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MINING ECOLOGY AND SUBSOIL MANAGEMENT

Justification of Potentiality of Mine Drain Water Injection in Deep Geological Structures: A Case-Study of Yakovlevsky Mine

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Abstract—Potentiality of drain water injection in deep geological structures is investigated as a case-study of drainage system at Yakovlevsky Mine. The problem ensues from the presence of a very high zone of conductive fractures and from the very intense hydraulic connection between the water-bearing bottom coal layer and crystal ore layer due to the increased size of the mined-out space as the mine reaches the production capacity of 5 Mt, which can lead to water inrushes to underground stopes. The authors perform the predictive modeling of the joint operation of the drainage system and drain water injection to the bottom-layer water-bearing coal stratum with a view to improving safety of mining.

Keywords: Yakovlevsky Mine, drainage system, water-bearing bottom coal layer, dewatering wells, directional upholes, drain water injection.

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INTRODUCTION

The Central section of Yakovlevsky iron ore deposit is mined by the underground method under protection of a 65 m thick safety pillar, the work involves injecting significant volumes of drain water. Water inflow to the stopes of Yakovlevsky Mine is formed by underground water of the water-bearing bottom coal layer and crystal ore layer, to a small extent the Callovian water-bearing layer, the water of which permeates into the Lower Carboniferous sediments in local areas in the center of depression through the Bathonian-Bajocian clay layer [1–5]. The ore body is drained by horizontal wells, directional upholes, exploration and technical wells that dewater crystal ore layer to proactively relieve the pressure in water-bearing bottom coal layer. Pumped out drain water is removed to the surface, settled in a pond and then discharged into the river Vorskla.

Water-bearing bottom coal layer was used as an absorbing stratum, in which a depression cone was formed as a result of previous water drawdowns, years-long operation of the mine drainage system and the existing crossflow into the crystal ore strata. Overlying water-bearing layers are used for domestic and drinking water supply; from an environmental point of view, drain water injection into them is not allowed, and crystal ore layer has low permeability parameters, it is impossible to inject a significant volume of mine drain water into it.

1. NUMERICAL HYDRODYNAMIC MODEL

Hydrogeological calculations in conditions of interacting water-bearing layers, inhomogeneous permeability of aquifers, insufficient knowledge of the sources of reserve formation and their possible change during the operation of the mine drainage system, the need to solve inverse calibration problems for constructing reliable hydrogeological models are satisfied using numerical modeling [6–14]. To estimate potentiality of drain water injection into the bottom-layer water-bearing coal stratum, a five-layer spatial model of groundwater filtration has been developed, including the Callovian water-bearing layer, low-permeable Bathonian-Bajocian clays, water-bearing bottom coal layer and crystal ore layer interconnected through a separating low-permeable layer.

The Callovian water-bearing layer is confined to a sandy stratum that has numerous thin interlayers of sandstones, less frequently clays, with a permeability coefficient $k_f = 0.3 - 2.2$ m/day. Water-bearing bottom coal layer occurs in a thickness of limestone with interlayers of shaly and coal clays in the lower part of the section, k_f of rocks is 0.01–10.0 m/day. Crystal ore layer is confined to the fractured zone of the weathering crust of Precambrian crystalline rocks and disjunctive dislocation zones. For friable varieties of rich iron ore, k_f changes from 0.04 to 0.28 m/day, in shales and quartzites it does not exceed 0.01 m/day. The water-bearing bottom coal layer and crystal ore layer are hydraulically connected through clay deposits in the bottom of carboniferous rocks, dense redeposited ores and carbonated bauxite formations at the top of crystal ore strata.

Mathematical modeling was carried out using the MODFLOW program of GMS license package widely used in Russia to solve various hydrogeological problems. The permeation area of 30×30 km was adopted for modeling. The external boundaries are natural catchment areas for groundwater flow. The seepage flow of the study area was modeled by a non-uniform rectangular grid consisting of 219.961 (469×469) blocks. Block sizes vary from 12.5×12.5 m in central part of the model to 100×100 m in peripheral areas.

Along the external boundary of the model, boundary conditions of the third kind are implemented (relationship between changes in flow rate at the boundary and changes in the water level in permeation area), taking into account the expansion of permeation area when water-bearing layers are drained by introducing additional flow coefficient calculated from [15]. The error introduced by artificial limitation of pressures along the external boundary of the study area was practically eliminated.

The lower boundary of the permeation area is set at elev. –800 m in accordance with data on the propagation of tectonic faults in a crystal ore rock mass to a depth of 1 km [1]. The stopes in the model were set using boundary conditions of the third kind at elev. –425 and –525 m through additional flow coefficient [16], taking into account the replacement of stopes with a calculation block associated with step size of the grid field and the discrepancy between block sizes of the model and the stope. Drainage facilities in underground stopes are implemented in the model by their provisional bringing to a vertical well using the method of flow coefficients and taking into account the discrepancy between the model and actual sizes of generalized drainage system.

Additional flow coefficient for setting boundary conditions of the third kind in a well where drainage devices are implemented was determined by the formula: $\Phi = 1 / km[0.366 \log(\Delta x / r_0) - 0.25]$, where km is the water-conducting capability of the layer; Δx is the block size of the grid model at the location of a drainage facility; r_0 is the reduced radius of drainage facility [15].

The solution of predictive problems was preceded by calibration of the mathematical model by solving the inverse problem, the main goal of which is to achieve the maximum possible correspondence of the simulation model to the hydrogeological object under study. In the process of model calibration, permeability characteristics of the water-bearing layer were specified in plan and section. It was determined that the permeability parameters of Callovian sands are relatively uniform; calculations yielded k_f of sands 0.5–0.7 m/day. Bathonian–Bajocian clays in the center of the depression cone have $k_f = 10^{-4}$ m/day, and beyond depression cone—$k_f = 10^{-6}$ m/day. A considerable differentiation of k_f is observed in water-bearing bottom coal layer: in the area of distribution of ore bodies and in northeastern part of the hanging wall 5 m/day, in the lying wall and in northwestern part of the hanging wall 0.08–0.25 m/day. In the center of depression cone, weakly permeable separating layer between the water-bearing bottom coal layer and crystal ore layer is characterized by coefficient $k_f = 2.5 \cdot 10^{-4}$ m/day, beyond depression cone—$k_f = 5 \cdot 10^{6}$ m/day. In crystal ore stratum, k_f in the area of ore bodies distribution was 0.10–0.06 m/day, hanging-wall shales—0.005 m/day, lying-wall shales—0.02 m/day.

The water inflow to the mine drainage system is formed mainly by groundwater from the crystal ore layer and the crossflow from the bottom-layer water-bearing coal stratum through low-permeable rocks occurring in the roof of crystal ore rock mass (540 m^3/h). About 65 m^3/h flows from the Callovian water-bearing layer into the bottom-layer water-bearing coal stratum through poorly permeable Bathonian-Bajocian clays.

2. PREDICTIVE MODELING OF JOINT OPERATION OF DRAINAGE SYSTEM AND DRAIN WATER INJECTION SITE

To determine the total amount of drain water that can be used for injection in deep geological structures, predictive modeling of water inflow to drainage system elements is carried out. In the absence of an approved drainage system for the water-bearing bottom coal layer, predictive calculations were performed for two basic options:

—the surface drainage method with a linear system of arrangement of dewatering wells beyond the boundary of the shear zone;

—the underground drainage method with areal arrangement of directional upholes laid at elevation of –370 m.

When surface drainage method is used, pressure in the bottom-layer water-bearing coal stratum is relieved by 26 dewatering wells located 200 m from the mined section of the ore field beyond the boundary of the shear zone in northeastern part of the hanging wall, where $k_f = 5$ m/day. The distance between wells is 150–200 m. Dewatering wells are implemented in the model using boundary conditions of the second kind (setting a constant flow rate over time) with the condition $Q = 60$ m^3/h. When underground drainage method is used, pressure in the bottom-layer water-bearing coal stratum is relieved by 74 directional upholes laid at elev. – 370 m along drainage channels with a step of 50 m. Directional upholes in a system of underground stopes are implemented in the model by their provisional bringing to vertical wells using the method of flow coefficients. The predictive water inflow to directional upholes is determined in the amount of 1500 m^3/h.

Predictive modeling was carried out with the joint operation of a surface drainage system for the water-bearing bottom coal layer and drain water injection. Flow rate of drain water injection corresponded to the inflow to the drainage system, for which an iterative procedure was used, which ended when the pumping and injection flow rates were equal. Reservoir and drain waters of the water-bearing bottom coal layer have the same composition. The ingress of drain water does not disturb the balance between groundwater and rocks, does not contribute to the development of physical and chemical interaction, which allows injecting mine drain water into the water-bearing bottom coal layer without water treatment.

The calculations complied with the basic requirement of injection—the levels in wells at injection sites must be below the Earth's surface, i.e. injection is carried out in a free mode. Injection sites were selected on the basis of knowledge of Lower Carboniferous limestones obtained in previous geological exploration. Four potential sites for drain water injection were selected. They are located in southeastern part of the hanging wall of the ore body, where the water-bearing bottom coal layer has $k_f = 5.0$ m/day, and one injection site in the lying wall with $k_f = 1.5$ m/day (Fig. 1).

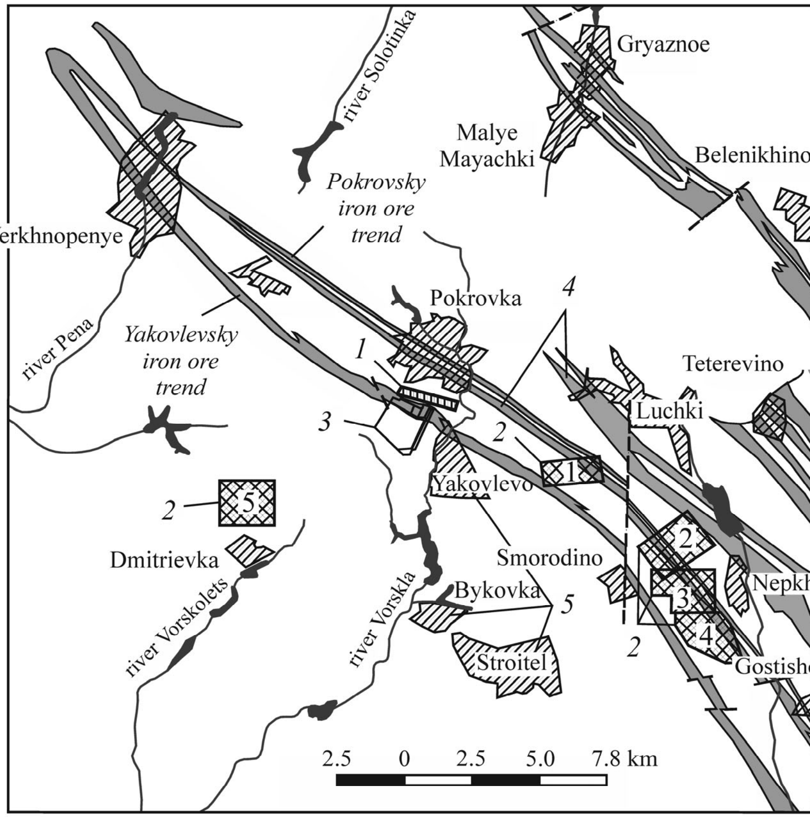

Fig. 1. Drain water injection sites under study: *1*—drainage area; *2*—drain water injection sites; *3*—stopes; *4*—ore trends; *5*—inhabited localities.

3. MODELING RESULTS

Results of predictive modeling for the joint operation of drainage system and drain water injection site are shown in Table 1.

Table 1. Results of predictive modeling

Section	Distance from the center of drainage system to the center of injection site, km	Water withdrawal by drainage system without injecting drain water, m^3/h	Number of dewatering wells in drainage system without injecting drain water	Number of wells at injection site	Flow rate of one injection well, m^3/h	Total injection rate taking into account the return of reclaimed drain water, m^3/h	Water inflow to drainage system, taking into account the return of reclaimed drain water, m^3/h	Increase in water inflow to drainage system due to the return of reclaimed water, %	Number of dewatering wells in drainage system
1	6.0	1560	26	90	30	2700	2700	73	45
2	10.8	1560	26	80	25	2000	2000	28	33
3	12.1	1560	26	80	23	1830	1830	17	31
4	13.7	1560	26	80	21	1670	1670	7	28
5	7.8	1560	26	100	11	1125	1125	—	—

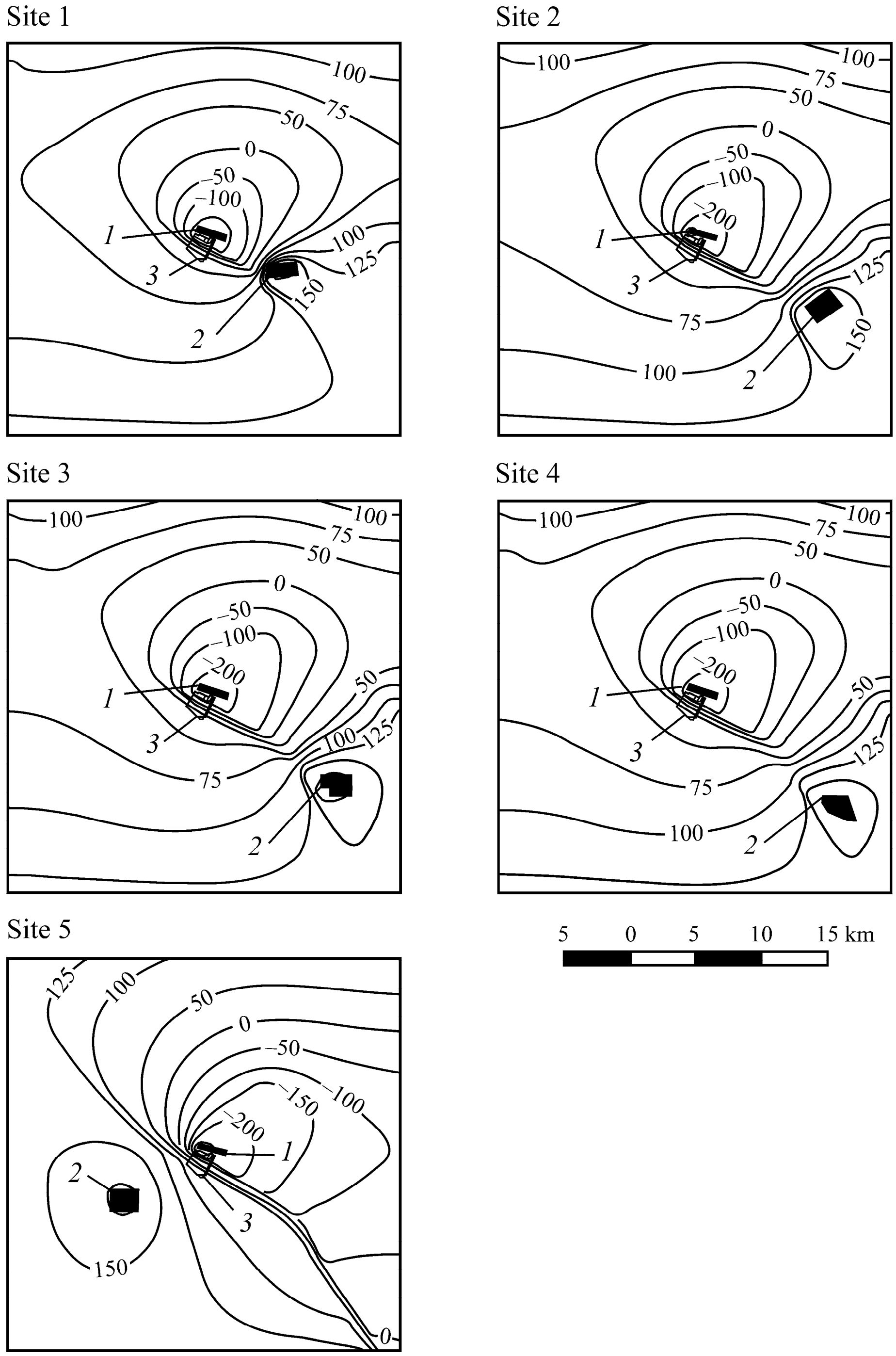

Fig. 2. Predictive distribution of level of water-bearing bottom coal layer at joint operation of drainage system and drain water injection sites (m abs.): *1*—pumping site; *2*—injection site; *3*—stopes.

Predictive distribution of groundwater levels in the water-bearing bottom coal layer under conditions of joint operation of surface drainage system and drain water injection sites under study is shown in Fig. 2. It is recorded that during the injection in Sites 1–4, the inflow of groundwater to the drainage system will increase to 2700–1670 m^3/h, the water inflow due to the return of reclaimed drain water to the drainage system will increase by 1140–110 m^3/h. When the injection site is located in the hanging wall of the ore body at a distance of 6 km from the drainage system, a maximum increase in water inflow to the drainage system is observed due to the return of reclaimed water

(73%). When the injection site is located at a distance of 13.7 km from the drainage system, there is a minimal increase in water inflow to the drainage system due to the return of reclaimed water (7%). An increase in water inflow to the drainage system leads to an increase in the number of surface dewatering wells. Thus, the operation of Site 1, closest to Yakovlevsky Mine, will lead to an increase in the number of wells from 26 to 45 in the drainage system with an average flow rate of 60 m^3/h for one well. Injection at the most remote site 4 requires an increase in the number of wells from 26 to 28 in the drainage system. To inject drain water into the water-bearing bottom coal layer, it is advisable to use sites 2–4 located in the hanging wall of the ore body at a distance of 10.8–13.7 km from surface drainage system. Sites 1 and 5 are not effective for injection: at Site 1, a very large volume of return injected drain water is expected, and at Site 5 it is impossible to reclaim all volume of pumped drain water due to the low permeability characteristics of rocks.

The most suitable place for injecting drain water into the water-bearing bottom coal layer is Site 3 according to the following parameters:

—the estimated volume of drain water in the amount of 1830 m^3/h can be injected;

—an increase in water inflow to the drainage system due to the return of reclaimed water will be 17% (270 m^3/h);

—a paved road passes through the territory of drain water injection site, which minimizes the cost of transport infrastructure during construction and operation.

CONCLUSIONS

The sources of formation of groundwater inflows to stopes in a layered water-bearing system have been identified in relation to the operating conditions of the Yakovlevsky deposit as the mine reaches the production capacity of 4.5 Mt/year. Hydrodynamic conditions for drain water injection into the Lower Carboniferous sediments have been determined: relatively high water conductivity of 100–350 m^2/day, similar composition of formation and drain waters, which allows injecting mine drain water without reclamation.

Numerical modeling has been used to obtain the parameters of joint operation of the drainage system for the water-bearing bottom coal layer and the site for drain water injection into the drainable water-bearing layer. Site 3, at which the injection of 1830 m^3/h of drain water is possible, including 270 m^3/h of return reclaimed water, is recommended for drain water injection.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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