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Pilot-scale testing of a technology for equipping deep hydrogeological wells with inverted block gravel filters

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Abstract

Purpose. The work is aimed at determining the efficiency of the technology of equipping the water intake part of a hydrogeological well with an inverse gravel filter and the economic efficiency of performing work using the proposed technology.

Methods. The tasks were solved using a comprehensive research method, which included analysis and generalization of geological and technical information, physical modeling, and experimental research and development.

Findings. Production tests of the technology of equipping hydrogeological wells with inverse gravel filters has been carried out, which confirmed the effectiveness of the developed and tested technology. The technology of manufacturing inverse gravel filter elements has been tested in production conditions. There has been shown the possibility of using the developed technologies for manufacturing an inverse gravel filter element and transporting an inverse gravel filter along the borehole of hydrogeological wells during their construction with a depth of more than 200 m, using standard drilling technological equipment and tools.

Originality. For the first time, there has been substantiated the use of a water-based mineral binder containing an organic polymer – technical gelatin – for the monolithization of loose gravel material in production conditions into a block structure of a gravel filter of a borehole. For the first time, there has been demonstrated the possibility of equipping the water-receiving part of hydrogeological wells, in fine-grained and fine-grained sands, with inverse gravel filters using the proposed technology.

Practical implications. As a result of experimental and production tests, there has been confirmed effectiveness of the developed technology for manufacturing inverse gravel filter elements and transporting the inverse gravel filter along the wellbore. During the tests, the following aspects have been determined: costs for manufacturing prototypes of inverse gravel filter elements; costs for equipping the water intake part of a hydrogeological well with inverse gravel filters; well productivity; economic indicators of the technology for equipping hydrogeological wells with filters using the proposed technologies.

Keywords: *gravel filter; water; hydrogeological well; water supply*

1. Introduction

The problem of high-quality drinking water is one of the priority challenges of our time. In particular, the UN General Assembly recognized water scarcity as the number 1 problem in the world and declared the period 2005-2015 the international decade “Water for Life”. According to UN data, currently 1.8 billion people on the planet do not have access to clean drinking water. And by 2025 this category may grow to 3.2 billion. Every day, the world consumes 10 billion tons of water, 80% of which is recycled into the subsoil, polluting them, which creates environmental and social threats [1]-[5].

Every year this problem is becoming more acute in our country, which is especially noticeable against the background of the existing trend of climate change, significant man-made load, catastrophic floods and inundations, the manifestation of the consequences of the Chernobyl disaster and the occupation of a significant part of the territory of Ukraine [6]-[9]. Currently, more than 500 settlements in the Odessa, Mykolaiv, Kherson, and Zaporizhia regions do not have reliable sources of drinking water. In the East of Ukraine, drinking water supply for the population and personnel of the Armed Forces of Ukraine is complicated by hostilities. The implementation of post-war reconstruction plans for the country will require a multiple increase in the provision of high-quality water to industry and the population [10]-[13].

The Law of Ukraine No. 3933-VI implemented the National Target Program “Drinking Water of Ukraine” for 2011-2020. Regional programs were also in effect, for example, “Drinking Water of the City of Kyiv for 2011-2020”, “Drinking Water of the City of Dnipropetrovsk for 2006-2020”, which provided for a significant increase in the use of subsoil water resources to solve the above problem through the drilling of thousands of hydrogeological wells [14]-[18].

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However, without proper groundwater purification, this critically important problem for humanity will not be solved [19], [20]. Moreover, recent studies emphasize that inadequate groundwater purification not only reduces water supply reliability but also disrupts ecosystem services and the functioning of novel anthropogenically transformed ecosystems, particularly in urban-industrial landscapes [21], [22].

Typically, formation fluids move in wells in the following directions: forward (from the well), backward (into the well), and reversible direction (underground gas storage wells) [23], [24]. Proper consumer quality of fluids, as well as ensuring the integrity of the well walls, is achieved by using special filters. Depending on the size of the particles of the productive layer rock, filter designs can be used from the simplest – tubular with perforation or frame-rod, – to the most complex – gravel type [25]. The latter are used in lithological and granulometric heterogeneity of reservoir rocks, where the generally known technologies and cleaning agents are extremely ineffective [26]-[31].

The work is devoted to solving this large and urgent scientific problem, which consists in scientifically substantiating the parameters of an effective environmentally safe technology for creating gravel filters for boreholes, the productive part of which is represented by medium-, fine-, very fine-grained and silty sands, which has considerable practical significance.

In recent years, due to the work of domestic and foreign researchers, the technology of constructing water wells has received proper development. The main studies on determining the scope of application, recommendations for the selection of parameters, technology and technical means of creating gravel filters are set out in the works [32]-[36]. Despite this, issues related to the equipment of gravel filters in the water intake part of the well, represented by medium-, fine-, very fine-grained and silty sands, remain unstudied.

Known solutions are quite effective in shallow wells, but they do not work in difficult thermobaric and mining and geological conditions [37]-[40]. At the same time, a number of studies have shown that the efficiency of groundwater intake and artificial recharge systems is largely limited by hydrodynamic features of infiltration processes and the development of colmatation phenomena in sandy and silty deposits. In particular, experimental and field investigations of infiltration basins under artificial groundwater replenishment conditions revealed a decisive influence of lithological composition, grain-size distribution, and filtration regime on clogging intensity and hydraulic resistance growth [41]-[44]. These factors significantly complicate the long-term operation of water intake structures and necessitate the development of more reliable filtration solutions adapted to heterogeneous fine-grained formations.

When making gravel filling on the surface, block and casing filters are used, which have increased hydraulic resistance and during operation quickly become clogged due to the manifestation of physical phenomena and processes. When transported along the wellbore, they collapse, which leads to the formation of voids.

When making gravel packing at the well bottom, there is no reliable technology for creating a gravel filter with high-quality packing in deep wells. There occur the following problems: significant time for transporting gravel material from the surface to the aquifer zone; high-quality formation of gravel packing requires complex surface and bottom equipment and tools, which significantly increases the cost of work; stratification of gravel material by size, both in height and in diameter of the created gravel packing; hanging of gravel material on the transportation path with a corking effect, which requires additional time to eliminate them; risk of formation of gaping cavities opposite the aquifer, which causes uncontrollable sand production in the well [45].

The use of fundamentally new technological solutions and modern, environmentally friendly materials will improve drinking water supply by using existing deep subsoil water resources.

The work is based on the authors' research carried out within the framework of the implementation of scientific research works (R&D): "Study of the features of groundwater resources of unconventional horizons in the territory of Odessa, Mykolaiv and Kherson regions and development of rational technologies and structures of hydrogeological wells for local water supply"; "Scientific justification of design parameters, manufacturing technologies and equipment of boreholes with cryogenic gravel filters". Within the framework of the above R&D, effective technologies for equipping hydrogeological wells with gravel filters up to 200 m deep, the water-receiving part of which is represented by very fine-grained sands, have been scientifically substantiated and introduced into production.

As shows the experience of drilling hydrogeological wells and the analysis of hydrogeological conditions in areas with low water supply in the deoccupied regions, southern and central regions of the country, water withdrawal can be carried out from the Pleistocene, Pliocene, Pontic, Meotic, Eocene (Kyiv) and Bucha aquifers [1], [40], [45]. Some of them have a depth of occurrence of more than 200 m. Therefore, the works carried out by the authors, within the framework of the projects "Development of water purification technology for deep hydrogeological wells", "Hydrogeological and technological justification of alternative water supply for the population of Ukraine during the period of martial law and post-war recovery", have developed technologies that allow equipping productive horizons with a depth of its roof of more than 200 meters. At the final stage of the research, experimental and production tests of one of them were carried out. The results are given below.

The purpose of the production tests was to determine the efficiency of the technology of equipping the water-receiving part of a hydrogeological well with an inverse gravel filter (IGF) and the economic efficiency of performing work using the proposed technology. During the tests, the following were determined: costs for manufacturing prototypes of inverse gravel elements (IGE) of the filter; costs for equipping the water-receiving part of a hydrogeological well with IGF; well productivity; economic indicators of the technology of equipping hydrogeological wells with IGF.

2. Methodology

2.1. Geological and technical conditions for conducting production tests

Production tests of the technology of equipping hydrogeological wells with inverse gravel filters were carried out from October 2023 to November 2023, with the participation of personnel and standard drilling equipment of the commercial enterprise Geological drilling company "Odesaburvod" in the conditions of the settlements of Bilousivka, Voznesensky district (Site 1) and Veselinov, Veselinivsky district (Site 2) of the Mykolaiv region in difficult geological and technical conditions, which are due to the presence in the sections of: loams, clays of high thickness, including in aquifers; saline formation waters; non-pressure, unprotected aquifers represented by fine-grained sands. Two tests of the technologies of manufacturing IGE filters in production conditions and equipping them with water-receiving parts of hydrogeological wells, the depth of which exceeded 200 m, were carried out.

2.1.1. Site 1

The site is located in the area of distribution of the main aquifer in the Bucha sediments. The geological structure includes Paleozoic and Cenozoic rocks. With an angular and stratigraphic unconformity, the sediments of the Bucha suite, represented by mixed-grained, carbonaceous sands, with layers of carbonaceous clays with a total thickness of 30.0-35.0 m, lie on the Carboniferous rocks. The Bucha sediments are overlain by marls of the Kyiv stage with a thickness of 40.0 to 80.0 m, in the roof of which there lies limestone with layers of clays, sandy clays of the Mezhyhirya suite with a thickness of 30.0-45.0 m. On the eroded surface of the Mezhyhirya sediments, the Middle-Upper Quaternary alluvium lies, composed of gray and yellowish-gray fine-grained sands with a thickness of 10.0-20.0 m. The main aquifer used for organizing autonomous and centralized water supply is the horizon in the Bucha deposits.

The depth of the wells is 210.0-230.0 m. The depth of the roof of the aquifer sands is 195-250 m, the uncovered capacity is 20.0-30.0 m. The horizon is pressurized, the water level is set at a depth of 8.0-23.0 m. Water mineralization is 1.5-2.0 g/dm^3, hardness is 5.0-9.0 mg.eq./dm^3. Possible flow rates of single wells are 1.0-1.5 m^3/hour with a decrease of 15.0-20.0 m, respectively. The aquifer is protected from the penetration of pollutants. The geological section and the design of the well are shown in Figure 1.

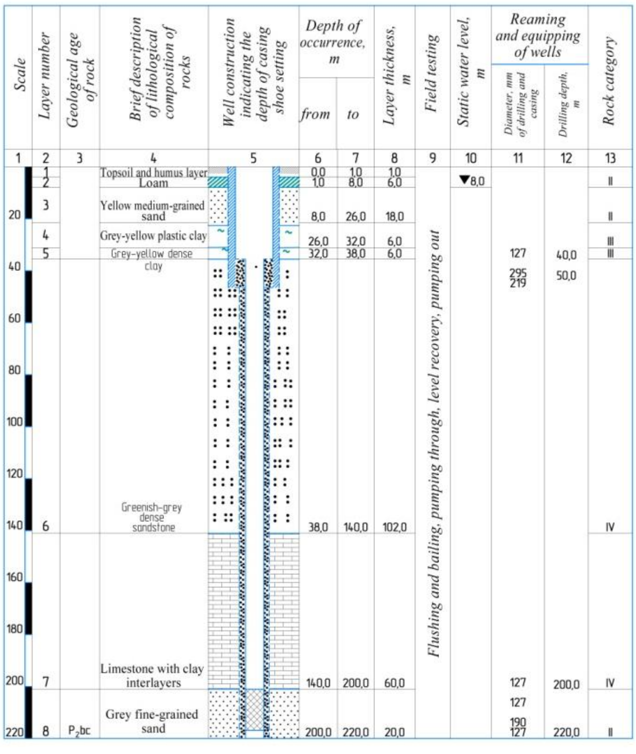

Figure 1. Geological section and well design at site 1

Drilling was carried out using the URB 3A-3.13 rig. The flushing fluid is normal clay slurry. The well design is single-stage. The interval 0.0-50.0 m was drilled with a 295.3 mm bit and covered with a casing string with a diameter of 219.0 mm. The string was cemented with the solution coming out to the surface. The interval from 50.0 to 220.0 m was drilled with a 190.5 mm bit and cased flush-mounted with a 127.0 mm screen column.

The assembly and running of the screen column were carried out in an "extended position". The upper part of the screen column extended 5 meters above the casing shoe. The annular space was sealed with a packer.

2.1.2. Site 2

The site is located in the area of distribution of the main aquifer in the Bucha-Kyiv deposits. The horizon is used for water supply of the population and various facilities through group and individual water intakes. (Fig. 2).

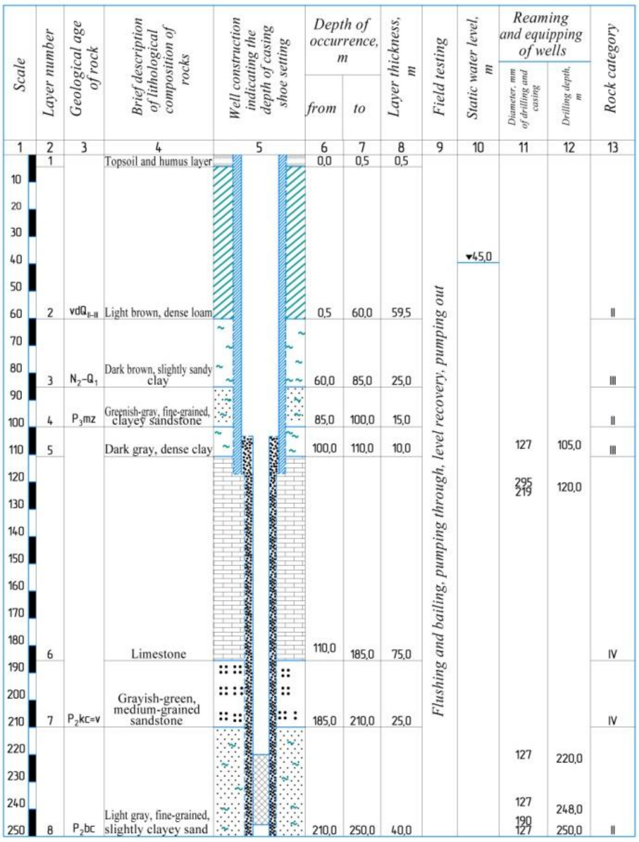

Figure 2. Geological section and well design at site 2

The geological structure of the area includes rocks of the Paleozoic (Carboniferous system), rocks of the Triassic and Jurassic systems and the Cenozoic (Paleogene, Neogene and Quaternary systems). The deposits of the Bucha suite, which lie unconformably on the Triassic-Jurassic deposits, are preserved in area and in section, and are represented by light gray with a brown tint of fine- and mixed-grained sands with a thickness of 30.0-70.0 m. The roof of the deposits is exposed at a depth of 110.0 m. The deposits of the Kyiv suite are represented by limestone and marls, lie at a depth of 110.0-210.0 m and have a thickness of 100 m. The deposits of the Mezhyhirya suite are represented by quartz-glauconite sands with a thickness of 10.0-20.0 m, their depth of occurrence is 80.0-120.0 m. Miocene sediments are common on watersheds and their slopes, lie on the eroded surface of Mezhyhirya sands and are represented by sands 10.0-20.0 m thick. Paleogene sediments are overlain by red-brown clays of the Pliocene and Quaternary yellow-brown loams 68.0-95.0 m thick.

The target aquifer is the Bucha aquifer. It is widespread in the area and is possible for organizing water supply. The characteristics of the aquifer are given based on previously drilled wells in the area. The roof of the water-bearing Bucha sands lies at a depth of 200.0-215.0 m, the thickness of the sands is more than 50 m. The waters are pressurized, the water level is set at a depth of 34.0-53.0 m.

The well flow rates vary from 5.4 to 11.9 m^3/hour with a drop of 40.0-55.0 m, respectively, and the specific flow rate is 0.1-0.3 l/s. The water mineralization is 1.1-1.3 g/dm^3 and the total hardness is 13.0-18.0 mol/dm^3. The aquifer is protected from the penetration of various contaminants.

The drilling was carried out using the URB 3A-3.13 rig. The well design is single-stage. The interval 0.0-105.0 m was drilled with a 295.3 mm bit and covered with a casing string with a diameter of 219.0 mm. The string was cemented with the solution coming out to the surface.

The interval 105.0-250.0 m was drilled with a 190.5 mm bit and cased flush-mounted with a filter column with a diameter of 127.0 mm. The washing liquid is a normal clay solution. The assembly and lowering of the filter column was carried out from the "extended position" position. The upper part of the filter column is 5 m higher than the casing shoe. The intercolumn space is sealed with a packer.

2.2. Block filter design and filter column layout

During the production tests, different filter column configurations were used. The diameters and material of the columns were the same. In all cases, the filter columns consisted of settling tanks, a filter and an overfilter part.

The IGF created on the daytime surface during visual control must have a block design (Fig. 3).

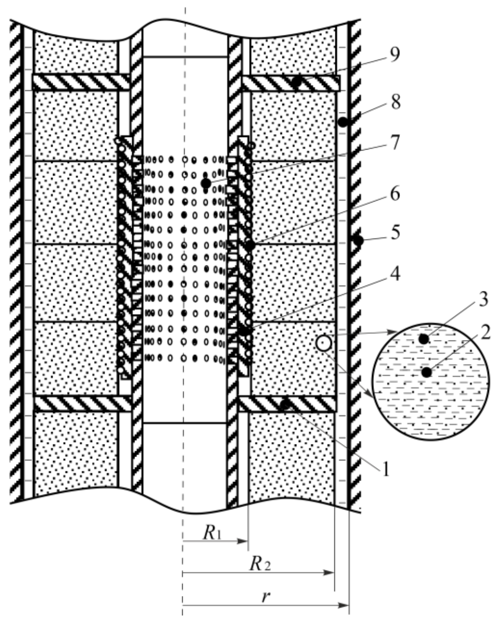

Figure 3. Scheme of the IGS filter during its descent down the borehole: 1 – lower support; 2 – gravel filling material; 3 – mineral binding material; 4 – supporting bars; 5 – well walls; 6 – wire winding; 7 – tubular frame of the filter; 8 – well fluid; 9 – upper support

It has a minimum gap between the inner diameter of the inverse gravel element (IGE) of the filter D_1 and the diameter of the working part of the filter column $D_{w.p}$. At the same time:

$$D_1 = D_{w.p} + (2 \div 4), \text{ mm}. \tag{1}$$

2.2.1. IGF parameters

The weight of the IGE $[m_{cm}]$ filter should not exceed 50 kg. The maximum permissible length of IGE $[l_{\text{IGE}}]$:

$$[l_{IGE}] = \frac{[m_{cm}]}{\rho_{IGE} F_{IGE}} = \frac{[m_{cm}]}{\rho_{IGE} \pi \left(R_2^2 - R_1^2\right)}, \tag{2}$$

where:

ρ_{IGE} – density of gravel backfill of IGE filter;

F_{IGE} – annular cross-sectional area of the IGE filter;

R_1 and R_2 – inner and outer radii of the IGE filter.

Estimated mass of the IGE filter is m_{IGE}:

$$m_{IGE} = \rho_{IGE} \pi \left(R_2^2 - R_1^2\right) \cdot l_{IGE}. \tag{3}$$

IGS consists of several IGE filters. The mass of the IGS filter is:

$$m_{IGS} = m_{IGE} \cdot N_{IGE}, \tag{4}$$

where:

N_{IGE} – is the number of IGE in IGS.

Outside diameter of block IGF D_{IGF} should be as close as possible to the actual diameter of the water-intake part of the borehole. To fit the IGF into the exposed water-intake part of the borehole, the following condition must be met:

$$D_{IGS} = d_d - (1 \div 20), \tag{5}$$

where:

d_d – diameter of rock cutting tool, mm.

Minimum volume of gravel in IGF V_{IGF}, required to create the backfill must be equal to the volume of the water-intake part of the well $V_{g.ip}$, which will be determined as:

$$V_{IGF} = V_{g.ip} + V_{g.c} = F_{g.ip}^{s} h_{a.t} + F_{cs} h_{g.c}, \tag{6}$$

where:

$V_{g.ip}$ – volume of gravel to fill the water intake part of the well;

$V_{g.c}$ – volume of gravel located above the production casing shoe;

F_{cs} – cross-sectional area of the annular space;

$F_{g.ip}^{s}$ – area of the annular space between the frame of the filter column and the walls of the water intake section;

$h_{a.t}$ – aquifer thickness;

$h_{g.c}$ – height of gravel pack in working condition above casing shoe.

After the IGF is brought into working condition, its height will decrease by the value Δl_{IGF}. This is due to the presence of gaps between the outer surface of the IGF and the walls of the water intake part and the inner surface of the production casing, and will be determined as:

$$\Delta l = l_{IGF}^{i} - l_{IGF}^{f}, \tag{7}$$

where:

l_{IGF}^{i} – initial length of the IGF after assembly;

l_{IGF}^{f} – final length of the IGF in working condition.

2.2.2. Site 1

The sump is made of a steel pipe with an outer diameter of 178.0 mm, an inner diameter of 163.8 mm and a wall thickness of 7.1 mm. Its length is 2.0 m. In the upper part, the sump is equipped with a double adapter, which is manufactured at the Odesaburvod enterprise. In its upper part, an adapter is installed, which is designed to connect the working part of the filter column with an outer diameter of 127.0 mm. The lower part of the filter column's sediment trap is equipped with a check valve fitted with a directional flow guide.

The working part of the filter column is made of a steel pipe with a nipple-free connection with an outer diameter of 127.0 mm, an inner diameter of 109.0 mm, and a wall thickness of 9.0 mm. The working part of the filter column had a round perforation. The length of the pipes was 4.5 and 6.0 m. The length of the "candle" was limited by the height of the mast of the URB 3A-3.13 drilling rig and was 12.0 m. The water-receiving surface of the filter column was made of a polymer mesh wound on a perforated pipe and secured with a wire winding. The outer diameter of the working part of the filter column was 132.0 mm.

Pre-fabricated IGE filters were placed on the working part of the filter column. The internal diameter of the IGE filter is 135.0 mm, the external diameter is 188.0 mm. (Fig. 4).

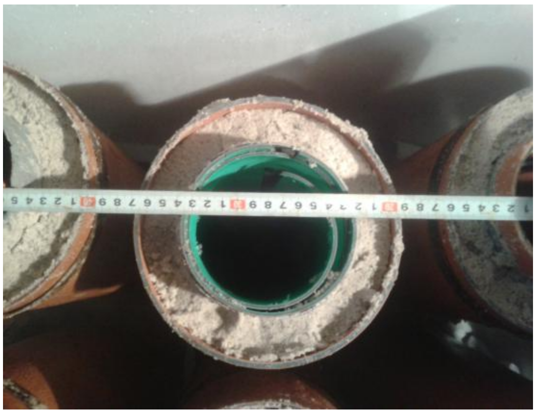

Figure 4. Manufacturing of IGE filters

For these geological and technical conditions of production tests, the following is accepted:
- total length of the IGE filter is 18.0 m;
- length of the IGS filter is 4.5 m;
- length of the IGE filter is 0.5 m.

For the manufacture of the IGE filter, heterogeneous, poorly rounded gravel from the Turbovsky quarry was used.

Between the joints of the pipes of the working part of the filter column, supports for inverse gravel filter elements were installed, which had an outer diameter of 188 mm.

The above-filter part of the filter column is made of a steel pipe with a nipple-free connection with an outer diameter of 127 mm, an inner diameter of 109.0 mm and a wall thickness of 9.0 mm. The layout of the filter column is given in Table 1. The length of the filter column in the first section was 180 m.

2.2.3. Site 2

The sump is made of a steel pipe with an outer diameter of 178.0 mm, an inner diameter of 163.8 mm and a wall thickness of 7.1 mm. Its length is 2.0 m. In the upper part, the sump is equipped with a double adapter, which is manufactured at the Odesaburvod enterprise.

Table 1. Filter column layout

Part of the filter column	Site 1	Site 2
Filter column sump:		
– outer diameter, m	0.178	0.178
– length, m	2.0	2.0
Working part of the filter column:		
– outer diameter, m	0.132	0.132
– length, m	18.0	28.0
The upper part of the filter column		
– outer diameter, m	0.127	0.127
– length, m	160.0	105.0

In its upper part, an adapter is installed, which is designed to connect the working part of the filter column with an outer diameter of 127.0 mm. The lower part of the sump of the filter column is equipped with a check valve fitted with a directional flow guide.

The working part of the filter column is made of a steel pipe with a nipple-free connection with an outer diameter of 127.0 mm, an inner diameter of 109.0 mm, and a wall thickness of 9.0 mm. The working part of the filter column had a round perforation. The length of the pipes was 4.5 and 6.0 m. The length of the "candle" was limited by the height of the mast of the URB3A-3.13 drilling rig and was 12.0 m. The water-receiving surface of the filter column was made of a polymer mesh wound on a perforated pipe and secured with a wire winding. The outer diameter of the working part of the filter column was 132.0 mm.

Pre-fabricated IGE filters were placed on the working part of the filter column. The internal diameter of the IGE filter is 135.0 mm, the external diameter is 188.0 mm.

For these geological and technical conditions of production tests, the following is accepted:
- total length of the IGE filter is 28.0 m;
- length of the IGS filter is 4.5 m;
- length of the IGE filter is 0.5 m.

For the manufacture of the IGE filter, heterogeneous, poorly rounded gravel from the Turbovsky quarry was used.

Between the joints of the pipes of the working part of the filter column, supports for inverse gravel filter elements were installed, which had an outer diameter of 188.0 mm.

The above-filter part of the filter column is made of a steel pipe with a nipple-free connection with an outer diameter of 127.0 mm, an inner diameter of 109.0 mm and a wall thickness of 9.0 mm. The layout of the filter column is given in Table 1. The length of the filter column in the first section was 145.0 m.

2.3. Indicators to be determined

During the production studies, the following were determined: the well flow rate at the time of test pumping; the water level in the well during pumping and after its restoration; the time costs for performing technological operations for the manufacture of experimental samples of the IGE filter and IGF equipment of the aquifer of the hydrogeological well; the consumption of materials, energy consumption, etc.

2.4. Processing of production test data

The processing and evaluation of the test results was as follows. Based on the test results, a report was drawn up for each well. The report provided data on the test conditions, test results, conclusions and recommendations for the use of the results obtained.

When processing the test results, the well flow rate was determined by the formula:

$$Q = \frac{U_0}{T}, \quad (8)$$

where:

Q – well flow rate, m^3/h;

U_0 – volume of measuring container, m^3;

T – tank filling time, h.

The amount of water level drop in the well during pumping:

$$H = D - C, \quad (9)$$

where:

H – decrease in level, m;

D – dynamic water level in the well during pumping, m;

C – static water level in the well, m.

Specific flow rate Q_y of the well, m^3/m·h:

$$Q_y = \frac{Q}{H}. \quad (10)$$

The criterion for the effectiveness of the application of the tested technology is the reduction in the cost of performing technological operations with inverse gravel well filters compared to standard technologies.

2.5. Production tests of the technology of equipping hydrogeological wells with an inverse gravel filter

At each well, production tests were carried out taking into account specific conditions: location of the work site, well depth, equipment used, etc. During the tests, a single procedure for performing all technological operations for the construction of a hydrogeological well was adopted. This procedure consisted of the following sequence:

– after arriving at the work site, technological equipment for drilling the well was placed (Fig. 5) and production of prototypes of the IGE filter;

– at the time of opening, washing of the opened aquifer, the work was carried out to manufacture prototypes of the IGE filter of the calculated length. This process consists of preparing the IGF materials, mixing them, forming and freezing prototypes of the IGE filter. At the same time, to determine the economic efficiency of the studied technology, the costs of time, materials and energy carriers were recorded;

– after flushing the aquifer, at the time of removing the drill string from the well, the IGE filter test samples were removed from the molds. (Fig. 5b) with subsequent assembly of IGF. The IGF assembly process consisted of connecting the IGE filter to the working part of the filter column. (Fig. 5c), as well as the installation of the lower and upper clamps. The assembly time was recorded in the log;

– after the drilling tool was removed from the well and the IGF was assembled, it was transported through the wellbore and placed in the water intake section.

Time of transportation of IGF to the drill pipe column along the wellbore (Fig. 6) conditionally can be divided into:

t_t^{sl} – the time of transportation in the air environment along the wellbore to the static level h_{st};

$t_t^{r.c}$ – the time of transportation of IGF in the medium of wellbore fluid for the rest of the length of the candle;

t_t^b – time of drilling string build-up;

t_t^d – the descent time of one candle in a water medium;

l_c – candle length.

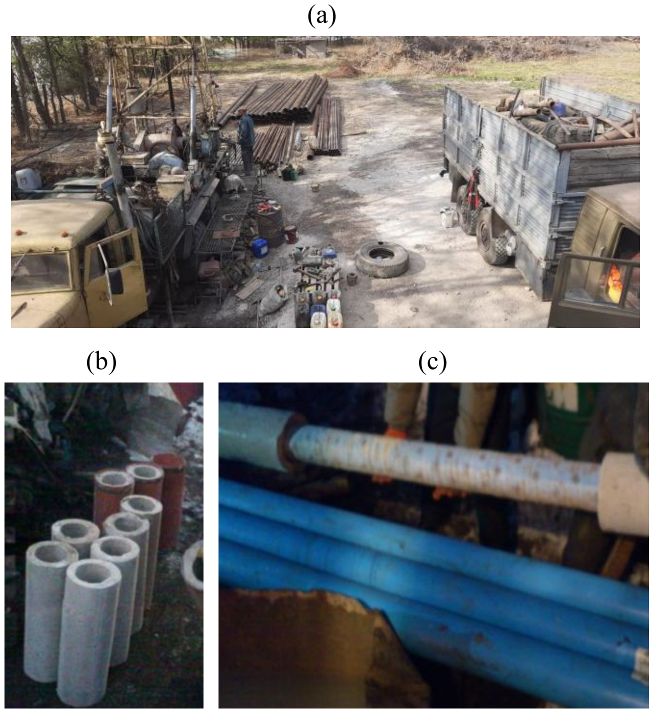

Figure 5. The process of constructing a hydrogeological well in the conditions of the Belousivka area of Voznesensky district, Mykolaiv region: (a) placement of technological equipment at the Bilousivka site, Voznesensky district, Mykolaiv region; (b) removal of IGE filter test samples from molds; (c) IGF assembly process

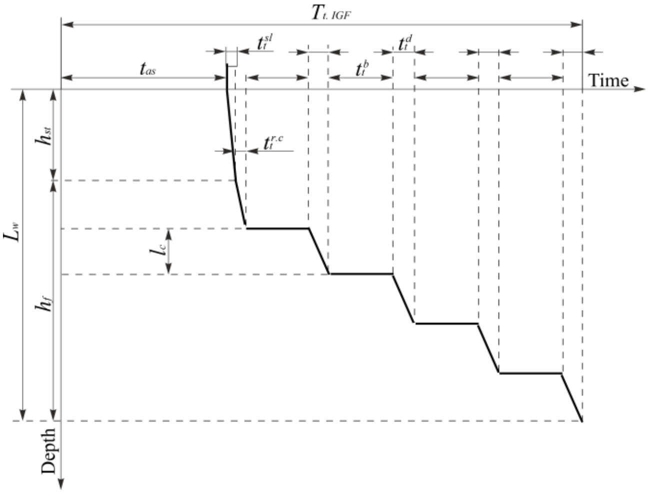

Figure 6. Time cost diagram for equipping a well with IGF: $T_{t. IGF}$ – time of transportation of IGF on a drill pipe string along the wellbore; t_{as} – IGF assembly time; t_t^{sl} – the time of transportation in the air environment along the wellbore to the static level h_{st}; t_t^d – the descent time of one candle in a water medium; t_t^b – time of drilling string build-up; $t_t^{r.c}$ – the time of transportation of IGF in the medium of wellbore fluid for the rest of the length of the candle; h_{st} – static level depth; h_f – column of borehole fluid above the bottomhole; L_w – well depth; l_c – candle length

When the set depth is reached L_w under the influence of positive temperatures of the aquifer, the transition of the IGF from a monolithic to a loose state is completed with the occurrence of filtration of formation waters through the gravel filter material. In this case, the mineral binder acquires the rheological properties of formation waters.

The physical model of the gravel filter is a cylindrical sample, which consists of gravel – the mineral component, and water – the dispersion medium. The dispersion medium, based on the technology of manufacturing the IGE filter, is in a liquid state in its initial period, and then in the solid state, when the temperature of the IGE composite decreases as a whole below the phase transition temperature. Thus, the dispersion medium undergoes a phase transition and the formulated problem is reduced to solving the Stefan problem.

To solve the problem of freezing a porous coarse-dispersed medium of the IGE filter, a differential equation of heat transfer in a dispersed water-saturated medium was used using the effective heat capacity method:

$$c_{ef}(T)\rho(T)\frac{\partial T}{\partial \tau}=\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\lambda(T)\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right); \quad (11)$$

$\tau > 0, R_1 < r < R_2, 0 < z < H$,

where:

H – height of the IGE filter.

We write the initial and boundary conditions in the form:

$$T\big|_{\tau=0}=T_0;$$

$$\lambda(T)\frac{\partial T}{\partial s}\bigg|_n=\bar{\alpha}\left(T\big|_s-T_\infty\right), \quad (12)$$

where:

T_∞ – temperature in the freezer;

n – outward normal to the surface;

$\bar{\alpha}$ – average heat transfer coefficient, which depends on the heat exchange mode and the shape of the IGE filter sample.

The problem is nonlinear. Its solution was obtained by the numerical finite difference method.

IGF is transported along the wellbore in the air environment, to the static level, and in the wellbore fluid environment to the bottomhole. When determining the heat transfer coefficient $\bar{\alpha}$ during transportation of the IGF on a pipe string along the wellbore, it is taken into account that at the moment of extension of the candle, the IGF is in a state of rest, and during descent, there is a hydrodynamic effect of the well fluid. During the drill string extension stage, the following dependence is used to determine the heat transfer coefficient $\bar{\alpha}_g$:

$$\bar{\alpha}_g=\frac{N\bar{u}_\infty\cdot\lambda_g}{d_2}, \quad (13)$$

where:

λ_g – thermal conductivity coefficient of air at temperature T_∞.

When descending the IGF, we use the expression of definition $\bar{\alpha}_2$ for a vertical hollow cylinder, which is under forced convection conditions. Then:

$$N\bar{u}=0.24\cdot\mathrm{Re}^{0.43}\,\mathrm{Pr}^{0.33},$$

where:

Re – Reynolds number.

The heat transfer coefficient is determined by the formula:

$$\bar{\alpha}_2=\frac{N\bar{u}\cdot\lambda_2}{d_2}. \quad (14)$$

In general, the heat transfer coefficient under boundary conditions is $\bar{\alpha}=f(\tau)$, taking into account (3), (4) is used with time average:

$$\bar{\alpha}=\frac{1}{T_{t.\,IGF}}\int_0^{T_{t.\,IGF}}\bar{\alpha}_i(\tau_i)\,d\tau, \quad (15)$$

where:

$\bar{\alpha}_i$ and τ_i – heat transfer coefficient and cycle time, respectively, when increasing $\bar{\alpha}_g$ and descent $\bar{\alpha}_2$ of IGF along the wellbore;

$T_{t.\,IGF}$ – time of transportation of IGF along the wellbore.

Results of the numerical solution of the problem (11)-(12) are given in Figure 7.

Within $T_{t.\,IGF}$, necessary for the implementation of all technological operations, the IGF blocks must have sufficient mechanical strength and, based on Figure 6, it can be defined as:

$$T_{t.IGF}=\sum t_t^b+\sum t_t^d+t_{as}+t_t^{sl}+t_t^{r.c.}, \quad (16)$$

where:

$\sum t_t^b$ – total time of drill string extension;

$\sum t_t^d$ – total time of descent of the drill string in the borehole fluid environment.

While:

$$\sum t_t^b=t_t^b\cdot n_b \qquad \sum t_t^d=t_t^d\cdot n_{n.c.}, \quad (17)$$

where:

n_b – number of operations to extend the drill pipe column;

$n_{n.c.}$ – number of candles in the column.

For successful completion of works on equipping the aquifer, it is necessary that the time of thawing of the IGF t_{IGF} exceeded the time of equipping the well's water intake section with a filter $T_{t.\,IGF}$, i.e. the condition must be met:

$$t_{IGF}>T_{t.IGF}.$$

It its turn, t_{IGF} depends on the IGF formulation, the length of the IGS and the heat exchange conditions. The formulation should be selected taking into account the specific geological and hydrogeological conditions of well drilling and should be no less than:

$$t_{IGF}=k\cdot T_{t.IGF},$$

where:

k – time reserve factor associated with the elimination of the consequences of possible complications that arise during the equipment of the IGF water intake part of the borehole.

The time of equipping the well $T_{t.\,IGF}$ depends on the time of thawing of the IGF in the air environment t_{air} and the thawing time in the well fluid t_f.

Time of thawing of IGF in air environment t_{air}:

$$t_{air}=t_{as}+t_t^{sl}+t_t^{r.c.}. \quad (18)$$

Time of thawing of IGF during transportation in well fluid t_f depends on time cycle t_c^d and their number n. At that $t_f < T_{t.\,IGF}$ by the value $t_{as}+t_t^{sl}+t_t^{r.c.}$, then, taking into account (17):

$$t_f=t_c^d n=t_t^d n_{n.c.}+t_t^b n_b, \quad (19)$$

where:

n – number of cycles for building-up and descending candles.

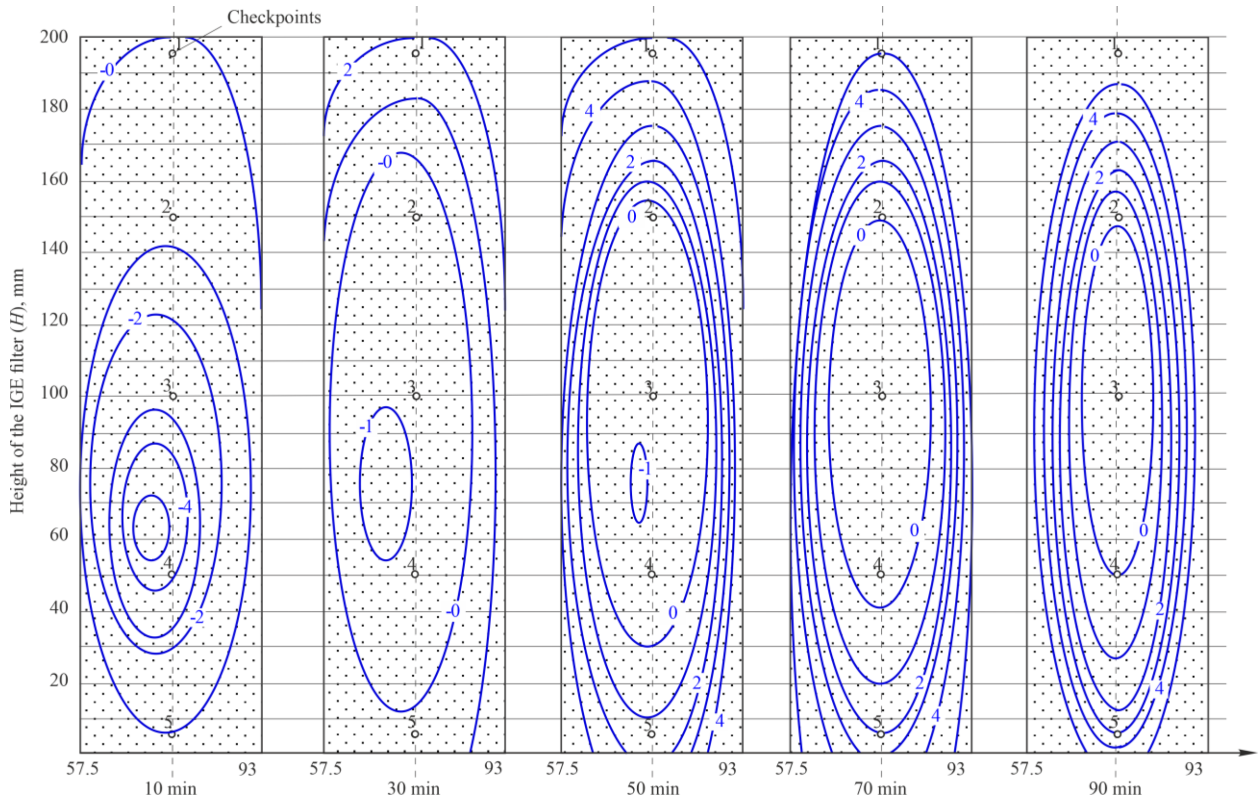

Figure 7. Temperature field in the IG filter with 5% mass concentration during its transportation along the wellbore in an aquatic environment at T_∞ =5°C

At that the time cycle t_c^d of transportation is determined by the formula:

$$t_c^d = t_t^d + t_t^b, \quad (20)$$

and is calculated based on the fact that:

– to connect the candle to the pipe column, it is necessary to spend t_t^b;

– to descend the candle down the wellbore in accordance with the selected speed U_{IGF} of transportation it is necessary to spend:

$$t_t^d = \frac{l_c}{\bar{U}_{IGF}}, \quad (21)$$

where:

$\bar{U}_{IGF}$ – the average speed of descent of the IGF along the wellbore (the time of the trip is recorded in the log).

After the IGF was installed in the water intake part of the well and a wooden seal was installed, the well was flushed through a filter column (Fig. 8). For this purpose, a drill string was installed in the inner cavity of the filter string and a stream of clean process water was used to remove sand particles from the filter, well, and bottomhole zone. The development time was recorded in the log.

The last stage of the work was the test pumping, which was carried out by a compressor that is part of the drilling complex located on the site. To do this, without removing the drill string, the three-way valve of the discharge pipeline was switched to the compressor position, the pump was turned off and the compressor was turned on. Air was supplied to the water intake part of the filter column through the injection pipeline and the drill pipe string, thereby intensifying the inflow of formation water and its removal to the surface.

Figure 8. Well flushing through a filter column at the Veselinov area of Veselinivskyi district, Mykolaiv region

The time of flushing and test pumping, well flow rate, static and dynamic levels, as well as the material composition of the flow that came out of the well, was recorded in the production research log.

3. Results and discussion

The wells were constructed in the autumn. The average daily air temperature +8.0…+14.0°C. The work on the manufacture of inverse gravel elements was carried out in the final period of flushing the exposed aquifer and removing the drilling tool from the well. The monolithization of the inverse gravel filter elements took place at a temperature of -20.0°C. The materials and their quantities used to manufacture the IGF are given in Table 2.

Table 2. Materials used to manufacture IGF

Parameter	Site 1	Site 2
Length of IGF, m	18.0	28.0
Gravel mass, t	0.7	1.1
Consumption of gelatin of T-11 brand, kg	4.5	7.0
Mass concentration of gelatin in IGE	3.5%	3.5%
Water volume, l	116.6	181.5

Given the small volumes, gravel was delivered from the enterprise base by drilling rigs, and water was delivered by water tankers from the nearest reservoirs.

After the aquifer was opened at full capacity, the following operations were carried out: washing of the productive horizon; removal of drill strings from the wells; measurement of the temperature of well waters; removal of IGE from the molds; preparation of filter columns; assembly of IGF. The temperature of the well fluid was: at the water surface +7.0°C; at the bottom of the well +13.0... +15.0°C.

After the drill strings were removed from the well, the IGF was transported through the wellbore with its landing in the water intake part. No complications were observed during transportation. The filter column shoes were installed at the design depths. After checking the gravel level in the wells with a probe, the above-filter parts of the columns were sealed with gland seals and the wells were subsequently flushed with process water. The flushing time was 4 hours.

When testing the manufacturing technologies and equipment of IGF hydrogeological wells, the timing of technological operations was recorded, the results of which are given in Table 3.

Table 3. Time costs for performing technological operations for equipping aquifers with IGF

Parameter	Site 1	Site 2
Drilling rig	URB 3A-3.13	
Time for removing the IGE filter from the molds, min	27.0	40.0
IGF assembly time, min	25.0	35.0
Candle length of filter column, m	12.0	12.0
Average time for the filter column candle to descend into the well, min	12.0	12.0
Filter column build-up time, min	6.0	6.0
Candle length of drill pipe, m	12.0	12.0
Average time for lowering the drill pipe candles into the well, min	12.0	12.0
Drill string build-up time, min	2.0	2.0
IGF transportation time through the wellbore, min	50.0	60.0

From Table 3 it is seen that the time spent on preparing the IGF for its transportation through the wellbore was 52.0 and 75.0 minutes, respectively, which is 0.1 work shift with a 10-hour shift. Considering that the preparatory period for the transportation of the IGF was carried out during the well flushing, it is insignificant and does not affect the economic indicators. Therefore, it was not taken into account.

In the final period of well construction, a test pumping of formation water was carried out. In its initial period, minor sanding of the wells was observed, but after 6.5-5.0 hours the water was completely clarified, and after another 2.5-3.0 hours, sanding stopped.

During the test pumping, the flow rates and liquid levels in the well were determined. The results are shown in Table 4.

Table 4. Flow rates and fluid levels in the well

Indicator	Site 1	Site 2
Well flow rate, m^3/h	1.25	10.8
Static level, m	8.0	45.0
Dynamic level, m	25.0	85.0
Specific flow rate, $m^3/m \cdot h$	0.07	0.27

Table 4 shows the flow rates at the time of the tests. Their values correspond to the forecast ones. The technical and economic indicators of the construction of water intake wells are largely determined by the time and money spent on their construction and equipment with filters, since the technology of drilling, well flushing, and material consumption largely depend on the technology of creating a gravel filter.

Most often in practice, two main types of gravel filters are used: drop-in filters, which are assembled on the surface of the earth with subsequent installation in wells in finished form (as in our case); created in the well using gravel, which is poured through the mouth and delivered to the water-receiving part along the wellbore filled with well fluid. Therefore, the second method was chosen as the basis for comparison during the analysis of technical and economic indicators of technologies.

To compare technologies, a number of factors can be identified that affect the cost of using technologies. The cost items do not take into account the technology of drilling a hydrogeological well, opening the horizon, flushing it, etc., because we consider them equivalent in both the first and second cases. In a certain sense, the process and cost of constructing hydrogeological wells are significantly affected by: the territorial location of the wells; diameters and depths of drilling; the tools used, flushing fluids and chemical reagents; well design; drilling equipment. But in our case, all this is insignificant. We are only talking about comparing the technologies of equipping the water-receiving parts of hydrogeological wells with gravel filters under the same conditions. When determining the economic efficiency of the compared technologies of equipping hydrogeological wells, the same costs were not taken into account.

Economic effect E from the introduction of the new technology was calculated based on the formula:

$$E = C^b - C^p, \quad (22)$$

where:

C^b and C^p – costs for equipment with gravel filters, respectively, by the basic and proposed method, thousand UAH.

In the general case, the material costs for equipment with gravel filters C^b using the basic technology will be determined by the formula:

$$C^b = C_f^b + C_w^b + C_r^b + C_{gr}^b + C_{t.g.}^b + C_p^b, \quad (23)$$

where:

C^b_f – cost of time for flushing the well with water, removing the clay crust, forming a cavity;

$C^b{}_w$ – cost of water required to replace the solution, flush the well, create a cavern;

$C^b{}_{r.}$ – cost of waste water removal;

$C^b{}_{gr}$ – cost of gravel consumed using the basic technology, (the cost of gravel from the Turbovsky quarry is 30 thousand UAH);

$C^b{}_{t.g.}$ – cost of time spent on backfilling through the wellhead and transporting gravel along the wellbore;

$C^b{}_p$ – cost of experimental pumping time.

Material costs for equipment with gravel filter C^p according to the proposed technology is determined as:

$$C^p = C^p_{p.IGE} + C^p_e + C^b_{gr} + C^p_{gl} + C^b_f + C^b_w + C^b_r + C^b_p, \quad (24)$$

where:

$C^p{}_{p.IGE}$ – cost of time spent by personnel for composite preparation, molding, mold disassembly and removal of the IGE filter;

$C^p{}_e$ – cost of electricity consumed by two 0.5 kW/h generators for 24 hours of IGE monolithization;

$C^p{}_{gr}$ – cost of gravel used according to proposed technology;

$C^p{}_{gl}$ – cost of gelatin used for the production of IGF;

$C^p{}_{f.}$ – cost of time for flushing the well with water, removing the clay crust;

$C^p{}_w$ – cost of water required to replace the solution, flush the well, create a cavern;

$C^p{}_r$ – cost of waste water removal;

$C^p{}_{p.}$ – cost of time for experimental pumping.

Comparative costs of time and money for the basic and proposed technology of equipment of the water-receiving part of hydrogeological wells depending on the area of work are given in Tables 5 and 6. The cost of materials and energy sources is accepted for the fall of 2023. The cost of a 10-hour work shift $C_{w.sh.}$ = 15 thousand UAH. In both cases, transportation costs are assumed to be equal.

Table 5. Results of calculating the economic efficiency of IGF equipment technologies for a hydrogeological well drilled at Site 1

Basic technology			Proposed technology		
Indicator	Duration of operations, work shift	Cost, thousand UAH	Indicator	Duration of operations, work shift	Cost, thousand UAH
–	–	–	$C^p{}_{p.IGE}$	0.25	3.75
–	–	–	$C^p{}_e$	–	0.10
–	–	–	$C^p{}_{gl}$	–	1.90
$C^b{}_f$	0.50	7.50	$C^p{}_{f.}$	0.50	7.50
$C^b{}_w$	–	4.20	$C^p{}_w$	–	4.20
$C^b{}_{r.}$	–	3.57	$C^p{}_r$	–	3.57
$C^b{}_{gr}$	–	27.00	$C^p{}_{gr}$	–	21.00
$C^b{}_{t.g.}$	0.20	3.00	–	–	-
$C^b{}_p$	3.00	45.00	$C^p{}_{p.}$	1.00	15.00
Total C^b	3.70	90.27	Total C^p	1.75	57.02

Table 6. Results of calculating the economic efficiency of IGF equipment technologies for a hydrogeological well drilled at Site 2

Basic technology			Proposed technology		
Indicator	Duration of operations, work shift	Cost, thousand UAH	Indicator	Duration of operations, work shift	Cost, thousand UAH
–	–	–	$C^p{}_{p.IGE}$	0.25	3.75
–	–	–	$C^p{}_e$		0.10
–	–	–	$C^p{}_{gl}$		2.94
$C^b{}_f$	0.50	7.50	$C^p{}_{f.}$	0.50	7.50
$C^b{}_w$		5.40	$C^p{}_w$		5.40
$C^b{}_{r.}$		4.60	$C^p{}_r$		4.60
$C^b{}_{gr}$		45.00	$C^p{}_{gr}$		33.00
$C^b{}_{t.g.}$	0.30	5.00	–	-	-
$C^b{}_p$	3.00	45.00	$C^p{}_{p.}$	1.00	15.00
Total C^b	3.80	112.50	Total C^p	1.75	72.30

Note: in case of "–" indicators, time and costs are absent

As a result of the assessment of the economic efficiency of the work on the Belousivka site (Table 5) it was found that: the technology of manufacturing the IGF filter allowed to reduce the consumption of gravel material by 1.3 times; the technology of equipping the water-receiving part of the IGF hydrogeological well under these geological and technical conditions allows to reduce unproductive time costs by 2.15 times or by 2.0 work shift; the economic effect of using the technology of equipping the water-receiving part of the IGF hydrogeological well is 33.25 thousand UAH.

Table 6 presents the data for calculating the economic efficiency of a well drilled in the Veselinove site, as a result of which it was established that: the technology for manufacturing inverse gravel filter elements allows reducing the consumption of gravel material by 1.4 times; the technology for equipping the water-receiving part of the IGF hydrogeological well under these geological and technical conditions allows reducing unproductive time costs by 2.2 times or by 2.1 work shift; the economic effect of applying the technology for equipping the water-receiving part of the IGF hydrogeological well is 40.20 thousand UAH.

The economic effect of using the proposed technology is achieved by significantly reducing the amount of gravel required for filter production, the time for its transportation along the wellbore to the aquifer by 0.25 work shift and the time for well development by 2.0 work shift. In addition, the advantages of the innovative technology for equipping the aquifer of deep hydrogeological wells are:

– reducing the consumption of gravel material and the time for its transportation to the aquifer;

– eliminating the hanging of gravel material during its transportation along the wellbore;

– improving the quality of gravel filters by forming a gravel coating on the surface during visual inspection and, if necessary, forming a multilayer coating with specified parameters;

– eliminating the likelihood of gaping voids;

– reducing the likelihood of sanding;

– reducing hydraulic resistance by increasing the effective porosity, etc. In this case, the well is equipped with a gravel filter with specified and unchanged geometric, hydraulic and granulometric parameters during transportation and installation in the aquifer.

The result of the application of the researched technologies is:

– increasing the durability and increasing the inter-repair period of well operation. Which ultimately reduces the cost of extracted water;

– improving the quality of work, thus improving the quality of drinking water supply for the population of Ukraine, thus improving the health of the nation and increasing the life expectancy of the country's population.

4. Conclusions

Production tests of the technology of equipping hydrogeological wells with inverse gravel filters confirmed the effectiveness of the developed and tested technology and showed that:

– the developed technology for manufacturing inverse gravel filter elements allows it to be used in drilling conditions;

– the developed technology for transporting inverse gravel filters along the wellbore and the standard technological equipment and the utilized tools do not complicate the process of equipping the water-receiving part of a hydrogeological well with a gravel filter, but rather simplify it.

The technology for manufacturing inverse gravel filter elements allows you to improve the gravel filter manufacturing process by forming a layer on the daysurface.

The proven technology of equipping the water-receiving part of a hydrogeological well with an inverse gravel filter allows reducing non-productive time costs by 2.1-2.2 times or by 2.0 work shift.

The economic effect of using the technology of equipping the water intake part of a hydrogeological well with a depth of 220.0-250.0 m with an inverse gravel filter was 33.25-40.20 thousand UAH.

The developed technologies for manufacturing an inverse gravel filter and transporting an inverse gravel filter along the wellbore can be used in the construction of hydrogeological wells with a depth of more than 200.0 m.

Author contributions

Conceptualization: AS, AK; Data curation: AS, DS; Formal analysis: IT, MI, MS; Funding acquisition: AS, AK; Investigation: IT, MI; Methodology: AS, AK, IT; Project administration: AS, AK; Resources: AS; Software: IT; Supervision: AS; Validation: AS, DS, MI; Visualization: DS, MI; Writing – original draft: AS, DS, MS; Writing – review & editing: AS, AK. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Дослідно-виробничі випробування технології обладнання інверсними блоковими гравійними фільтрами глибоких гідрогеологічних свердловин

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Мета. Робота спрямована на визначення ефективності технології обладнання водоприймальної частини гідрогеологічної свердловини інверсним гравійним фільтром та економічної ефективності виконання робіт за пропонованою технологією.

Методика. Поставлені задачі вирішувалися комплексним методом дослідження, що включав аналіз і узагальнення геолого-технічної інформації, фізичне моделювання, проведення експериментальних дослідно-виробничих досліджень.

Результати. Проведено виробничі випробування технології обладнання гідрогеологічних свердловин інверсними гравійними фільтрами, які підтвердили ефективність розробленої та випробуваної технології. У виробничих умовах апробовано технологію виготовлення інверсних гравійних елементів фільтра. Показана можливість застосування розроблених технологій виготовлення елемента інверсного гравійного фільтра та транспортування інверсного гравійного фільтра по стовбуру гідрогеологічних свердловин при їх спорудженні глибиною понад 200 м, із застосуванням стандартного бурового технологічного обладнання та інструменту.

Наукова новизна. Уперше обґрунтовано застосування для омонолічування у виробничих умовах рихлого гравійного матеріалу в блокову конструкцію гравійного фільтру бурової свердловини мінералов'яжучої речовини на водній основі, що містить органічний полімер – технічний желатин. Уперше показано можливість обладнання водоприймальної частини гідрогеологічних свердловин, в тонкозернистих і дрібнозернистих пісках, інверсними гравійними фільтрами за запропонованою технологією.

Практична значимість. У результаті дослідно-виробничих випробувань підтверджено ефективність розроблених технологій виготовлення інверсних гравійних елементів фільтра та транспортування інверсного гравійного фільтра по стовбуру свердловини. Під час випробувань визначено: витрати на виготовлення дослідних зразків інверсно-гравійних елементів фільтра; витрати на обладнання водоприймальної частини гідрогеологічної свердловини інверсними гравійними фільтрами; продуктивності свердловини; економічні показники технології обладнання гідрогеологічних свердловин фільтрами за запропонованими технологіями.

Ключові слова: *гравійний фільтр; вода; гідрогеологічна свердловина; водопостачання*

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