4.1. Initial data for the calculation of the structure “embankment-fiberglass pipe”

To study the deformed state of the transport structure “embankment-fiberglass pipe” under the action of dynamic load from the railroad rolling stock, the estimation scheme

shown in Fig. 2 was used. The body of a railroad subgrade hosts a fiberglass pipe. To study the deformed state of the structure “embankment-fiberglass pipe”, pipes with a diameter of 1.0 m, 1.5 m, 2.0 m, 3.0 m, and 3.6 m were used.

The height of the mound of subgrade is 6.7 m. The pipe is surrounded by loamy sand. The backfill with crushed rubble ballast over the pipe, counting from the sole of the sleeper of a railroad track to the top of the outer diameter of the pipe, is 1.47 m.

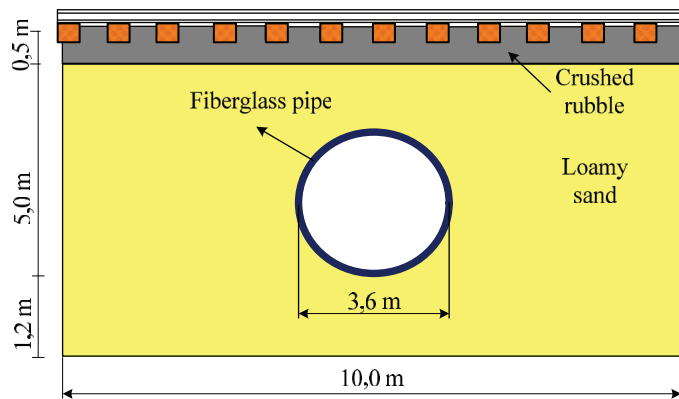


Fig. 2. Estimation scheme of the transport structure “embankment-fiberglass pipe” of a railroad track

In our calculations, it is accepted that the top layer of subgrade to a height of 4.3 m is water-saturated with a specific water weight equal to 10 kN/m<sup>3</sup>.

The physical and mechanical parameters of the subgrade soils, shown on the estimation scheme (Fig. 2), are given in Table 1.

Table 1

#### Physical and mechanical characteristics of pipe backfill

Mechanical characteristics of soil	Crushed rubble	Loamy sand
Specific weight, $\gamma$ kN/m <sup>3</sup>	13.5	21.5
Poisson's ratio, $\nu$	0.26	0.26
Adhesion coefficient $c$ , kPa	0.1	4
Inner friction angle, $\phi^\circ$	43	37
Dilatation angle, $\psi^\circ$	0	1
Young modulus, $E$ , MPa	150	110

Uniformly distributed temporary load from railroad rolling stock, given by the value  $q=249.5$  kN/m, under the action of the equivalent load SK 14 and the loading length of the line of influence  $\lambda=5.0$  m, and at the relative position of the top of the line of influence  $\alpha=0.5$ . The model also takes into consideration the additional load from the influence of materials in the upper structure of a railroad track (rail-sleeper grid).

The fiberglass pipe is specified under the following physical and mechanical parameters: Young modulus,  $1.5 \cdot 10^4$  MPa; Poisson's ratio, 0.3; density, 2000 kg/m<sup>3</sup>; permissible bending deformation when internal fiber break occurs is 2.2 % [1].

#### 4.2. A finite-element model of the transport structure “embankment-fiberglass pipe” of a railroad track

We calculated the stressed-strained state of the railroad subgrade and fiberglass pipe in a nonlinear statement using the elastic-plastic Moore-Coulomb model [25]. The calculation was performed by finite-element analysis.

The soil massif was modeled with fifteen-node finite elements [25] while assigning the physical and mechanical characteristics of each layer of soil given in Table 1.

When calculating the stressed-strained state of the subgrade with a fiberglass pipe, the following boundary conditions were set – on the sides of the estimated model, a ban on movements in the horizontal direction is imposed, and at the bottom there is a ban on vertical and horizontal movements.

The finite-element model of subgrade with a fiberglass pipe is shown in Fig. 3.

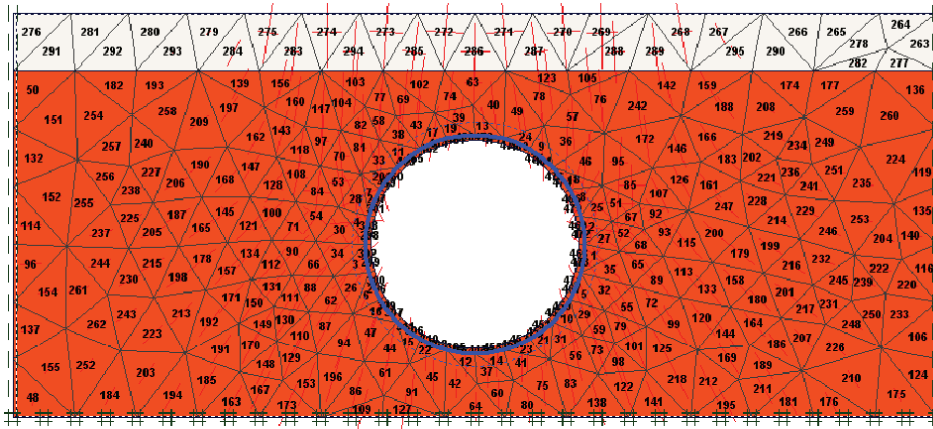


Fig. 3. The finite-element model of subgrade with a fiberglass pipe

Thickening of the grid of finite elements is performed at the points of contact between the fiberglass pipe and the subgrade.

Underlying the estimated model is the fixed fastening; movable fastening was accepted on the sides, which allows the movement of the subgrade and pipe in the vertical direction.

### 5. Results of studying the stressed-strained state of a fiberglass pipe under the influence of loads from the railroad rolling stock

#### 5.1. Improved analytical model for assessing the stressed-strained state of a fiberglass pipe

To simulate the stressed-strained state of flexible water culverts arranged in the body of railroad embankment, we adopt a flat rod model. The calculations are simplified by replacing the cross-section of a pipe with a polygonal one, that is, the cross-section is considered as a regular polygon.

To take into consideration the interaction between the pipe and soil, radial and tangential elastic ligaments are introduced into the estimation scheme, which make it possible to simulate elastic soil pressure, as well as friction forces arising from soil contact with the structure. To properly reflect the physical nature of the soil, it is necessary to exclude radial ligaments from consideration when stretching efforts appear in them.

In our studies, the circle was replaced by a proper 8-angle shape, to determine the effort in which, under the action of a load evenly distributed on the surface of the soil, we used the method of forces.

To get rid of extra ligaments in the closed octagonal contour, hinges were placed at angular points. Each one rejects two “extra” forces – the bending moment  $X_{2i-1}$  and the longitudinal force  $X_{2i}$ , where  $i$  is the top number. The estimated scheme of the cross-section of a pipe is shown in Fig. 4.

The ligaments that are discarded in the node of the main system are shown in Fig. 5.

The system of canonical equations of the force method for the adopted scheme is on the order of 16 and is written in the following matrix form:

$$\delta X + \Delta q = 0, \tag{1}$$

where  $\delta$  is a square matrix of single movements;  $X, \Delta q$  are the matrices-columns of unknown efforts and cargo movements. The elements of matrices  $\delta$  and  $\Delta q$  are calculated using the Moore integral, taking into consideration the influence of bending moments and longitudinal forces; the summation is carried out according to the number of rods in the estimation scheme:

$$\delta_{ij} = \sum_k \left( \int \frac{\bar{M}_{ik} \cdot \bar{M}_{jk}}{E_k I_k} dx + \int \frac{\bar{N}_{ik} \cdot \bar{N}_{jk}}{E_k A_k} dx \right), \tag{2}$$

$$\Delta_{iq} = \sum_k \left( \int \frac{\bar{M}_{ik} \cdot M_{qk}}{E_k I_k} dx + \int \frac{\bar{N}_{ik} \cdot N_{qk}}{E_k A_k} dx \right)$$

where  $\bar{M}_{ik}, \bar{N}_{ik}$  are the single diagrams of bending moments and longitudinal forces for the  $k$ -th rod;  $M_{qk}, N_{qk}$  – cargo diagrams of bending moments and longitudinal forces;  $E_k I_k, E_k A_k$  are, respectively, the stiffness at bending and stretching of the  $k$ -th rod.

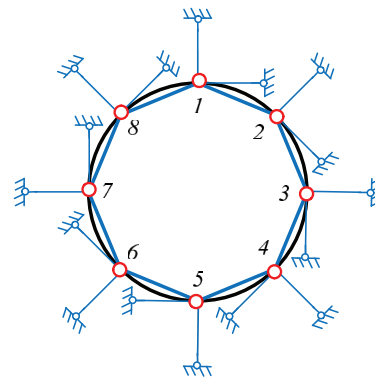


Fig. 4. Estimation scheme of the model “embankment-fiberglass pipe”

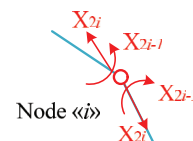


Fig. 5. Diagram of ligaments discarded in the node of the main system

Based on the unknown  $X$  found as a result of the calculation, the  $U_{i,r}$  and  $U_{i,\tau}$  forces, acting in the radial and tangential elastic rods attached to the  $i$ -th node, were established. According to Hooke’s law, we determined deformations in these rods:



$$\delta_{i,r} = \frac{U_{i,r}}{\left(\frac{EA}{l}\right)_{i,r}}, \tag{3}$$

$$\delta_{i,\tau} = \frac{U_{i,\tau}}{\left(\frac{EA}{l}\right)_{i,\tau}},$$

where  $\left(\frac{EA}{l}\right)_{i,r}$ ,  $\left(\frac{EA}{l}\right)_{i,\tau}$  is the rigidity of the radial and tangential rods, respectively, through which the vertical and horizontal components of the movement of the  $i$ -th node of the system as a result of deformation were expressed:

$$\delta_{iB} = -\delta_{i,r} \cdot \cos \frac{\varphi_i + \varphi_{i+1}}{2} - \delta_{i,\tau} \cdot \sin \frac{\varphi_i + \varphi_{i+1}}{2}, \tag{4}$$

$$\delta_{iV} = -\delta_{i,r} \cdot \sin \frac{\varphi_i + \varphi_{i+1}}{2} + \delta_{i,\tau} \cdot \cos \frac{\varphi_i + \varphi_{i+1}}{2}.$$

Thus, one determines the deformed state of a fiberglass pipe under the action of the railroad rolling stock.

### 5. 2. Results of calculating the deformed state of subgrade depending on the diameter of a fiberglass pipe

Fig. 6 shows the distribution of vertical deformations of railroad subgrade with the HOBAS GRP fiberglass pipe. In this case, the distribution of the deformed state was derived for pipes with diameters of 1.0 m, 2.0 m, and 3.6 m.

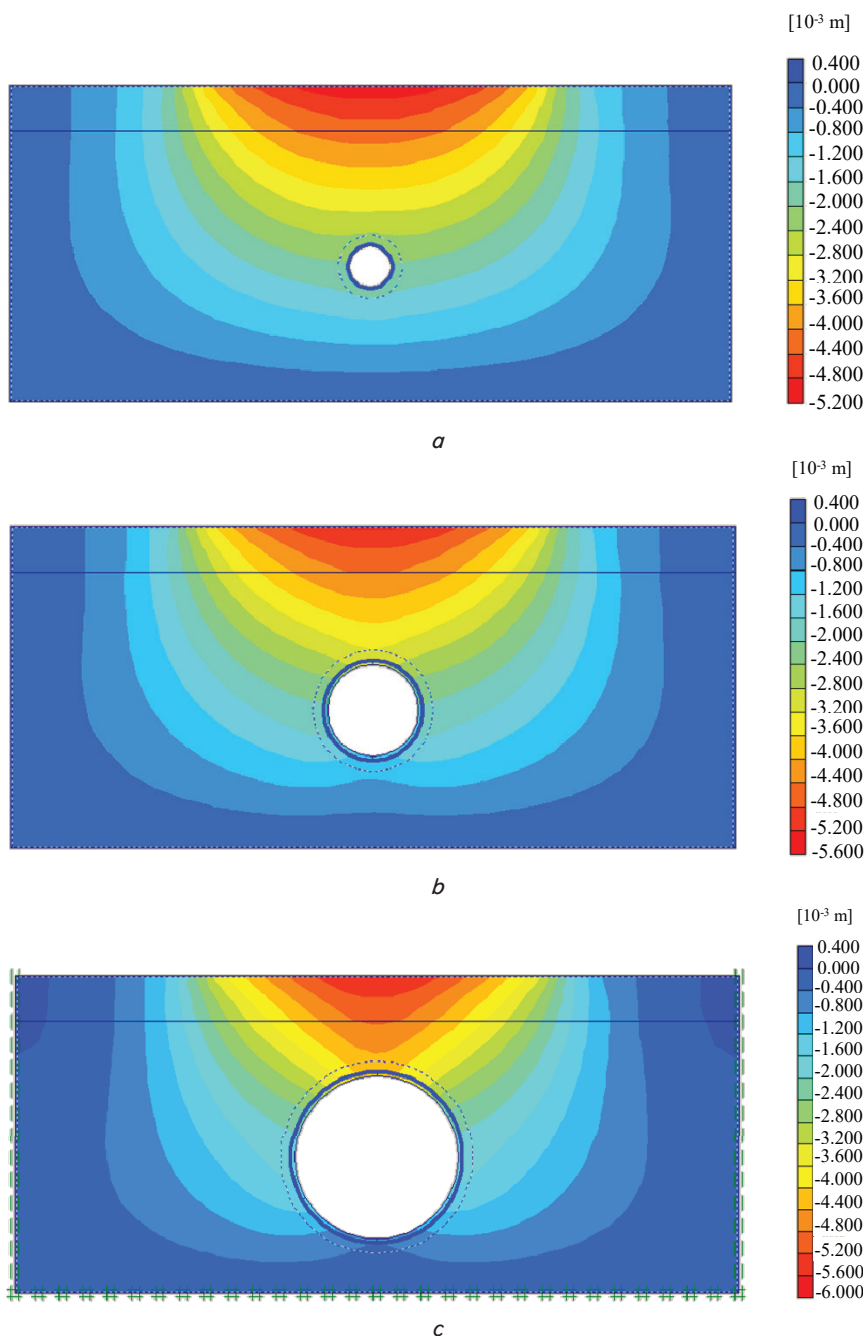


Fig. 6. Distribution of vertical deformations in subgrade with a fiberglass pipe of the following diameters: a – 1.0 m; b – 2.0 m; c – 3.6 m

Fig. 6 shows that the maximum vertical deformations of subgrade arise directly under the railroad rolling stock and are 1.0 mm for the diameter of the pipe of 5.2 mm; with a diameter of 2.0 m – 5.25 mm; with a diameter of 3.6 m – 6.0 mm.

The maximum vertical deformations of subgrade arising above the pipe, with a pipe diameter of 1.0 m, are 2.72 mm; with a diameter of 2.0 m – 2.94 mm; with a diameter of 3.6 m – 4.46 mm.

It is established that with an increase in the diameter of the fiberglass pipe, the value of deformations of the subgrade and fiberglass pipe increases. With a pipe diameter of 1.0 m, the value of deformations in the pipe vault is 2.72 mm, and with a pipe diameter of 3.6 m – 4.46 mm. At the same time, the value of deformations of the subgrade under a sleeper is 5.2 mm and 6.0 mm, respectively.

The results of the calculation of the deformed state in the horizontal direction of the subgrade with pipe diameters of 1.0 m, 2.0 m, and 3.6 m are shown in Fig. 7.

Fig. 7 shows that the maximum horizontal deformations of subgrade occur at points lying on the horizontal diameter of the pipe. They are 1.0 mm with a pipe diameter of 1.0 m; 1.2 mm – with a diameter of 2.0 m; and 1.93 mm – with a diameter of 3.6 m.

It should be noted that the isolines of vertical deformations are as tightly as possible at the top of the subgrade and above the pipe. The maximum concentration of horizontal deformation isolines is observed on the sides of the pipe. In fact, these areas of the railroad subgrade undergo the greatest deformations under the action of the railroad rolling stock.

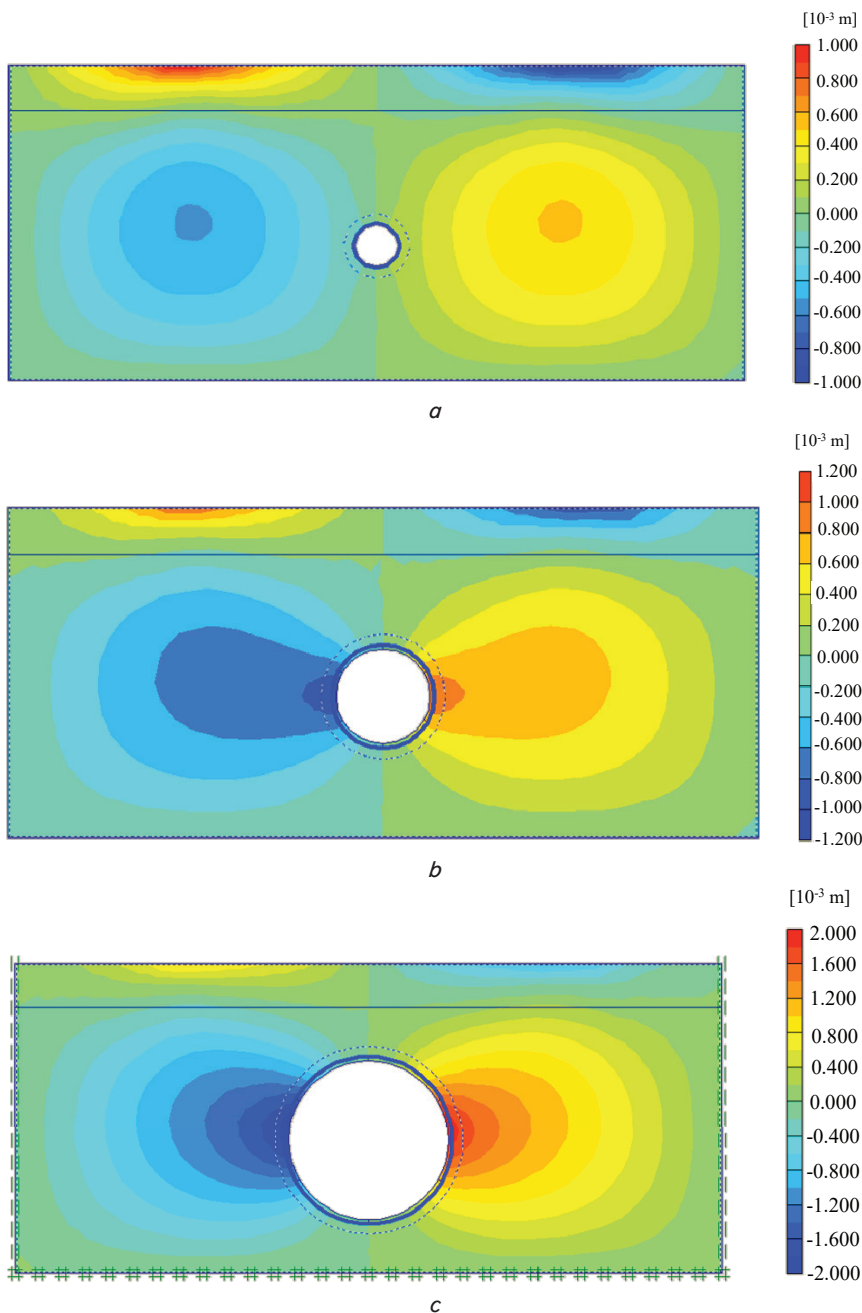


Fig. 7. Distribution of horizontal deformations in subgrade with a fiberglass pipe of the following diameter: a – 1.0 m; b – 2.0 m; c – 3.6 m

Consequently, the maximum vertical deformations of subgrade arise directly under the influence of the load at the top of the subgrade, and the maximum horizontal deformations of subgrade occur on the horizontal sides of the pipe.

Our numerical calculations have established that the maximum vertical deformations of railroad subgrade above a pipe under the action of load SK14 are 4.46 mm for a pipe with a diameter of 3.6 m. It should be noted that the maximum horizontal deformation of subgrade on the sides of the pipe is 1.93 mm.

**5. 3. Results of calculating the deformed state of the HOBAS fiberglass pipe**

The results of the calculation of deformations of the fiberglass pipe by the analytical method for the maximum diameter of the pipe of 3.6 m are given in Table 2.

Table 2

Deformed state of fiberglass pipes with a diameter of 3.6 m

Point No. (Fig. 4)	Deformation in the radial direction	Deformation in the tangential direction	Total deformation
1	3.06	0	3.06
2	1.73	2.6	3.12
3	0.175	2.24	2.25
4	0.756	0.63	0.985
5	0.637	0	0.637

Our calculations (Table 2) have established that the maximum deformations of the pipe occur at the top of the pipe and they are 3.06 mm; the minimum deformations of the pipe occur at the base of the pipe and they are 0.637 mm.

The results of calculating the stressed-strained state of fiberglass pipes by a finite-element method are given in Table 3.

Table 3

The deformed state of a fiberglass pipe derived by using a finite-element method

Point No.	Fiberglass pipe diameter, m					
	1.0	1.5	2.0	2.5	3.0	3.6
	Pipe deformation, mm					
1	2.12	2.45	2.88	3.28	3.78	4.16
2	2.01	2.44	2.55	2.69	2.84	3.21
3	1.64	1.75	1.89	1.91	2.08	2.45
4	0.87	1.02	1.11	1.21	1.28	1.37
5	0.15	0.19	0.26	0.32	0.37	0.54

It follows from our calculations of the deformed state of a fiberglass pipe using a finite-element method (Table 3) that with a decrease in the diameter of the pipe, the value of its deformation decreases. With the maximum possible diameter of the pipe of 3.6 m, the deformation value at the top (point 1) is 4.16 mm, whereas with a diameter of 3.0 m – 3.78 mm, diameter 2.5 m – 3.28 mm, diameter 2.0 m – 2.88 mm, diameter 1.5 m – 2.45 mm, and diameter 1.0 m – 2.12 mm.

The maximum deformation of the fiberglass pipe is at the top of the pipe (point 1). Further, the values of the deformations of the pipe on the radial coordinate are reduced and, at the base of the pipe, reach the lowest value. With a pipe diameter of 3.6 m, the values of the pipe deformation at the

top (point 1) are 4.16 mm, at point 2 – 3.21 mm, at point 3 – 2.45 mm, at point 4 – 1.37 mm, and at the base of the pipe (point 5) – 0.54 mm.

Our study of the deformed state of a fiberglass pipe has shown that the maximum vertical deformation of the pipe does not exceed the allowable amount of bending deformation, which is 2.2 % [1]. Thus, for a pipe with a diameter of 3.6 m, the allowable deformation is 79.2 mm, which is much larger than the calculated value of 4.16 mm.

Thus, it can be argued that fiberglass pipes have a large reserve of bearing capacity under the action of railroad rolling stock and, accordingly, can be used in the design of a railroad track.

**6. Discussion of results of assessing the stressed-strained state of transport structures “embankment-fiberglass pipe”**

A flat rod model has been improved to assess the deformed state of fiberglass pipes. To this end, the cross-section of the pipe is represented in the form of a regular octagon, in the nodes of which there are radial and tangential ligaments that simulate the interaction of the pipe with the subgrade. To take into consideration the interaction of the pipe with the soil, radial and tangential elastic ligaments are introduced into the estimation scheme, which make it possible to simulate elastic soil pressure, as well as friction forces arising from soil contact with the structure. This approach most accurately corresponds to the actual working conditions of fiberglass pipes under the action of transport load.

It should be noted that for the correct physical nature of the soil, it is necessary to exclude radial ligaments from consideration when stretching efforts appear in them.

The nature of the deformation of a fiberglass pipe demonstrates that the pipe decreases in the direction of vertical diameter with an increase in its horizontal size. This, in turn, leads to deformations of subgrade on the sides of the pipe (Fig. 6, 7). With a pipe diameter of 1.0 m, the value of horizontal deformations of the subgrade is 1.0 mm, with a diameter of 2.0 m – 1.2 mm, and with a diameter of 3.6 m – 1.93 mm.

The maximum vertical deformations of subgrade arise directly under the railroad rolling stock and are, for the diameter of the pipe of 1.0 m – 5.2 mm, with a diameter of 2.0 m – 5.25 mm, and with a diameter of 3.6 m – 6.0 mm. At the same time, the maximum vertical deformations of subgrade arising above the pipe with a pipe diameter of 1.0 m are 2.72 mm, with a diameter of 2.0 m – 2.94 mm, and with a diameter of 3.6 m – 4.46 mm.

The results of our calculation of deformations of a fiberglass pipe showed that with a pipe diameter of 3.6 m, the value of the deformation of the pipe at the top is 4.16 mm, whereas with a diameter of 3.0 m – 3.78 mm, diameter 2.5 m – 3.28 mm, diameter 2.0 m – 2.88 mm, diameter 1.5 m – 2.45 mm, and diameter 1.0 m – 2.12 mm.

It should be noted that the maximum deformation values are reached by a fiberglass pipe at the top. Further, the values of the pipe deformations on the radial coordinate are reduced and, at the base of the pipe, reach the lowest value. Thus, with a pipe diameter of 3.6 m, the values of the pipe deformations at the top (point 1) are 4.16 mm, at the point 2 – 3.21 mm, at the point 3 – 2.45 mm, at the point 4 – 1.37 mm, and at the base of the pipe (point 5) – 0.54 mm.

Our study into subgrade deformation (Fig. 6, 7) has revealed that the maximum deformations of the subgrade occur with a pipe diameter of 3.6 m. It is established that with the decrease of the pipe diameter, the deformations of the subgrade and fiberglass pipe decrease.

Our study of the deformed state of a fiberglass pipe has demonstrated that the obtained maximum deformations of 4.16 mm when calculating a pipe with a diameter of 3.6 m are less than the permissible ones (79.2 mm). This allows us to conclude that fiberglass pipes have a large reserve of bearing capacity when exposed to railroad rolling stock, so it is recommended to use them on railroad tracks.

One of the limitations of the present study is a two-dimensional method for calculating the deformed state of the transport structure “embankment-fiberglass pipe”. It should also be noted that the improved analytical model for assessing the deformed state of fiberglass pipes is suitable for calculating fiberglass pipes with a maximum diameter of 3.6 m. When using the model to calculate pipes with a cross-section greater than 3.6 m, additional research is required.

Building on methods for using a spatial mathematical model in calculating the deformed state of fiberglass pipes is a promising direction for further research work.

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## 7. Conclusions

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1. To determine the deformed state of flexible fiberglass water pipes placed in the body of railroad embankment, we have improved a flat rod model by replacing the transverse round section of the pipe with a polygonal one. To take into consideration the interaction of the pipe with the soil of backfilling, radial and tangential elastic ligaments are introduced into the estimation scheme, which make it possible to

simulate elastic soil pressure, as well as friction forces arising from soil contact with the structure. This most accurately corresponds to the actual working conditions of fiberglass pipes under the action of railroad rolling stock.

2. It has been established that with the vertical and horizontal deformation of a fiberglass pipe in the subgrade of the railroad line, deformations occur. With a pipe diameter of 1.0 m, the value of the maximum horizontal deformations of the subgrade was 1.0 mm, with a diameter of 2.0 m – 1.2 mm, and with a diameter of 3.6 m – 1.93 mm. The maximum vertical deformations of the subgrade above the pipe with a pipe diameter of 1.0 m were 2.72 mm, with a diameter of 2.0 m – 2.94 mm, and with a diameter of 3.6 m – 4.46 mm. It has been determined that the maximum vertical deformations of the subgrade arise directly under the railroad rolling stock. With a pipe diameter of 1.0 m, the deformation is 5.2 mm, with a diameter of 2.0 m – 5.25 mm, and with a diameter of 3.6 m – 6.0 mm.

3. The results of our studies into the deformed state of a fiberglass pipe have shown that with a decrease in the diameter of the pipe, its deformations decrease. The maximum deformation of the pipe is obtained with the largest diameter of the pipe of 3.6 m, produced by the plant manufacturer of fiberglass pipes Hobas GRP. The values of pipe deformations at the top (point 1) are 4.16 mm, at point 2 – 3.21 mm, at point 3 – 2.45 mm, at point 4 – 1.37 mm, and at the base of the pipe (point 5) – 0.54 mm. Our study of the deformed state of a fiberglass pipe has demonstrated that the obtained maximum deformations of 4.16 mm when calculating a pipe with a diameter of 3.6 m are much smaller than the permissible ones (79.2 mm). This allows us to assert that fiberglass pipes have a large reserve of bearing capacity when exposed to the railroad rolling stock and to recommend them for use on railroad tracks.

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