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DIGITAL TOOLS IN THE DESIGN PRACTICE FOR RECONSTRUCTION OF UNDERGROUND PIPELINES WITH TRENCHLESS METHODS

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Abstract. The article focuses on the possibilities of multi-optional design of repair and rehabilitation works on dilapidated pressure pipeline networks with the use of automated complexes in order to achieve minimum energy costs in water transportation with regard to the temperature factor. Two automated programs based on hydraulic and energy calculation operations are presented as digital tools. As a basic variant of reconstruction of dilapidated pipelines, the trenchless Swagelining technology was accepted. It is realized by pulling pre-compressed polymer pipes into old pipelines with their subsequent straightening. The paper presents information on regulatory and technical documentation and the application of advanced technology, installation and operation conditions, as well as comparative assessment of energy consumption after reconstruction of dilapidated sections of pipelines with polymer pipes with the possibility of minimizing energy consumption during water transportation under non-isothermal conditions of pipeline operation.

Keywords: automated programs, pipelines, temperature conditions, hydraulic characteristics, trenchless technologies, energy consumption

ИНСТРУМЕНТЫ ЦИФРОВИЗАЦИИ В ПРАКТИКЕ ПРОЕКТИРОВАНИЯ ПРИ РЕКОНСТРУКЦИИ ПОДЗЕМНЫХ ТРУБОПРОВОДОВ БЕСТРАНШЕЙНЫМИ МЕТОДАМИ

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Аннотация. В статье рассматриваются возможности многовариантного проектирования ремонтно-восстановительных работ на ветхих напорных трубопроводных сетях с помощью автоматизированных комплексов в целях достижения минимальных энергетических затрат при транспортировке воды с учетом температурного фактора. В качестве инструментов цифровизации представлены две автоматизированные программы, в основу которых заложены операции по гидравлическим и энергетическим расчетам. За базовый вариант реконструкции ветхих трубопроводов принята бестраншейная технологии Swagelining, реализуемая путем протаскивания в старые трубопроводы предварительно сжатых полимерных труб с последующим их распрямление. Представлены сведения по нормативной и технической документации и области применения передовой технологии, условиям монтажа и эксплуатации, а также сравнительной оценки энергопотребления после реконструкции ветхих участков трубопроводов полимерными трубами с возможностью минимизации энергозатрат при транспортировке воды в условиях неизотермического режима работы трубопровода.

Ключевые слова: автоматизированные программы, трубопроводы, температурные условия, гидравлические характеристики, бестраншейные технологии, энергопотребление

INTRODUCTION

In recent years, Russia has seen an intensification of the digitalization process, as evidenced by the federal project "Digital Public Administration" proposed by the Ministry of Digital Development, Communications and Mass Media. This project includes the automation of all stages of the real estate life cycle from design to operation of buildings and structures. The most important achievement of digitalization is the possibility of implementing multi-optional design in the field of water supply and sanitation [1]. At the same time, the practice of construction and reconstruction of underground pipelines using numerous operational and cost-effective trenchless methods can be considered as a particular very significant aspect [2].

Currently, more than 40% of underground steel pipeline networks of water supply systems on average in the Russian Federation require prompt repair due to aging, accompanied by the appearance of various kinds of defects (damage) in the form of through holes (fistulas), corrosion of internal walls of pipelines, divergence of welds, thinning of walls and thus violation of load-bearing capacity [3].

Restoration of pipelines consists of a set of technical measures to improve the functional properties of the existing pipeline with full or partial use of its structure [4]. Pipeline damage leads to water leakage and negative phenomena of groundwater level rise above the pipeline network, which leads to a decrease in the porosity of the soil mass and suffusion failures.

According to the standard service life, steel pipes should be used for 20 years. However, they fail much earlier due to the above-mentioned damages, exhausting their resource. Emergencies associated with the failure of dilapidated and obsolete engineering networks in Russian cities account for 31% of the total number of emergencies, which is second only to fires and explosions, which account for 34% [5].

If we talk about pipelines of domestic and drinking water supply, a big problem is the deterioration of organoleptic properties of water supplied to consumers. Despite the fulfillment of regulatory requirements for water treatment technology at water treatment plants, the consumer receives water with significantly inferior quality indicators due to numerous pipe defects [6]. In addition, the flow velocities in previously designed water supply networks decrease due to the increased roughness of their walls due to various deposits, which affects the deterioration of organoleptic indicators of water related to sanitary and hygienic parameters that characterize the optimal conditions of human activity [7, 8].

Reliable performance of pipeline networks under construction and reconstruction can be ensured if designers take into account the hydraulic performance of pipes and of new materials. There is a need for accurate data on their hydraulic characteristics, which can be found both in industry standards and technical documents and in business models [9].

There are also on the agenda the issues of effective management of electricity consumption in water transportation [10]. Electricity consumption in liquid transportation systems mainly depends on the power and efficiency of the pump units used, as well as on the optimal selection of the cross-section of pipeline networks, reduction of local resistance and head losses along the length of pipelines [11]. It follows that the key aspects in the design of new pipeline systems, as well as in the renovation (modernization) of dilapidated pressure pipelines is to ensure their appropriate energy performance, providing conditions for long-term and energy-efficient operation of pipeline communications [12].

Researchers repeatedly note not only the need to use pipelines with low roughness, but also to take into account the temperature factor, which affects the change in electricity consumption during water transportation. [13].

A number of investigators consider a promising and necessary measure for effective management of water supply networks (in particular, flow distribution at certain temperature ranges during the implementation of repair and rehabilitation works) a wide application of automated computer complexes with various subsystems [14].

The effects of resource and energy saving are achieved by applying trenchless pipeline repair technologies. In particular, it includes the technology of repair by preliminary thermomechanical compression of polymer pipes and pulling them into old pipelines (Swagelining), as well as the quality indicators of transported drinking water are preserved by increasing its flow velocities [15].

Modern urban construction is impossible without utilization of the underground space of the city. Placement of all transporting routes of underground engineering systems is limited by residential buildings and transportation routes. Especially acute is the issue of accessibility of communications during repair works. To date, about 50% of engineering networks of various materials need to be replaced or restored. This only increases the urgency of solving this issue and the need to search for new methods of laying and reconstruction [16].

In some municipal districts of the Russian Federation, such as Podporozhsky and Volkhovsky in the Leningrad region, 62.8 and 84.2% of pipelines of water supply networks are in need of capital repair, respectively [17].

Lack of prompt measures to improve the efficiency, serviceability and renovation of underground water pipelines aggravates the situation with numerous negative consequences for the population and the natural environment. Water supply networks should provide a guaranteed physical barrier against contamination of the supplied water and maintain the required sanitary and hygienic indicators in it [18].

The application of traditional methods for reconstruction can be problematic under the modern urban development and traffic intensity, bring great inconvenience and financial costs.

METHODS AND MATERIALS

The study focuses on one of the numerous technologies for renovation of dilapidated pipelines using polymer pipes. These pipes are subjected to thermomechanical compression with subsequent straightening in the reconstructed pipeline after being pulled into the dilapidated existing pipeline (Swagelining).

The research method is the analysis of the results of automated calculation of electricity consumption during water transportation with different ambient temperature conditions, as well as identification of the most economical variant from among the alternatives for saving electricity costs during water transportation through reconstructed pipelines with different diameters and SDR values (Standard Dimensional Ratio, that is diameter to wall thickness ratio).

Two automated calculation programs were used to achieve the above objectives [19, 20].

Swagelining method is used for trenchless repair of all types of pipeline networks: pressure, gravity, underground, surface. The method is applicable for reconstruction of pipelines with diameter from 100 to 1200 mm with the length of the repaired section up to 1000 m.

The technology allows fast installation of polymer pipe of larger diameter into old pipelines of smaller diameter due to its preliminary thermomechanical compression. Thus, a new pipe, tightly pressed to the inner surface of the main pipe and superior to the latter in a number of characteristics, is formed inside worn-out pipelines during rehabilitation. In this way, the pipeline acquires a two-layer construction and is an independent structure. The tight fit of the new polymer pipe to the walls of the old pipeline creates conditions for a very slight reduction in its diameter with a simultaneous reduction in the coefficient of hydraulic friction, i.e., ensuring the energy-saving effect in water transportation.

Swagelining sanitized pipes have successfully passed tests for rapid crack localization during operation (a series of tests were conducted for more than 5000 hours) on fracture and temperature tests with a notch at +80 C.

The Swagelining method was applied for the reconstruction of 3.5 km of water supply networks in Moscow.

The advantages of the Swagelining method also include the possibility of providing such an internal diameter of the reconstructed pipeline system, at which through varying the value of SDR water flow velocities correspond to the design ones for drinking water supply systems (i.e. about 1 m/s). This measure leads to preservation of organoleptic characteristics of water.

The technology includes the process of compression of the pipeline, preheated to a temperature of 70-80 C (Figure 1). A conical matrix ensures that the pipeline is narrowed so that it can be pulled through the existing pipeline without obstruction. At the next stage, a new pipe with a reduced diameter is pulled into the old pipe by means of a cable and a winch installed in the next manhole along the course of the pipe. The pulling is carried out until the pipe is in the required position.

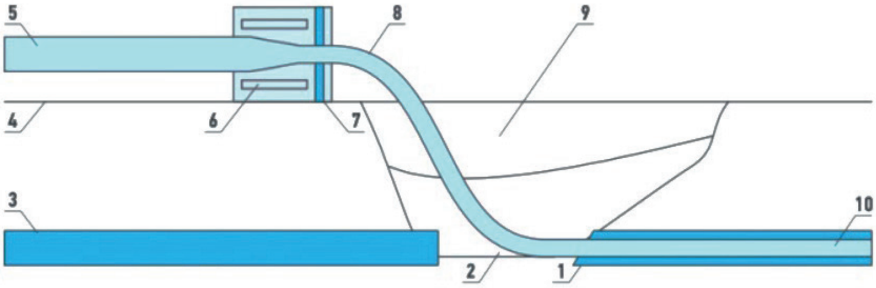

Figure 1. Pipeline rehabilitation scheme using the Swagelining method
1,3 - fragments of the dilapidated (restored) pipeline; 2, 9 - small-sized pit (or well); 4 - ground level; 5 - initial polymer pipeline, 6 - infrared heaters, 7 - conical matrix (narrowing device); 8 - pipeline after thermomechanical compression; 10 - double-layer pipeline

The reverse process of deformation of the polymer pipe inside the old pipeline occurs automatically due to the "memory" effect. The pipe expands until its outer diameter reaches the size of the inner diameter of the old pipeline and forms a tight joint with its wall. This eliminates the need for cement mortar or special hardeners. Figure 2 shows the result of rehabilitating an old pipeline to form a two-pipe construction.

Figure 2. View of the pipeline rehabilitation

In order to calculate power consumption ΔE while using polyethylene pipes during the period of Swagelining technology implementation for water transportation, including those depending on temperature conditions, equation (1) was applied:

$$\Delta E = 0{,}81 \cdot Q^3 \cdot l \cdot \lambda \cdot 24 \cdot 365 / (d^5 \cdot \eta_p) \quad (1)$$

where ΔE is the value of consumed electricity, kWh/year; Q is the flow rate of water supplied by the pipeline, m^3/s; l s the length of the pipeline section, m; η_p is the efficiency factor of the pumping unit; 24 is the work hours of the pump per day, h; 365 is number of days per year; λ is the coefficient of hydraulic friction; d is the internal diameter of the pipeline, m.

RESULTS

To determine the level of deformation of pipelines (changes in the diameter and wall thickness of polymer pipe after its thermomechanical compression and straightening operations) when using Swagelining technology, a special automated program was applied [20].

The initial parameters used in the automated calculations in both programs are as follows:

-internal diameter of the dilapidated steel pipeline 500 mm;

-length of the pipeline 600 m;

-internal diameter of polyethylene pipes 560 and 630 mm (SDR 21);

-Average temperature of the pipeline wall (soil around the pipe) 160 C;

- average temperature of water in the water supply source 160 C (summer period) and 80 C (winter period);

-flow rate of transported water 0.14 m3/s;

-internal diameters of the rehabilitated pipeline after renovation of the steel pipeline with polyethylene pipe with original diameters of 560 and 630 mm, respectively: 446.04 mm and 438.51 mm;

-coefficient of efficiency of the pumping unit 0.9.

Summary output information on the automated calculation of parameters in summer and winter periods is presented below (Tables 1 and 2) according to the data obtained from the results of the automated program [19].

Table 1. Summarized output information on the results of hydraulic and energy calculation of two-pipe construction in summer and winter periods at the internal diameter of the pipeline 446.04 mm

No	Estimated indicators	Indicator values	
		Summer period	Winter period
1	Water flow velocity in the pipeline, m/sec	0.896	0.896
2	Coefficient of dynamic viscosity related to the liquid flow, Pa-s.	0.001131151	0.001406528
3	Coefficient of dynamic viscosity related to the pipe wall temperature, Pa-s.	0.001131151	0.001131151
4	Dynamic viscosity ratio	1.0	1.243
5	Coefficient of kinematic viscosity of liquid, m2/sec.	0.000001096	0.000001380
6	Reynolds number	364758.11	289680.3
7	Calculated coefficient of hydraulic friction	0.013853	0.013885
8	Electricity consumption through the coefficient of hydraulic friction, kWh per year	10217.143	10224.114

Table 2. Summarized output information on the results of hydraulic and energy calculation of a two-pipe structure in summer and winter periods at the internal diameter of the pipeline 438.51 mm

No	Estimated indicators	Indicator values	
		Summer period	Winter period
1	Water flow velocity in the pipeline, m/sec	0.927	0.927
2	Coefficient of dynamic viscosity related to the liquid flow, Pa-s.	0.001131151	0.001406528
3	Coefficient of dynamic viscosity related to the pipe wall temperature, Pa-s.	0.001131151	0.001131151
4	Dynamic viscosity ratio	1.0	1.243
5	Coefficient of kinematic viscosity of liquid, m2/sec.	0.000001096	0.00000138
6	Reynolds number	371021.66	294654.63
7	Calculated coefficient of hydraulic friction	0.013897	0.013929
8	Electricity consumption through the coefficient of hydraulic friction, kWh per year	11089.143	11115.787

Comparing the values of electricity consumption in Tables 1 and 2 for points 8, i.e., with and without consideration of water and pipeline wall temperatures, there is a discrepancy. This indicates the influence of water temperature on electricity consumption: as the temperature in the water supply source increases, electricity consumption decreases. For example, for the winter period the difference in electricity consumption is as follows:

- for diameter 446.04 mm 10224.114 - 10217.143 = 6.971 kWh per year
- for diameter 438.51 mm 11115.787 - 11089.143 = 26.644 kWh per year.

In addition, it should be noted that even with a slight decrease in the diameter of polyethylene pipe (from 446.04 to 438.51 mm) there is an increase in energy costs. For example, for winter conditions it is 26.644 - 6.971 = 19.673 kWh per year or 26.16%.

It follows that the design and possible control of the water transportation process requires accounting for temperature factors to obtain the most probable values of electricity consumption. It is necessary to include data on the temperature parameters of the pipeline wall and transported water in the pipeline network construction projects and to calculate electricity consumption. This is facilitated by modeling, which allows to identify the optimal parameters of water transportation process control based on the search for minimum values of electricity consumption. Using the capabilities of the automated program, calculations of power consumption can be carried out in a wide range of temperatures of the pipe wall (corresponding material and diameter) and transported water for both northern and southern regions at different values of water flow rates and values of the efficiency factor of pumping units.

Below are presented summary calculation data (Tables 3-5), as well as graphical material regarding the most economical variant among the alternatives in terms of energy cost savings for water transportation through the Swagelining-rehabilitated pipelines with different diameters and SDR values. The tables clearly illustrate the dynamics of change in such indicators as wall thickness and the value of the new internal diameter of the repaired pipeline, as well as energy costs depending on the SDR of the pipe after the reconstruction of the steel pipeline by Swagelining.

The following initial data were adopted for the calculations: pipeline material is steel; internal diameter is 800 mm; length of the repaired section is 800 m; design water flow rate is 0.51 m^3/s, at which the head loss along the length in the steel pipeline is 1.12 m; efficiency factor of the pump and electric motor is 90%.

External diameters of the new polymer pipeline using Swagelining technology are: d_1=1000 mm, d_2=900 mm and d_3=800 mm.

Table 3. Indicators at outer diameter of a new pipeline d_1=1000 mm

Estimated values	*SDR*11	*SDR*17	*SDR*21	*SDR*26	*SDR*33	*SDR*41	*SDR*50
Inner diameter of the new pipeline after renovation, mm	608.84	677.78	702.43	722.04	737.84	748.89	759.62
Wall thickness after compression-straightening operations, mm	95.58	61.11	48.79	38.98	31.08	25.56	20.19
Head loss along the entire length of the pipeline after renovation, m	1.428	0.772	0.629	0.538	0.475	0.436	0.402
Average annual electricity savings							
Along the entire length of the pipeline thousand kWh/year	-16.549	18.906	26.637	31.606	34.996	37.093	38.403

Table 4. Indicators at outer diameter of a new pipeline d_2=900 mm

Estimated values	*SDR*11	*SDR*17	*SDR*21	*SDR*26	*SDR*33	*SDR*41	*SDR*50
Inner diameter of the new pipeline after renovation, mm	632.24	691.63	713.19	730.47	744.45	754.26	763.82
Wall thickness after compression-straightening operations, mm	83.88	54.19	43.40	34.77	27.78	22.87	18.09
Head loss along the entire length of the pipeline after renovation, m	1.15	0.688	0.577	0.503	0.451	0.419	0.389
Average annual electricity savings							
Along the entire length of the pipeline thousand kWh/year	-1.544	23.476	29.478	33.476	36.276	38.041	39.617

Table 5. Indicators at outer diameter of a new pipeline d_3=800 mm

Estimated values	*SDR*11	*SDR*17	*SDR*21	*SDR*26	*SDR*33	*SDR*41	*SDR*50
Inner diameter of the new pipeline after renovation, mm	654.8	705.2	723.8	738.8	751.0	759.6	768.
Wall thickness after compression-straightening operations, mm	72.6	47.4	38.1	30.6	24.5	20.2	16.0
Head loss along the entire length of the pipeline after renovation, m	0.941	0.615	0.53	0.471	0.429	0.402	0.377
Average annual electricity savings							
Along the entire length of the pipeline thousand kWh/year	9.779	27.396	32.008	35.188	37.471	38.937	40.265

According to the results of the modeling presented in Tables 3-5, the following conclusions can be drawn on the application of Swagelining technology for rehabilitation works:

- for the range of diameters considered (1000, 900 and 800 mm), the larger the SDR value (i.e., the smaller the wall thickness), the smaller the head losses along the length of the pipeline;
- the smaller the diameter of the pipeline, the lower the head losses and the greater the average annual energy savings, which is clearly illustrated by graphical relationships (Figure 3);
- at SDR 11 values for pipelines with diameter d_1=1000 mm and d_2=900 mm no energy saving is achieved (negative calculation result);
- at SDR 50 the values of average annual energy savings for three diameters of pipelines practically coincide.

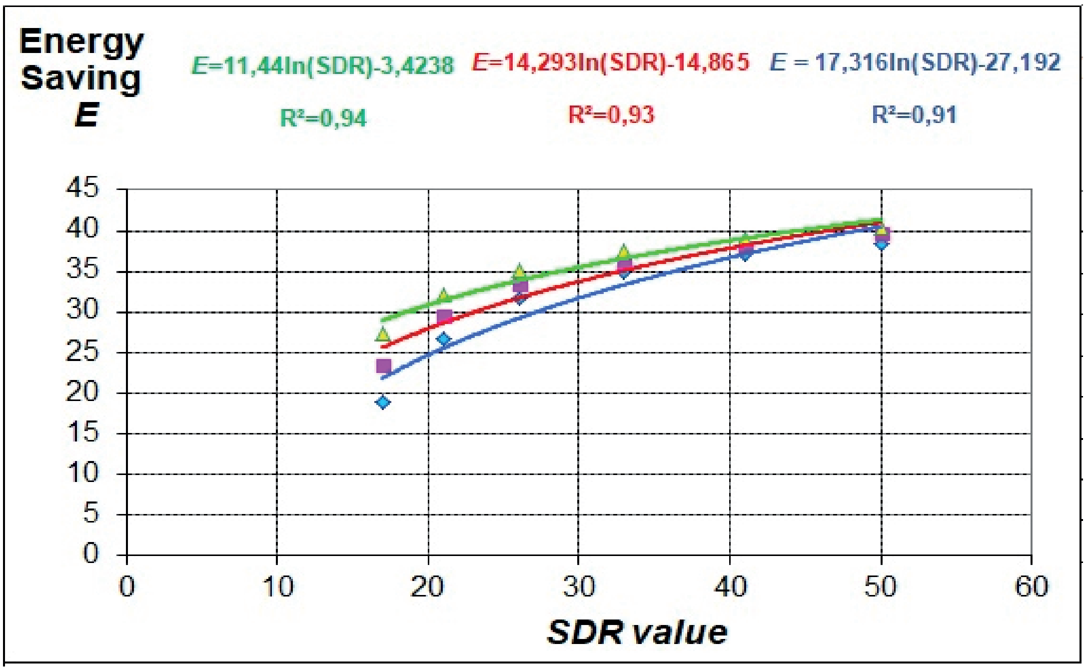

Figure 3. Graphs for average annual energy savings E, thousand kWh/year, depending on the value of SDR for the corresponding pipeline diameter: 1000 mm - blue (lower curve), 900 mm - red (middle curve); 800 mm - green (upper curve)

CONCLUSIONS

The analysis of the literature and practice of designing repair and restoration works on the underground pipeline network shows that the current state of pipelines of water supply and drainage systems in the countries of the world is unsatisfactory. There is a tendency of dynamic wear of pipelines with exceeding the normative service life of their service. This indicates the need for rapid replacement of individual sections of engineering networks.

The trenchless methods are promising approaches to the reconstruction of underground pipelines. They allow to significantly reduce the time and cost of construction works, ensure resource and energy efficiency of the reconstructed pipeline systems, as well as maintain organoleptic characteristics of transported water and reduce the risk of harm to the environment.

The performed research has established the advantages of trenchless reconstruction methods and recommended the wide use of Swagelining method. It allows to achieve a double effect at the same time: resource saving, as after the repair water leaks (exfiltration) and groundwater infiltration into pipelines (infiltration) will be eliminated, as well as energy saving, i.e., reduction of energy costs during water transportation, including at different ambient temperatures.

Hydraulic and energy calculations of a two-pipe underground structure of a certain diameter during various seasons of the year are presented on specific examples with the use of computer-aided programs, which showed the possibility of saving energy resources depending on temperature conditions.

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