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DIAGNOSTICS AND RENOVATION METHODS FOR STEEL PIPELINES

Vladimir A. Orlov, Sergey P. Zotkin, Dmitry V. Podolyan

National Research Moscow State University of Civil Engineering, Moscow, RUSSIA

Abstract. The article explores the analytical challenges and potential applications of diagnostic equipment and tools for cost-effective restoration of aging pressure pipeline systems at minimum costs for water transportation. The study focuses on a section of a water supply network made of steel pipes that requires repair and restoration due to corrosion damage and wall thinning.

The paper presents an analysis of effective non-destructive pipeline diagnostic methods, details the design and technical specifications of the domestic diagnostic system HeatScan. Provided are sample magnetograms that indicate defect zones and the absolute residual wall thickness at the defect locations. The benefits of the HeatScan system over the Inspector Systems flaw detector are also shown.

To identify the most cost-effective pipeline repair method, three alternative technologies for inserting polymer pipes into the existing pipeline are considered, along with a calculation of the energy consumption for water transportation. It is noted that the most cost-efficient repair method could be the Swagelining technology, which involves pre-compressing the polymer pipe with the subsequent straightening. Information on the return-on-investment period for the diagnostic system when used in pipeline restoration projects is provided.

Keywords: pipelines, diagnostics, repair methods, energy consumption, return on investment period

ДИАГНОСТИКА СТАЛЬНЫХ ТРУБОПРОВОДОВ И МЕТОДЫ ИХ РЕНОВАЦИИ

В.А. Орлов, С.П. Зоткин, Д.В. Подолян

Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ), г. Москва, РОССИЯ

Аннотация. В статье рассматриваются поисковые задачи анализа и возможного использования оборудования и приборной базы по диагностике для решения вопросов эффективной реконструкции ветхих напорных трубопроводных сетей при минимальных денежных затратах на транспортировку воды. Объектом исследований является участок стальной водопроводной сети, который подлежит ремонтно-восстановительным операциям в связи с наличием дефектов в виде коррозионных повреждений и утонения стенок.

Представлен анализ эффективных методов диагностики трубопроводов методами неразрушающего контроля, описана конструкция и приведены технические характеристики и результаты работ отечественного диагностического комплекса HeatScan. Приведены образцы магнитограмм, свидетельствующих о наличии дефектных зон и абсолютных величин остаточной толщины стенок в местах дефектов. Представлены преимущества комплекса HeatScan по сравнению с дефектоскопом Inspector Systems.

В целях выявления наиболее экономичного метода ремонта трубопровода рассмотрены три альтернативные технологии протягивания в старый трубопровод полимерных труб и проведен расчет потребления электроэнергии на транспортировку воды. Выявлено, что наиболее экономичным методом ремонта, может служить применение технологии предварительного сжатия полимерной трубы и последующего распрямления Swagelining. Представлены данные о сроке окупаемости диагностического комплекса при его использовании на линейных объектах реконструкции трубопроводов.

Ключевые слова: трубопроводы, диагностика, методы ремонта, энергопотребление, срок окупаемости

INTRODUCTION

Organizations and enterprises involved in construction, repair, and modernization of urban and rural pipeline infrastructure are tasked with maintaining efficient operation of utility networks. This is achieved through extensive use of diagnostic systems to assess the technical condition of specific sections of underground pipelines, including culvert crossings, and to select the optimal repair method for these networks [1].

Particular emphasis is placed on conducting diagnostics under challenging conditions (for instance, in wells where pipeline access is difficult), during emergency excavations requiring prompt measurements, and when laying steel pipelines in urban areas with uniform and non-uniform layers of backfill soil, where steel degradation may occur, etc. [2]. The primary objective of diagnosing pressure pipelines is to promptly identify any operational failures and minimize the impact in an emergency. It is necessary to consider such factors as the type and parameters of defects, the actual thickness of the pipe wall after prolonged use, and the residual life of steel pipelines. The concluding phase of pipeline network restoration programs involves selecting the most urgent reconstruction project and the best method of pipeline restoration, focusing on trenchless repair technologies, i.e., without excavation work (with or without access inside the pipeline).

The modernization of diagnostic work on aging operational sections of water supply and drainage networks, including culverts, should be carried out by using (or purchasing) new process equipment and its subsequent testing. This requires a thorough analysis of the market for diagnostic devices, up-to-date regulatory and technical documentation, scientific literature, as well as information available on the official websites of companies that manufacture equipment for inspecting and repairing underwater pipeline crossings and offer diagnostic, installation, and repair services for such facilities [3].

Comprehensive diagnostics of underwater pipeline crossings can be categorized as either external or internal. External diagnostics involve locating the pipeline, inspecting its surface (either visually or with simple measuring tools), instrumentally examining the pipeline surface and insulation, and monitoring channel processes. Internal diagnostics are carried out by putting instruments and devices inside the pipeline to assess its technical condition. The surface and internal examination of underwater pipeline crossings is conducted using non-destructive testing methods: magnetographic, ultrasonic, electromagnetic, and radiographic [4].

Several non-destructive testing methods can be used to assess the technical condition and position of underwater pipeline crossings relative to the seabed profile, according to an analysis of the diagnostic equipment used [5, 6]:

1) Magnetographic methods (based on recording changes in magnetic field lines in the zone of pipe wall and insulation defects).

2) Ultrasonic methods (based on changes in the reflection of ultra-short sound waves in the zone of pipe defects).

3) Electromagnetic methods (similar to magnetographic ones, but involve the use of electromagnetic sensors rather than magnetite sensors).

4) Radiographic methods (based on the use of γ-radiation).

There are two primary categories of methods for inspecting pipelines using electromagnetic phenomena [7, 8]:

- methods that measure the electromagnetic fields generated by the pipelines themselves; these methods are based on measurements of the fields created by the pipelines, and
- methods for measuring electromagnetic fields induced on the pipeline using specialized systems and devices.

Several other methods have been utilized for detecting leaks from underwater pipeline crossings, such as analyzing pressure diagrams along the pipeline's length at its initial and final points, as well as optical methods that involve introducing a fluorescent dye into the pumped medium and subsequently detecting it under a certain light spectrum above the pipeline's location [9-13].

Acoustic methods, which are based on recording sound signals arising from liquid turbulence when it flows into a low-pressure space [14, 15], and physical methods, which use measuring devices to track pressure levels and flow in the pipeline system [16], are also utilized.

It's crucial to note that in Russia, there is no approved regulatory and technical documentation governing the inspection procedures for underwater water supply and sewerage culverts. Existing regulations, such as SP 272.1325800.20161, are centered around visual diagnostic methods for drainage systems, as well as methodological guidelines for assessing the technical state of other systems like heating, hot water, cold water, and wastewater disposal.

The external inspection of underwater pipelines involves monitoring parameters such as pipeline shape, characteristics of the water body's bottom beneath the pipeline, thickness of the soil layer covering the pipeline, condition of corrosion protection, overall technical state of the pipeline, and geotechnical properties of the surrounding soil.

Inline diagnostics of such structures are typically conducted in several stages. First, the internal cavity of the diagnostic area is cleaned to a level mandated by regulatory and technical documentation. This is followed by the deployment of special profile-measuring and defect-detecting devices (including robotic devices), with a subsequent prompt analysis of the gathered data. Then, a stress-corrosion device is deployed. Finally, a comprehensive analysis of the diagnostic study results is conducted and documented in specific reports.

Inline inspection makes it possible to monitor parameters such as pipe geometry alterations, metal loss due to corrosion, presence of cracks and erosion, as well as pipeline profile, including shifts in plan or elevation caused by soil erosion.

Russian scientists are working on innovative instrument systems that facilitate diagnostic studies of underwater culverts. Specifically, a method [17] for evaluating the technical condition of underwater utilities has been developed that makes it possible to promptly obtain real-time information about the object's condition, even as the vessel is passing over the pipeline being diagnosed. This method employs hydroacoustic tools to measure seabed topography and assess the technical condition of the pipeline, including the state of its insulation coating, based on electromagnetic field parameters.

The paper [18] showcases the successful use of the long-wave ultrasound system *Wavemaker* developed by *Guided Ultrasonics Ltd.* from the *UK* for diagnosing and monitoring hard-to-reach pipelines. One of the key benefits of the *Wavemaker* system is its ability to gather data on the condition of a pipeline up to 50 meters long by installing a special ring with piezoelectric transducers at a single network point, eliminating the need to move it along the entire pipeline length. The system package comprises a control unit and *WavePro* software for a personal computer. The system can identify zones of crack formation, corrosion, and mechanical damage with metal loss of up to 5%, as well as welded joint defects. A significant advantage of this system is that there's no need to strip all insulation from the pipeline, as it is enough to strip it only at the ring's installation point. The existence of flange connections does not impact the effectiveness of the diagnostics. The manufacturer also offers various types of fastening ring transducers for ultrasonic scanning.

Russian organizations engaged in the operation and examination of underwater pipeline crossings have gained positive experience using domestic electronic information systems (IS "Duker" and IS "Duker 2.0") [19]. These systems not only store and organize information about the facility but also provide a comprehensive assessment of the technical condition of underwater crossings, and generate report documentation, including data visualization.

Currently, the diagnostics of underwater gas and oil pipelines are performed using advanced and highly precise equipment, including multibeam and narrow-beam echosounders, hydroacoustic (ultrasonic) profilers, side- and circular-scan sonars, devices for measuring water flow direction and speed, as well as satellite navigation systems [20-22].

Side-scan sonars are advised for use in deep waters and large water bodies. Conversely, 360-degree sonars are suitable for use in areas with limited depth and confined spaces. Side-scan sonars generate ultrasonic pulses directed at the seabed at a sharp angle and then record the reflected signals. There are analog and digital versions of sonars, with the latter considered more advanced.

For specialists working in construction and pipeline maintenance, where precise location and depth of underground objects is crucial, radio telescopes like the *Radiodetection RD*8100 [23, 24] are an essential tool.

Pipeline swabs (also known as smart pigs) have gained popularity for in-line diagnostics of gas and oil pipelines [25]. These devices provide simultaneous information about the pipeline's spatial configuration, the geometry of the pipe walls, and allow for monitoring of the network's technical condition through integrated non-destructive testing systems (typically of magnetic or ultrasonic types).

A detailed description of these devices' functions and their application in design solutions can be found in the article [26].

METHODS AND MATERIALS.

To choose the optimal diagnostic complex design, we studied the main types of products offered by both Russian and international manufacturers for the diagnostics and repair of water supply and sewerage pipelines. As a result of collection, processing, and analysis of information, it was proposed to use Russian-made equipment, specifically the *HeatScan* diagnostic complex from the Russian company Octanta. The study was carried out with the direct participation of representatives from JSC Mosvodokanal.

The *HeatScan* complex is designed for measuring pipeline wall thickness in zones of area thinning and for detecting defects during continuous in-line diagnostics of steel pipelines using a magnetic inspection method (Figure 1). No prior preparation of the pipe is required. The diagnostic robot in the complex is equipped with six tracks, enabling it to traverse areas with large deposits on the pipeline walls, and can monitor the condition of metal through a deposit layer up to 30 mm thick.

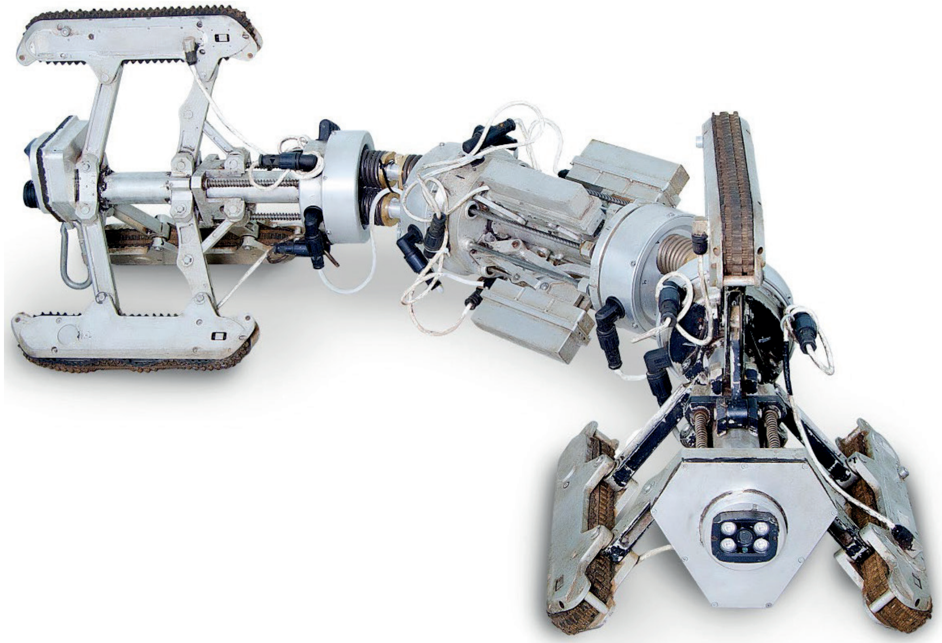

Figure 1. HeatScan robot

The robot is operated by a technician inside the autolaboratory, which is a mobile control panel for the complex, located near the robot's pipe entry point. The robot is loaded into the pipe through a 600×600 mm process cut, either inside a heat recovery chamber or at pipeline pits.

Table 1 summarizes the robot's technical capabilities for pipeline diagnostics.

Table 1. Technical specifications and capabilities of the HeatScan complex.

Range of inspected pipe diameters, mm	400-1600
Range of pipe wall thickness, mm	3-16
Length of inspection, m	500
Thickness of deposits on the pipe's inner surface, mm	15 (up to 30 with reduced sensitivity)
Size of detected/measured defects, mm	- a through defect of 6 mm diameter
Performance, m/h	no less than 100
Number of branches passed, pcs	2
Passing through tees	yes
Measurement error from the remaining wall thickness in the defect zone, %	20
Relative humidity, %	100%
Range of working temperatures, °*C*	0-70

Presented below are the additional technical specifications for the *HeatScan* diagnostic system (КМВТД-01), which has valid calibration certificates:

- manufactured in 2018 by NPO *Oktanta LLC* in the Russian Federation,
- equipped with programs for remote control, data processing, and pipeline technical condition report generation, including defect coordinates (*MFC control*),
- design type: portable,
- performance: no less than 100 m/h;
- voltage: 220 V, 50 Hz,
- power consumption: no more than 1 kVA.

RESULTS

Experimental studies of the *HeatScan* diagnostic system efficiency for in-pipe diagnostics were carried out at the Mosvodokanal JSC facility.

The diagnosed facility was a 158.4 m long steel pressure pipeline for process water (Figure 2). Pipeline design parameters: outer diameter 500 mm, wall thickness 10 mm. The diagram in Figure 3 illustrates the coding of loading points and travel routes (No. 1 and No. 2) as an example.

Figure 3 also shows the points where hydraulic tests were conducted and the locations of vertical attachments (risers).

Figure 2. The pipeline's location

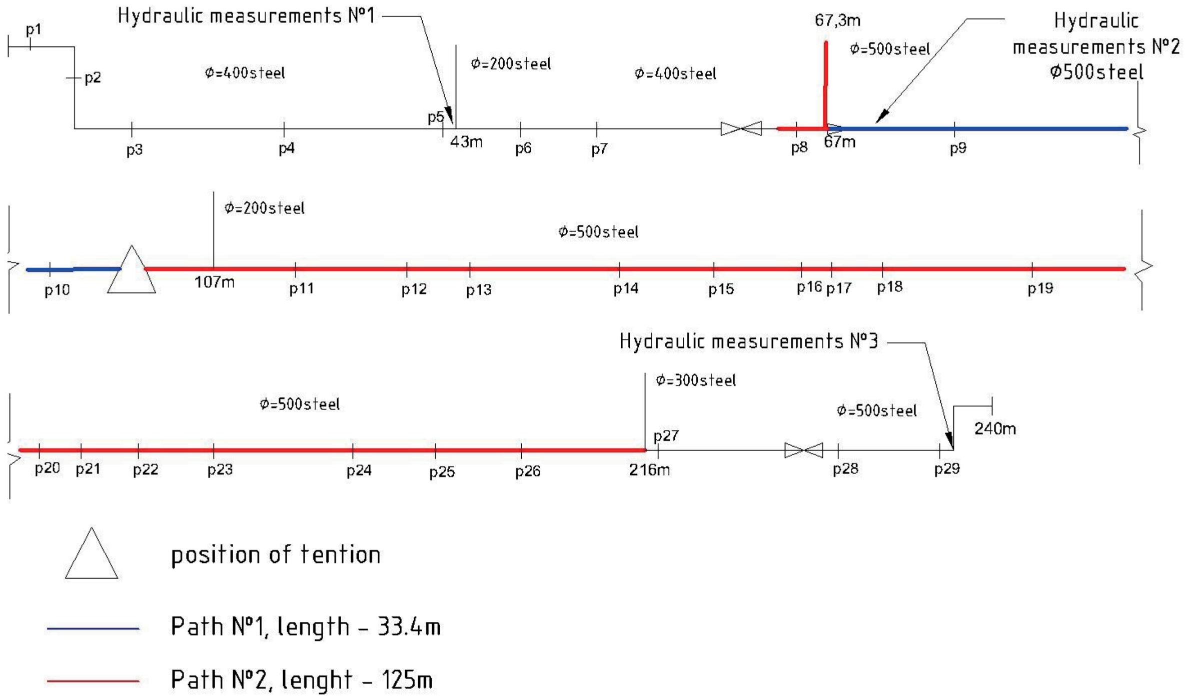

Figure 3. Loading point and travel routes

The magnetic inspection revealed critical defects that are detailed in Tables 2 and Table 3. The process of recording and coding the inspection results involved documenting the travel distance covered by the diagnostic system (m), as well as the angular coordinates of points within the pipeline's circumference (degrees). Measurements were taken from the cross-sections of the pipeline for each of the two routes. The angular coordinate was measured counterclockwise, with the top of the pipe circumference taken as zero.

Table 2. Indicators at outer diameter of a new pipeline d_1=1000 mm

Route number	Zone number	Distances and angular coordinates of points along the pipeline's circumference meters/degrees	Minimum remaining wall thickness, mm	Comments
1	1	15.6/186	5.5	-
	2	38/261	3.7	-
		38/13	6.3	-
	3	42.5/149	3.8	-
		42.8/233	3.7	-
		43.1/163	5.1	-
2	4	48.2/219	2.5	*Corrosion area with spot thinning and substantial defect area*
		48.4/123	< 1	
		48.2/204	< 1	
		48.6/196	< 1	
		49.2/179	< 1	
		49.1/135	< 1	
	5	51.9/195	3.7	-
		51.6/52	4.0	-

Table 3. Experimental data for the second route (zones 6-9)

Route number	Zone number	Distances and angular coordinates of points along the pipeline's circumference meters/degrees	Minimum remaining wall thickness, mm	Comments
2	6	61.1/261	3.9	-
	7	79.7/167	2.9	-
		80.2/85	3.5	-
		80.5/191	3.6	-
	8	84.4/204	3.2	-
	9	118.3/244	5.4	-

Below are selected magnetograms of defective zones with the most significant defects (see Figures 4 and 5).

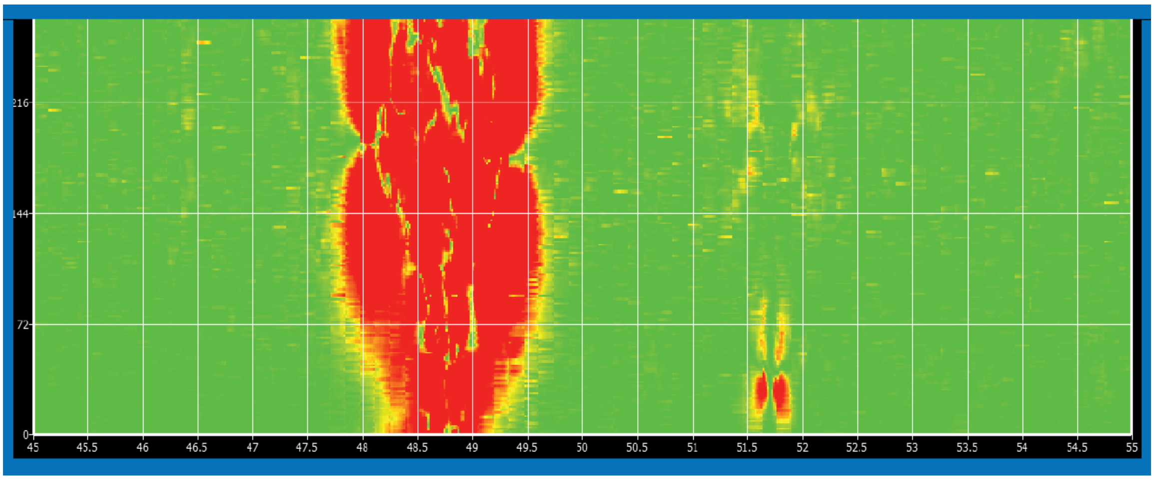

Figure 4. Illustration of defects and their areas on route 2 (Zone 4)

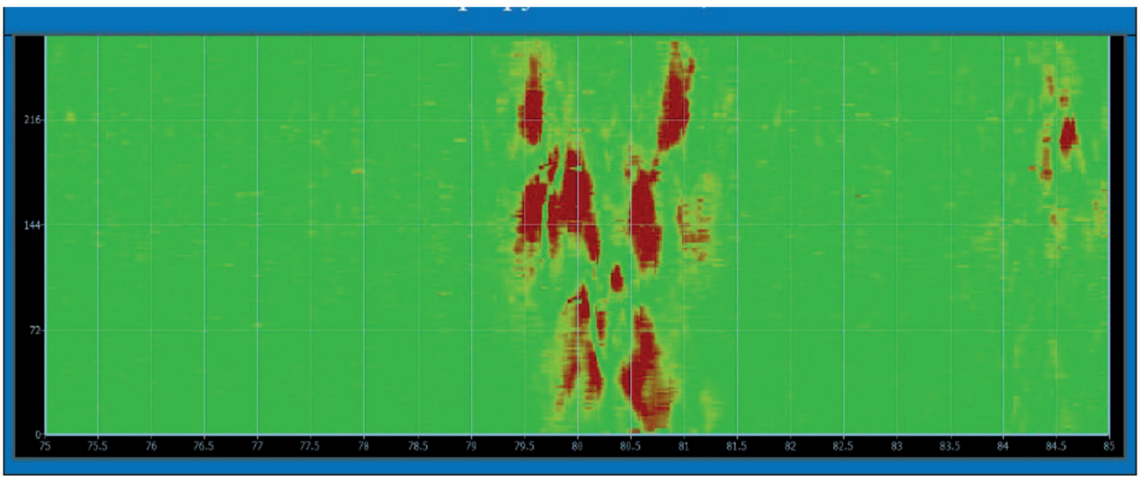

Figure 5. Illustration of defects and their areas on route 2 (Zones 7 and 8)

Thus, as the magnetograms indicate, the most defective zones for the earliest pipeline failure are the coordinates of 5 points along route 2 (zone number 4), which have a bright trace and, accordingly, the minimum values of the residual wall thickness (less than 1 mm), which is less than 10% of the original wall thickness and it indicates the exhaustion of the pipeline's resource. Thus, the wide and bright trace on the magnetogram of Figure 4 indicates the need to replace the dilapidated pipeline as soon as possible or reconstruct it using appropriate methods. In turn, Figure 5 shows only minor small traces, for example, from 3.7 to 6.3 mm (zones 1, 2 and 3 along route 1), which allows us to assess the condition of the pipeline as satisfactory at this point in time. As for the data on route 2 (zone numbers 6-9), the so-called "average values" of the residual wall thickness are observed here. In this case, the technical condition of the pipeline should be considered as potential for reconstruction.

When comparing the diagnostic results of the *HeatScan* system with those of the *Inspector Systems* flaw detector, which was also tested at the research site as an alternative device for assessing pipeline condition, it is clear that *HeatScan is superior.* Specifically, for larger defect areas, the differential signal from the *Inspector Systems* flaw detector showed quite low values that did not accurately represent the actual corrosion zone.

Regarding the restoration methods, the most suitable solution for a timely repair could be pulling new polymer pipes inside the old steel pipeline, which has an inner diameter of 480 mm, using the appropriate technologies [27], i.e.:

- A deformed *U*-shaped pipe with an outer diameter of 450 mm, an inner diameter of 428 mm (*SDR* 41), and a wall thickness of 11 mm.
- A pipe pre-compressed using *Swagelining* technology with an outer diameter of 500 mm, an inner diameter of 454.32 mm (*SDR* 41) after straightening, and a new wall thickness of 12.84 mm.
- A *Primus Line* hose with an outer diameter of 450 mm, an inner diameter of 437 mm, and a wall thickness of 6.5 mm.

It's important to note that there will be no significant alterations in the hydraulic characteristics of the pipeline when using the repair methods presented, as the hydraulic friction coefficient λ of new pipes is considerably lower than that of old steel ones.

The optimal choice among the technologies presented above is determined by calculating the annual energy savings ΔE_{1m} for each unit length of the restored pipeline. The energy calculation is performed using the following formulas (1 and 2) [28].

$$\Delta E_{1m}=[9.81\cdot Q^3(A_s - A_n)\cdot 24\cdot 365]/\eta_p \qquad (1)$$

where ΔE_{1m} is the amount of electricity saved, kWh/year; Q is the flow rate of water supplied by the pipeline, m^3/s; A_s and A_n are the resistivity coefficients of the old and new pipes, respectively; η_p is the efficiency factor of the pumping unit; 24 is the number of pump operating hours per day, h; 365 is the number of days in a year.

$$A_s = 0.0017 d^{-5.1359}, \quad A_n = 0.0004 d^{-5.7276} \qquad (2)$$

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

In the calculations, it was assumed that the flow rate of transported water Q=0.23 m^3/s, the efficiency factor of the pumping unit η_p = 0.9, the inner diameter of the old pipeline d=480 mm and the new diameters d of polymer pipes when using the relevant renovation technologies were 438, 454.32 and 437 mm.

Therefore, by substituting the initial data into formulas (1 and 2), the following energy saving values are obtained for water transportation through the pipeline after its restoration using:

– a deformed *U*-shaped pipe

ΔE_{1m} = $[9.81\cdot 0.23^3(0.0017\cdot 0.48^{-5.1359} - 0.0004\cdot 0.428^{-5.7276})\cdot 24\cdot 365] / 0.9$ = 25.644 kWh per year per each meter of pipeline length

– a precompressed pipe

$\Delta E_{1m} = [9.81 \cdot 0.23^3(0.0017 \cdot 0.48^{-5.1359} - 0.0004 \cdot 0.45432^{-5.7276}) \cdot 24 \cdot 365] / 0.9 =$ 43.015 kWh per year per each meter of pipeline length

– a hose

$\Delta E_{1m} = [9.81 \cdot 0.23^3(0.0017 \cdot 0.48^{-5.1359} - 0.0004 \cdot 0.437^{-5.7276}) \cdot 24 \cdot 365] / 0.9 = 32.386$ kWh per year for each meter of pipeline length

Therefore, the maximum energy saving potential during water transportation through the restored pipeline will be achieved by utilizing the *Swagelining technology.* In this scenario, the average energy savings will be 25-40% higher than when using the previously discussed alternative repair technologies.

The expected savings of water supply network operating organizations purchasing the *HeatScan* diagnostic complex (КМВТД-01) amounts to 46.0 million rubles. When purchasing the complex, it is highly desirable that the equipment's return on investment period does not exceed one year. Therefore, relevant market research was conducted, specifically analyzing the potential use of the complex for diagnosing steel pipeline networks in the area serviced by Mosvodokanal JSC.

Concerning the return on investment period, a preliminary calculation was made, based on the length of steel networks that need diagnosing, with the condition that the cost of the *HeatScan* complex is not exceeded.

Based on the budget data incorporated into the automated "Stroyinformresurs" program and the current prices for 2023, diagnosing (video inspection of a steel pipeline 158.4 m long and 500 mm in diameter with preliminary washing and drying operations) costs 81,346.73 rubles.

To achieve the desired return on investment period for diagnostic equipment using the *HeatScan* complex and implementing the aforementioned restoration technologies, the total length of steel pipeline networks diagnosed annually should not exceed 89 km (0.1584 × 46,000,000 / 81,346.73). This figure falls within the range of annual diagnostic and pipeline restoration targets set by Mosvodokanal JSC.

CONCLUSIONS

1. Following an analysis of advanced diagnostic tools for assessing the condition of pressurized steel pipelines, Russian-made equipment — the *HeatScan* diagnostic complex — was identified and tested on an actual site.
2. Based on the results obtained from the operation of the *HeatScan* diagnostic complex, which identifies the locations and nature of steel pipeline defects, three trenchless repair technologies were suggested as alternative renovation options, which involve pulling new polyethylene pipes into the existing pipeline.
3. The calculations showed that the most significant economic benefit in terms of energy savings for water transportation through the pipeline post-restoration was achieved when using *Swagelining* technology.
4. An estimate has been made of the length of pipeline networks that can be diagnosed to ensure a return on investment for the diagnostic complex.
5. The main directions for the implementation of the results of the conducted research may be the widespread use in the practice of water utilities of the described in-line diagnostic complexes and alternative options for the reconstruction of pressure pipelines of water supply systems that ensure the effect of energy saving.

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Orlov Vladimir A., Professor, Doctor of Technical Sciences; National Research Moscow State Construction University (NIU MSCU), Russia, 129337, Moscow, 26 Yaroslavskoe Shosse, ph. +7(917) 538-43-16; E-mail: OrlovVA@mgsu.ru.

Орлов Владимир Александрович, профессор, доктор технических наук; Федеральное государственное бюджетное образовательное учреждение высшего образования «Национальный исследовательский Московский государственный строительный университет» (НИУ МГСУ), Россия, 129337, Москва, Ярославское шоссе, 26; тел. +7(917) 538-43-16; E-mail: OrlovVA@mgsu.ru.

Zotkin Sergey P., Professor, Candidate of Technical Sciences; Russia, National Research Moscow State Construction University (NIU MSCU), Russia, 129337, Moscow, 26 Yaroslavskoe Shosse; ph. +7(916) 868-34-48; E-mail: ZotkinSP@mgsu.ru.

Зоткин Сергей Петрович, профессор, кандидат технических наук; Россия, Федеральное государственное бюджетное образовательное учреждение высшего образования «Национальный исследовательский Московский государственный строительный университет» (НИУ МГСУ), 129337, Москва, Ярославское шоссе, 26; тел. +7(916) 868-34-48; E-mail: ZotkinSP@mgsu.ru.

Podolyan Dmitry V., PhD student; National Research Moscow State Construction University (NIU MSCU), Russia, 129337, Moscow, 26 Yaroslavskoe Shosse; ph. +7(917) 543-94-84; E-mail: dim.p-2010@yandex.ru.

Подолян Дмитрий Владимирович, аспирант; Федеральное государственное бюджетное образовательное учреждение высшего образования «Национальный исследовательский Московский государственный строительный университет» (НИУ МГСУ), Россия, 129337, Москва, Ярославское шоссе, 26; тел. +7(917) 543-94-84; E-mail: dim.p-2010@yandex.ru