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SIMULATION OF THE STRENGTH OF TWO-LAYER PIPE STRUCTURES IMPLEMENTED IN THE TRENCHLESS REPAIR METHOD AND ASSESSMENT ITS ENERGY SAVING DURING WATER SUPPLYING

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Abstract. The article proposes approaches for assessing the strength characteristics of two-layer pipelines formed as a result of using a trenchless method for the reconstruction of dilapidated steel pipeline networks by pulling pipes made of unplasticized polyvinyl chloride (UPVC) into them. The results of simulation of filling the annular space between steel and polymer pipes are presented with an analysis of the three states of a two-pipe system in order to ensure strength characteristics. The paper provides an analysis of the possibility of saving energy when using PVC-U pipes in a two-layer pipe structure at various temperatures of supplying water and a stable temperature of the pipeline wall. Besides, it proposes the introduction of a set of developed automated programs for design.

Keywords: underground pipelines, reconstruction, strength analysis, simulation, automated programs, energy saving

МОДЕЛИРОВАНИЕ ПРОЧНОСТНЫХ ХАРАКТЕРИСТИК ДВУХСЛОЙНЫХ ТРУБНЫХ КОНСТРУКЦИЙ ПРИ РЕАЛИЗАЦИИ БЕСТРАНШЕЙНОГО МЕТОДА РЕМОНТА С ОЦЕНКОЙ ЭНЕРГОСБЕРЕЖЕНИЯ ПРИ ТРАНСПОРТИРОВКЕ ВОДЫ

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Аннотация. Предложены подходы к оценке прочностных характеристик двухслойных трубопроводов, образующихся в результате использования бестраншейной технологии реконструкции ветхих стальных трубопроводных сетей путем протаскивания в них труб из непластифицированного поливинилхлорида (НПВХ). Представлены результаты моделирования процесса забутовки межтрубного пространства между стальной и полимерной трубами с анализом трех состояний двухтрубной системы на предмет обеспечения прочностных характеристик. Выполнены расчета и представлен анализ возможности экономии электроэнергии при использовании труб из НПВХ в двухслойной трубной конструкции при различных температурах транспортируемой воды и стабильной температуре стенки трубопровода с предложениями внедрения комплекса разработанных автоматизированных программ при проведении проектных разработок.

Ключевые слова: подземные трубопроводы, реконструкция, прочностные расчеты, моделирование, автоматизированные программы, энергосбережение

INTRODUCTION

The situation in the field of underground pressure pipelines of water supply systems both in our country and abroad remains very difficult, since almost half of their total number needs to be repaired or replaced (modernized) [1]. This brings the problems of prompt restoration of aging pipeline networks and increasing the reliability of their operation. The ensuring of the strength and hydraulic characteristics required by the project play a dominant role when using various types of repair materials [2, 3].

The trenchless method of reconstruction is the most effective one in terms of saving material and monetary costs, as well as the efficiency of performing restoration work on dilapidated pipeline networks made of various materials that is worn-out structure with reduced deformation and strength characteristics. This method allows not only to eliminate existing defects in the pipeline network, but also to increase their throughput [4, 5]. One of the most popular methods for the reconstruction of aged pipelines in a trenchless way is the pulling and fixing of new pipelines made of polymeric materials into them. That allows obtaining a two-layer pipeline with the required technical indicators, which include, first of all, the high strength characteristics of the new two-pipe structure, as well as the possibility of energy saving during fluid motion due to relatively small specific resistances [6]. However, among the many modern polymeric materials used for the manufacture of pipes (polyethylene, polybutylene, polypropylene, polyvinyl chloride, etc.), it becomes necessary to choose one that has a number of advantages compared to others, in particular, to ensure the required strength characteristics of a new double-pipe structure, lower coefficient of linear elongation, energy savings when supplying liquids, durability and other factors [7]. Such materials include unplasticized polyvinyl chloride (UPVC). The PVC-U pipe dragged into the dilapidated pipeline after the operations of backfilling the annular space with mortars in order to increase the load capacity of the new two-layer pipe structure. Another actual task is introducing electronic models for assessing the integrated operation of water supply systems, including water supply networks and their repair by various methods with the achievement of the energy saving effect [8, 9].

SIMULATION APPROACHES FOR THE STRENGTH CHARACTERISTICS OF TWO-LAYER UNDERGROUND PIPE STRUCTURES.

The pressure pipes manufactured by Chemkor JSC from non-plasticized polyvinyl chloride (UPVC) made in accordance with GOST 32415-2013 and used both for open laying and restoring the performance of dilapidated supplying networks from various materials using trenchless technology for pulling new pipes into the aged pipeline with the formation of a two-layer structure were the materials for research. The low value of the resistivity coefficient of the internal walls of AUPVC = 0.0008d-5.1977 (where d is the diameter of the pipeline in m), as well as a 2.5 times lower coefficient of linear extention compared to traditional ones for use in trenchless technologies repair of pipelines with polyethylene pipes. It reduces the likelihood of a significant curvature of the new pipeline in the old one under the influence of ambient temperature and the supplied liquid. However, this does not exclude the filling of the annular space, which guarantees the provision of the required strength indicators (load capacity) of the two-pipe structure.

The paper provides the methods of computer simulation of the strength characteristics of two-layer pipe structures during the implementation of repair work using the trenchless approach, as well as an assessment of the possibility of energy saving when supplying water through a two-layer pressure system after repair work.

The process of simulation of strength characteristics consists of applying the algorithm developed by the authors of the article and an automated computation program, which analyzes the static and dynamic components of

ensuring the load capacity of the restored pipeline system [10]:
- the strength of the PVC-U pipe, pulled in the aged pipeline;
- allowable deformations of the diameter of the new pipeline in the aged one under the influence of mortars filling the annular space, i.e., compliance with the conditions for not exceeding the degree of ovalization of the circular cross-section of the pipe by a value of not more than 5% in diameter;
- the probability of the PVC-U pipe floating due to the Archimedean force and thereby eliminating the negative case of its support on the inner surface (hard arch) of the old pipeline, which can provoke the early appearance and propagation of cracks near point loads and increase the abrasion of the walls of the new pipeline [11].

Figure 1 shows a cross-sectional diagram of the repair two-layer pipe structure.

The most popular in practice mortars on gravel or crushed stone with a density of 24,000 N/m^3 and, as an alternative, a cement-slag mortar with a density of 8,000 N/m^3, were considered as mixtures used for backfilling during the simulation period. The tasks of modeling, in particular, included the determination of the loads that counteract the mixture. These loads act on the PVC-U pipe with various options for filling the annular space (uniform or uneven) with mortar.

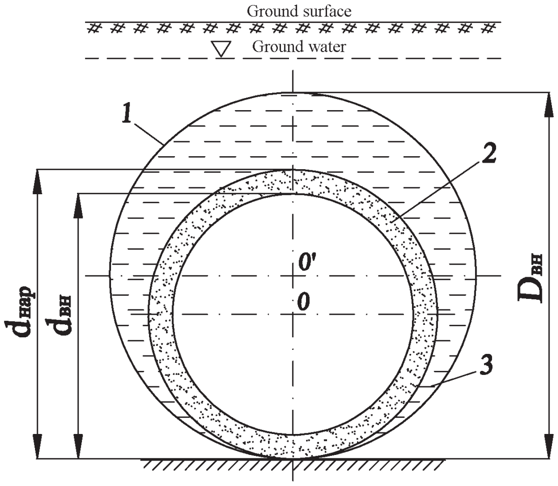

Figure 1. Cross section of a repair pipeline with backfilling of the annulus with mortar
1 - the inner wall of the aged pipeline renovated with an internal diameter D_{in}.; 2- PVC-U pipeline with outer diameter d_{out} and inner diameter d_{in}; 3- mortar in the annulus

Table 1 presents the values of the initial parameters of the input information for one of the considered examples of automated simulation.

Table 1. Initial information for strength calculation

Number	Names of parameters and their designation	Values
1.	Inner diameter of the pipeline to be renovated, D_{in}, m	0.6
2.	Diameters of the new pipeline being pulled into the aged one, - *d* external, m - *d* internal, m	 0.476 0.452
3.	Volume weights, N/m^3 - cement mortar *g cm* - pulled pipe *gpp* - supplying liquid (water) *gw*	 24000.0 9500.0 9800.0
4.	The internal pressure of the supplied medium, corresponding to reduced design stresses *P*, *MPa*	0.0
5.	The value of the possible vacuum in the annulus *Pvac*, *MPa*	0.0
6.	Standard service life of the pulled pipeline *t*, years	50.0
7.	Maximum operating temperature of the pulled pipeline *T,°C*	20.00

8.	Characteristic long-term strength of the pipe material (depending on the values of t and T) *R*ch, *MPa*	5.0
9.	Depth of the pipeline from the ground *H*, m	10.00
10.	The value of groundwater pressure on the arch of the pipeline *Pgw*, *MPa*	0.02
11.	Coefficients: - laying conditions k_1 - stability of the pulled pipeline k_2 - working conditions k_y - joint strength k_c 0.90 - influence of temperature on the deformation properties of the material k_e - load distribution and support reaction of the base z	 0.80 0.60 0.60 0.90 0.80 1.30
12.	Maximum permissible value of ovalization of the cross section E, %	5.000
13.	Creep modulus of the pipe material in tension (depending on the values of t and Rch) *E*o, *MPa*	100.0
14.	Backfill deformation modulus, depending on the backfill material *Eg* , *MPa*	0.50

According to the results of the field survey, the aged pipeline under operation is a worn-out structure with reduced deformation and strength characteristics. It is necessary to strengthen the pipe structure operating in these conditions which consists of separate modules of PVC-U socket pipes connected in series. The pipe pulled into the dilapidated pipeline should ensure increase the load capacity of the two-layer pipe structure and be a barrier against the phenomena of groundwater infiltration into the pipeline body and exfiltration of the transported water into the annulus after the operations of filling the annular space with mortars.

Below, paper provides examples of automated calculations and their interpretation based on the results of the reconstruction of an aged pressure steel pipeline with an internal diameter of 600 mm for two selective options for the diameters of PVC-U pipes from among the available products in the range of Chemkor JSC:

- PVC-U SDR 41-500, having a socket with a diameter of 549 mm, an inner diameter of 475 mm and an outer diameter of 487 mm (hereinafter, the term SDR refers to the ratio of the pipeline diameter to its wall thickness);
- PVC-U SDR 21-500, having a socket with a diameter of 578 mm, an inner diameter of a pipe of 452 mm and an outer diameter of 476 mm.

Thus, the pipes presented above differ in wall thickness (for the first example 12 mm and for the second one 24 mm), i.e., it is conventionally considered as thin-walled and thick-walled.

Additional information includes the following: the maximum allowable water pressure in the pipeline is 0.8 MPa;

The significant depth of the pipeline of 10 m (see Table 1) was chosen as extreme one, i.e., it guarantees that compliance with (not exceeding) the basic values of the design parameters will be ensured due to a certain margin of safety at a lower pipe penetration. In addition, it should be noted that a prerequisite for the implementation of the method for pulling new pipes into the old one and backfilling it is performing of preliminary dewatering using wellpoints when there is groundwater above the pipeline.

Table 2 presents the results of automated calculation for two selective pipe options.

Table 2. Summary output information on the results of the strength analysis of two-pipe structures when mortar with a density of 24000 N/m³ is used for backfilling

Name of design indicators of bearing capacity	uPVC pipe	
	SDR 41-500	*SDR* 21-500
1. By strength to the effect of internal water pressure, MPa	0,8	0,8
2. According to the maximum permissible ovalization (deformation) of the cross section of the pipeline, %:		
- for the case of uniform filling of the annular space in the absence of water in the pipeline	13,398	3,438
- the same if there is water in the pipeline	7,073	1,778
- for the case of uneven filling of the annular space in the absence of water in the pipeline	11,309	3,055
- the same if there is water in the pipeline	9,1214	2,526
3. On the stability of the round shape (profile) of the pipeline being pulled to the ascent through the value of the radial pressure on the pipe walls, MPa:		
- for the case of uniform filling and the absence of water in the pipeline	0,019	0,021
- the same if there is water in the pipeline	0,026	0,027
- for the case of uneven filling of the annular space in the absence of water in the pipeline	0,045	0,044
- the same if there is water in the pipeline	0,043	0,043

Analysis of the data presented in Table 2 shows that both pipelines are able to withstand the established pressure standards (0.8 MPa) according to the first condition. There are some discrepancies in terms of the second and third conditions. In particular, ovalization exceeds the established standards by 5% for the PVC-U SDR 41-500 pipeline, and it remains within the normal range for the PVC-U SDR 21-500 pipeline. A similar trend is observed when analyzing data for the third condition, where the value of the radial pressure on the pipe walls for various cases exceeds or does not exceed the critical values. In particular, the ascent resistance has been provided only for the case of uniform backfilling and the absence of water in the pipeline for the PVC-U SDR 41-500 pipe, since in this case the radial pressure on the pipeline walls is 0.019 MPa, i.e., less than critical one which is 0.0254 MPa. The ascent stability is not respected for another cases. According to the third condition, the standards are observed in all cases for PVC-U pipe SDR 21-500, since the critical pressure is 0.074 MPa according to the calculation.

Thus, the option of pulling PVC-U SDR 41-500 pipes into an old pipeline with backfilling of the annular space using trenchless method cannot be considered acceptable due to the relatively small thickness of the pipe wall.

As noted above, the strength characteristics of a two-pipe system were analyzed using a cement-slag mortar with a density of 8000 N/m3 as an alternative backfilling option. This circumstance was due to the fact that the practical application of the option of pulling PVC-U SDR 21-500 pipes into the old pipeline with filling with mortar with a density of 24,000 N/m3 can lead to relatively large deformations of the pipeline cross-section (in the range of 1.778-3.438) as presented in Table 2.

The calculations which have been performed using an automated program showed that a lighter construction backfilling material allows reducing the probability of ovalization of the pipeline cross section according to the second strength condition for 4 cases under consideration to values of 0.924, 0.735, 0.961 and 1.4638%, respectively. This will affect positively on the durability of the restored two-pipe structure. In addition, all cases also have positive results of 0.029, 0.036, 0.037 and 0.038 MPa, respectively, at a critical pressure of 0.077 MPa according to the third strength condition for checking the stability of a two-pipe structure for ascent.

An intermediate conclusion on the analysis of the results of automated calculation is a recommendation for the use of pipe modules made of PVC-U SDR 21-500 for the reconstruction of an old steel pipeline with backfilling of the annular space with cement-slag mortar.

ASSESSMENT OF THE ELECTRICITY SAVING WHEN USING PVC-U PIPES FOR WATER SUPPLYING DEPENDING ON TEMPERATURE CONDITIONS.

At the present stage of development of underground infrastructure, design, construction, reconstruction and modernization of pipeline transport should be based not only on creating conditions for the strength of structures and their durability, but also on ensuring energy saving during their operation. and, if possible, managing the process of water supplying to achieve an economic effect.

The calculation of electricity consumption E (kWh per year) at water supplying through pressure pipelines made of various materials, as a rule, is performed using the universal formula (1):

$$E=[9,81Q^3(A_i \cdot l)/\eta_{pump..}]\cdot 24\cdot 365, \qquad (1)$$

where Q is the supplying water consumption, m^3/s; A_i is the coefficient of specific resistance of the pipeline wall material c^2/m^6; l is the pipeline length, m; $\eta_{pump.}$ is the efficiency of the pumping unit; 24 and 365 are the number of hours in a day and days in a year, respectively.

The presented universal formula does not fully reflect the needs of designers and operating personnel of water utilities when they applied it tothe reconstruction an old pipeline by creating a two-layer pipe structure "steel + PVC-U", since it does not consider temperature conditions, in particular, the temperature of the supplied water. Previously, it was found that the coefficient of hydraulic friction λ of pipelines depends on the temperature of the supplied water and, accordingly, the pipe walls [12]. With an increase in temperature, the value of λ decreases due to a decrease in the viscosity of water, which ultimately creates the possibility of saving energy during the water supplying.

The basic calculation formula for determining the cost of electricity accounting the coefficient of hydraulic friction λ, has the form (2):

$$E=0,81\cdot Q^3\cdot l\cdot \lambda\cdot 24\cdot 365/(d^5\cdot \eta_{pump.}), \qquad (2)$$

where d is the internal diameter of the pipeline, m.

Thus, formula (2) allows calculation when a certain inner diameter of the pipeline d and the coefficient of hydraulic friction λ are involved.

A specially developed automated calculation program [13] has been used in order to analyze the consumption of electricity during water supplying. The program allows you to calculate the hydraulic and energy parameters of the pressure pipeline in a wide temperature range. At the same time, the previously identified ranges of restrictions on the recommended range of Reynolds numbers and the ratio of dynamic viscosities related to the fluid flow and the pipe wall, respectively, were observed in the algorithm of the automated calculation program which accounts the non-isothermal movement of fluid in pipes [14].

Computer simulation has been carried out in order to assess the effect of water temperature and the pipeline wall on electricity consumption. We accepted PVC-U pipes for trenchless repair of a dilapidated steel pipeline, and the central areas of the Russian Federation as the place for repair work.

The initial parameters entered into the calculation program were as follows:
- depth of occurrence of the restored pipeline of a two-layer structure "steel + PVC-U SDR 21-500" 1.6 m;
- the length of the pipeline is 3000 m;
- average temperature of the pipeline wall (soil around the pipe) 15.50 C;
- water intake by a pumping unit is carried out from a surface reservoir from a depth of 10 m;
- average water temperature 22.10 C (summer) and 80 C (winter);
- consumption of transported water 0.15 m^3/s;
- efficiency of the pumping unit 0.9.

Table 3 presents summary output information on individual parameters of the calculated parameters of the summer and winter periods.

Table 3. Summary output information based on the results of hydraulic and energy analysis of a two-pipe structure in summer and winter periods

Calculated indicators	Indicator values	
	Summer	Winter
1. Water flow rate in the pipeline, m/s	0.9348	0.9348
2. Dynamic viscosity coefficient related to fluid flow, Pa*s	0.0009703	0.0014065
3. Dynamic viscosity coefficient related to pipe wall temperature, Pa*s	0.0011461	0.0011461
4. Ratio of dynamic viscosities	0.847	1.227
5. Fluid kinematic viscosity coefficient, m2/s	0.00000094	0.00000138
6. Reynolds number	449597.47	306279.24
7. Estimated coefficient of hydraulic friction	0.013787	0.013819
8. Electricity consumption through the coefficient of hydraulic friction, kWh per year	58333.698	58470.157
9. Electricity consumption through the coefficient of resistivity, kWh per year	47962.585	47962.585

An analysis of the calculated data presented in Table 3 for items 8 and 9 is typical for the following two conclusions.

Firstly, electricity consumption in winter increases by 58470.157-58333.698=136.459 kWh per year compared to summer according to the calculations in 8 for the summer and winter periods. With an average cost of 1 kWh of electricity of 9.13125 rubles (at the current time), the savings is 136.459x9.13125=1246.04 rubles per year.

Secondly, a comparison of the values of electricity consumption in 8 and 9, i.e., considering the temperatures of the water and the pipeline wall and without it, shows a significant discrepancy. For example, the difference in electricity consumption is 58470.157-47962.585=10507.572 kWh per year, or 17.97% less for the winter period. This leads to the conclusion that designing, requires considering temperature factors in order to obtain the most probable values of electricity consumption, i.e., it is necessary to include data on the temperature parameters of the pipeline wall and transported water in projects for the construction of pipeline networks and to carry out calculations of electricity consumption. This is facilitated by simulation, which allows identification of the optimal parameters for controlling the process of water transportation based on the search for the minimum values of electricity consumption. Using the capabilities of the automated program, it is possible to calculate the cost of electricity in a wide range of temperatures of the pipe wall (of the appropriate material and diameter) and transported water for both northern and southern regions at various values of water flow rates and efficiency values of pumping units.

COMCLUSIONS

1. The simulation of the strength characteristics of two-layer pipe structures using an automated program allowed determination of parameters that allow choosing the most acceptable technical solutions for filling the annular space with mortars from alternative options.
2. The values of the permissible ovalization (deformation) of the cross section of the new pipeline dragged into the old pipeline, as well as its resistance to ascent under various conditions through the magnitude of the radial pressure of the mortar on the pipe walls, are proposed as criteria for comparing the options for filling the annular space with mortars.
3. The article substantiated the application of new PVC-U SDR 21-500 pipes during the period of trenchless repair of an old steel pipeline for specific design conditions. This approach has a number of positive properties compared to other polymer pipes, and use cement-slag mortar as a material for backfilling the annular space, which provides less deformations of the cross section of new pipes.
4. An example of designing an underground pressure pipeline network for the conditions of the middle area of the Russian Federation, based on the results of automated calculations, presented the values of saving energy costs for transporting water under various temperature conditions. This allows performing managerial functions of the operation of pipelines from various materials and diameters, varying costs of transported water and the type of pumps used, and during operation to monitor the real effect of reducing cash costs at the stage of design.

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