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HYDROMECHANICAL PARAMETERS OF SAFE COAL SEAM EXTRACTION WITHIN A ZONE OF FLOODED MINE WORKINGS EFFECT

The article substantiated of rational parameters of a barrier safety pillar using an example of real mining and technical situation near the flooded 1st southern stope of the seam l21 of the southern slope of the Dobropilska mine of Industrial-Structural Enterprise "Colliery Group Dobropilske" for safe development of ventilation drift of the adjacent 2nd southern stope of the seam l21.

Parameters of safety pillar stability and risk of filtration water influx considering the changes of filtration, capacity, and geomechanical properties of a rock massif in time are qualitatively estimated. The estimation is based on a synthesis of models of non-stationary filtration in finite differences and profile finite-element hydrogeomechanical model of discrete medium.

It is established that the developed and flooded field of stopeshas a lasting draining influence oncoal–waste rock massif, while creating lowered values of pressures within the developed areas. In addition, permeability parameters of collapsed rocks approach the natural values in a process of their gravitational densification for 25 years. For sizes ofa safety pillar with width of 20 and 5 meters water inflows from the side of the flooded field have a secondary value and are 8…17 % of the total drainage of a new stope under design. During this, the risks of water influx from stratified zones of a roof of contiguous coal seamare present, where zones of the most intense crack looseningare formed in the interval of rock interlayer at joints of preparatory workings.

Key words: *hydrogeomechanical processes, flooding, barrier safety pillar, modelling, water inflow, deformations.*

Formulation of the problem and analysis of recent studies and publications. Along with the problems concerning predictable and controllable hydrodynamical mode to close down mines and flood them [1–5] as well as the use of their alternative water resource [6–8], the problems of mining within a zone of flooded workings, controlled by normative documents, remain topical. According to the Instruction on the safe mining in the neighbourhood of the flooded mine workings, Ukraine implements two techniques to provide water inrush safety. Technique one involves safety pillar remained between flooded mine workings and mine workings being driven; technique two involves unwatering of the flooded mine workings plus implementation of measures in the context of specific project. Safety pillar width is calculated according to analytical dependence where the pillar geometry is determined by means of the extracted seam thickness, depth, and the flooded mine working extension. However, the above involves neither filtration parameters nor capacity parameters of the pillar rocks and the flooded formation or water pressure values.

Analysis of actual data concerning parameters of safety coal pillars and their state, performed by [7–9], shows that calculations on the technique involves insupportable reliability margin resulting in the groundless losses of the mineral. Additional reserve of the pillar stability has been confirmed by authors of [10–13] while substantiating a modified criterion of a peak filtration pressure effect on a safety pillar according to which normative mechanism of water pressure shear effect cannot correspond to actual data resulting in up 10 times excess of project dimensions (or actual ones) of a pillar against the required geometry.

Thus, the problem to identify optimum pillar geometry within the flooded mine workings effect remains topical requiring parameter substantiation taking into consideration temporal changes in filtration and capacity properties of rock mass as well as in its geomechanical properties since on the one hand, it provides safe mining, and its completeness on the other hand. *Objective* of the work is to substantiate rational parameters of a safety pillar in terms of actual mining situation in the neighbourhood of the flooded southern longwall of l_2^1 seam of southern slope of *Dobropolskaia* mine (Production structural subdivision *ShU Dobropolskoie*) to drive safely ventilation drift for contiguous southern longwall 2 of l_2^1 seam. In line with the objective, a *problem* of quantitative estimation as for the pillar stability as well as a risk of filtration water inrush has been solved relying upon synthesis of models of nonstationary filtration in terms of finite differences (S*tage 1*), and a profile finite-element hydromechanical model *(*S*tage 2)*.

Experimental part. Both filtrational and capacity parameters of rock mass are the key uncertainty while solving hydrodynamical prognostic problems since, in the context of natural rock occurrence, the parameters experience their areal changes then being subject to temporal variations during each process cycle taking place when a mine functions. Inverse solution while developing a target filtration model of a mine field is the most acceptable technique to determine their variational regularities.

Stage 1. To identify prognostic water inflows as for the mine working, locating within an area of worked-out and flooded sites effect*, numerical geofiltrational model* of the mine field site has been developed. The model has been implemented with the help of finite differences method using MODFLOW software system. A model of three-dimensional flow of constant-density underground water within porous medium is described using the partial differential equation

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where k_{xx}, k_{yy}, and k_{zz} are hydraulic (filtrational) conductivities towards X, Y, and Z coordinate axes; h unknown water pressure function (L); t is time (T); W is unit flow capacity: $W > 0$ is for incoming flow, and $W < 0$ is for outgoing flow; and S_s is specific capacity of porous medium (L^{-1}).

Together with boundary conditions and initial conditions, equation (1) describes three-dimensional nonstationary flow of underground water within heterogeneous and anisotropic mediums if the main directions of vectors of hydraulic conductivities coincide with the coordinate axes directions.

In the plan, the study area, being of 2000×2500 m dimensions, has been approximated by means of a net domain with 50×50 pitch; it represents both hydrodynamic and mining-technical situation of the southern sloped share of contiguous seams l_3 and l_2^1 within 450 m level in *Dobropolskaia* mine as of the year of 2018.

Each of the nodes reflects seam hypsometry, filtration parameters and capacity parameters of water-bearing levels as well as separating formations (Tables 1, and 2), and initial position of underground water level.

According to its geological structure and hydrogeological conditions, the filtration area is schematized vertically by means of 11 simulation layers covering following water-bearing levels and aquitards (Fig. 1): Layer 1 is water-bearing level of the Neogene-Quarternary deposits; Layer 2 is averaged formation with argillite, aleurite, sandstone, limestone, and coal interbedding in 79:18:1:2 percentage ratio; Layers 3 and 5 are water-bearing sandstones; Layer 4 is argillite-aleurite aquitard;

Table 1

Initial values of the model filtration parameters

Filtration coefficient ($K_ф$), [m/day] of rocks (formation percentage)				
Limestone (1 %)	**Sandstone (18 %)**	**Coal (2 %)**	**Argillite and aleurite (79 %)**	**Average weighted in terms of *X* and *Y* axes; within brackets – in terms of *Z* axis**
Coal-bearing formation with 50–150 m depth from overburden floor				
0.25–2.0	0.3	0.3	0.005	0.077 (0.006)
Coal-bearing formation with 150–300 m depth from overburden floor				
0.20–0.75	0.1	0.1	0.003	0.028 (0.004)
Coal-bearing formation with 300–500 m depth from overburden floor				
0.2	0.04	0.07	0.002	0.011 (0.0025)
Coal-bearing formation with more than 500 m depth from overburden floor				
–				0.007 (0.0013)

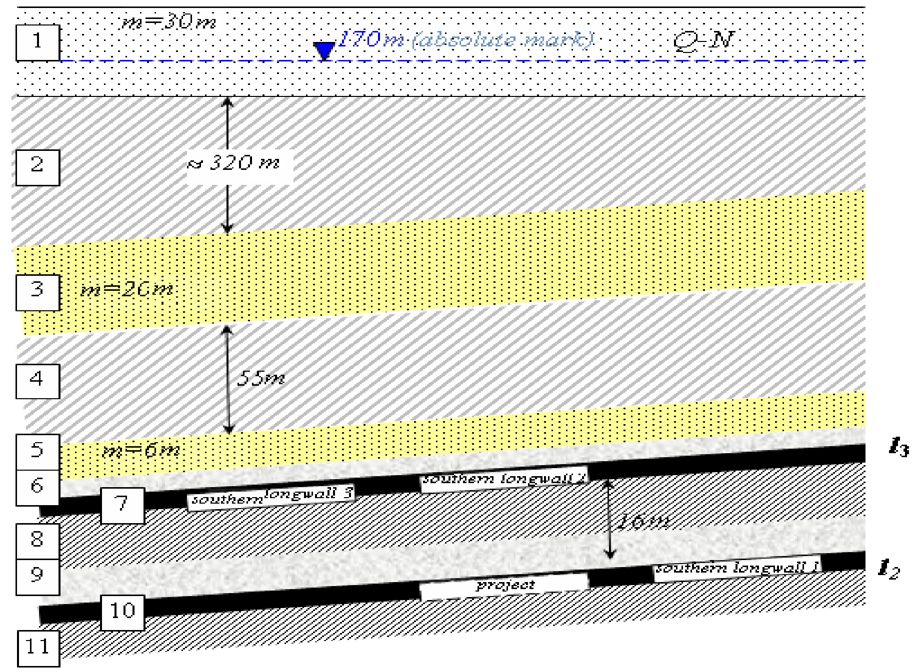


Fig. 1. Schematic view of the formation being modeled

Layers 6 and 9 are argillite aquitards; Layers 7 and 10 permeable coal seams l_3 and l_2^1 respectively; and Layers 8, and 11 are aleurite aquitards.

Table 2

Initial capacity parameters of the model [%]

Simulation layers	Gravitational capacity	Elastic capacity
Overburden (simulation layer 1)	20	0.1
Coal-bearing formation (simulation layers 2-11)	0.1	$8 \cdot 10^{-5} \ldots 10^{-3}$

3rd type boundaries with the provided supply ($H = Const$), reflecting general nature of underground water inflow/outflow within the studied area, have been given as external hydrodynamic boundaries of simulation layer 1 of the Neogene-Quarternary deposits. Water pressure values within the model boundaries have been taken in accordance with watermarks, determined by exploratory drilling; they vary within 147–178 m. Thickness of the aquifer is 10 m.

Boundary conditions of a coal-bearing formation (i.e. simulation layers 2–11) are of the same type; at the northern boundary they are preset in the formed of a 3rd type remote boundary ($H = Const$) characterizing the deposit basseting to overburden with such water pressure values as 162–178 m.

Conductivity within external lines of the simulation layers has been determined relying upon the averaged values of their filtration characteristics within the area being modeled.

Mine workings of l_3 and l_2^1 seams, being drainage line ($H = Const$) with known (preset) lowering level of underground water at a mark of coal seams floor (simulation layers 7 and 10), are internal boundaries of the model.

The represented model structure makes it possible to take into consideration hydraulic connection between coal-bearing formation and overburden as well as to estimate quantitively the disturbed model of underground water in the context of the worked-out southern sloped share of mine field and its share planned to be mined.

Particularity of the current problem is to estimate water balance within a local site of the mine field which hydrodynamic situation depends upon the development of contiguous (18–22 m) coal seams l_3 and l_2^1 within a zone of flooded mine workings effect.

l_3 seam, located in the southern sloped share, was mined from 1959 till 1992. Southern longwall 3 (Fig. 1) was mined in 2017-2018; a pillar with up to 37 m width was remained in the neighbourhood of the flooded mine workings of southern longwall 2 (1991–1993 extraction period). When the longwall was mined under such conditions, water inflows were registered in the form of seepage from the seam roof within certain sites only.

Southern sloped share of l_2 seam was under mining from 1969 till 1990; southern longwall 1 within 450 m level was extracted from 1989 till 1990; water inflows demonstrated themselves in the form of seepage and currents (up to 1.0 m^3/hour rate). Since 2005, belt road has been isolated; mine workings and development workings have been flooded; access to them is not available. Up to the year of 2005, water inflow with up to 20 m^3/hour rate was registered within the mine field site.

As of August 2018, water inflow into a water collector of the end slope from the southern side of l_2^1 seam was 15 m^3/h; in terms of l_3 seam, it was 7 m^3/h.

The described actual hydrodynamical situation has been simulated to identify and determine both capacity parameters of the disturbed rock mass and filtrational ones. Lines of the worked-out longwalls are preset in the form of drains with 10 m^2/day simulation capacity of the rock mass corresponding to 0.004 m/day value of filtrational permeability.

According to inverse solutions, imbalance of geofiltrational model is not more than 1.48 m^3/day; relative error is 0.02 %. Value divergence between model water inflows and actual ones is up to 4.6 m^3/hour.

The model has been identified to real conditions; water transmissivity for mined-out space of longwalls is 0.08 to 0.1 m^2/day; gravitational capacity of broken rocks is $\mu = 0.3$; and elastic filtration characteristic is $^* = 10^{-5}$.

Inverse epignosis solution has helped determine following regularities of the disturbed rock mass:

1) southern longwalls 1 and 2, mined-out previously in terms of l_2^1 and l_3 seams within southern slope, keep exerting their drainage action on the coal rock mass developing lowered water pressure values inside of the mined-out sites of 450 m level;

2) water pressure values within the flooded area (7–13 m) form water inflows of 20–30 m^3/h rate; they are determined using water discharge characteristics in the context of complicated inclined occurrence of coal seams. With that, local backwater is formed within hypsometrically lowered sites of extraction pillars; and

3) filtrational parameters of the disturbed rocks within the mined-out sites of a mine field are characterized by values being proximal to natural ones which can be explained by their gravitational 25–29 year compaction starting from the moment of extraction of southern longwalls 1 and 2 (l_2^1 and l_3 seams).

The prognostic modeling involved qualitative estimation of values of water inflows towards southern longwall 2 upon availability of a safety pillar and without it within a zone where the flooded mine workings of l_2^1 seam take action. The calculations were performed in terms of nonstationary filtrational mode when average face advance is 100 m/month.

Formation of water inflows towards the projected longwall 2 of l_2^1 seam if safety pillar is available takes place mainly at the expense of capacity reserves within the coal seam roof; it takes place partially (i.e. 8 to 17 %) at the expense of a water inflow through a safety pillar from the mined-out longwall 1 of seam l_2^1. Thus, the water inflows towards the projected longwall vary during the whole period of mining operations (i.e. 10 months) from 3.72 to 14.07 m^3/h if safety pillar is available, and from 2.88 to 11.18 m^3/ if not (a development drift was driven by means of coal-cutting with stone similarly to the southern longwall 1). In this context, for the considered variants, water inflows from the mined-out of the extraction pillar of longwall 1 of seam are l_2^1 0.65-1.16 and 0.39-1.03 m^3/h respectively.

If safety pillar is not available, then the lowered values of the prognostic water inflows from a mine field of the flooded longwall can be explained by low water pressure values formed within a line of a southern belt road of the mined-out longwall under the effect of the current drainage and specific features of inclined occurence of the coal seam.

Stage 2. Stress-strain state of barrier (or safety) pillar rocks within a zone, effected by the flooded mine workings, depends upon the pillar geometry, and characteristics of enclosing rock mass determining its filtrational permeability as well as a value of water inflows. Hence, joint solution of hydrodynamic and geomechanical problems to evaluate its hydrogeomechanical operational state in terms of out-of-limit deformations has been simulated using profile model of a mine field site where the results of scheduled filtration, concerning water pressure fields around mine workings, have been applied.

Basic differential equation of the profile filtration, used by finite-element formulation of PHASE2 software system, is

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = m_w \gamma_w \frac{\partial H}{\partial t}. \quad (2)$$

where H is water pressure; k_x and k_y are hydraulic (i.e. filtrational) conductivities towards coordinate axes X and Y; Q is the flow rate at the boundary; t is time; m_w is a coefficient of changes taking place in the capacity; and γ_w is specific water weight.

Application of a method of weighted residuals of Galerkin to the differential equation (2) helps generate such a finite-element expression to describe two-dimensional filtration

$$\tau\int_A\left(\left[B\right]^T\left[C\right]\left[B\right]\right)dA\left\{H\right\}+\tau\int_A\left(\lambda<N>^T<N>\right)dA\left\{H\right\},$$

$$t=q\tau\int_L\left(<N>^T\right)dL \qquad (3)$$

where $[B]$ is gradient matrix; $[C]$ is a matrix of hydraulic (i,.e. filtrational) conductivities of the elements; $\{H\}$ is nodal water pressure vector; $<N>$ is a vector of interpolational functions; q is unit rate through the element line; τ is the element thickness; t is time; λ is capacity parameter for nonstationary filtration being equal to $m_w\gamma_w$; A is a symbol to sum up in terms of the element area; and L is a symbol to sum up in terms of the element line.

Compactly, the filtrational equation for finite element is

$$[K]\{H\} + [M]\{H\}, t = \{Q\}, \qquad (4)$$

where $[K]$ is a matrix of the element properties; $[M]$ is a matrix of the element masses; and $\{Q\}$ is a vector of a flow rate within the element.

Equation (4) is a general form of finite-element equation of nonstationary filtration within the profile model.

Geomechanical state of coal rock mass within the area of the planned extraction of the southern longwall 2 of seam l_2^1 was evaluated for characteristic section being perpendicular to the strike of extraction pillars within seams l_2^1 and l_3 (Fig. 1)

Geostatic pressure, corresponding to the mining depth in terms of l_2^1 seam extraction by means of the southern longwall 2, depended upon the weight of overlying rock formation within the model upper line. Values of physical and mechanical characteristics of the rock layers were taken according to the data of the mine field prospecting.

The stope was modeled with the help of the known level of the mined-out space rock deformation corresponding to 1.2 being a coefficient of the immediate roof loosening.

The profile hydrodynamical model was patterned relying upon the data of solving target-spatial filtration problems where constant water pressure were defined within a line of the area under modeling as well as drainage lines within both mined-out and projected extraction pillars.

Prognostic modeling of stress-strain state of the disturbed rock mass has been performed for extraction conditions of the southern longwall 2 with40, 35, 30, 25, 20, 15, 10 and 5 m pillar width from the flooded belt road of the southern longwall 1 of seam l_2^1.

Evaluation of the water inflows, formed from the flooded mine workings, involves the conditions when drainage either is not available or it is limited within a line of the southern belt road 1; high filtration permeability of the caved rocks within the mined-out area (i.e. up to 1 m/s) has already been considered.

When the projected longwall was mined, stress-strain state of the rock mass at the territory of the safety pillar was controlled with the help of values of movements, deformations, and stresses within the rock mass as far as the line of the development mine working of the southern longwall 2 approached the mined-out area of longwall 1 of the seam l_2^1. Evaluation of the rock mass geomechanical state with the help of the3 model involved the effect of distribution of water pressures which values were obtained at the stage of profile hydrodynamical problems solving in terms of different widths of the barrier pillar.

Fig. 2 demonstrates a character of out-of-limit deformation of coal rock mass for those solution variants where widths of the barrier pillar were 35, 20, and 5 meters. Out-of-limit rock deformation involvement into the barrier pillar neighbourhood takes place within a roof in the range of 45-65 m of the coal seam being mined. Formation of excessive fissuring zones within the ranges results in the decreasedwater pressures from the flooded belt road of the southern longwall 1.

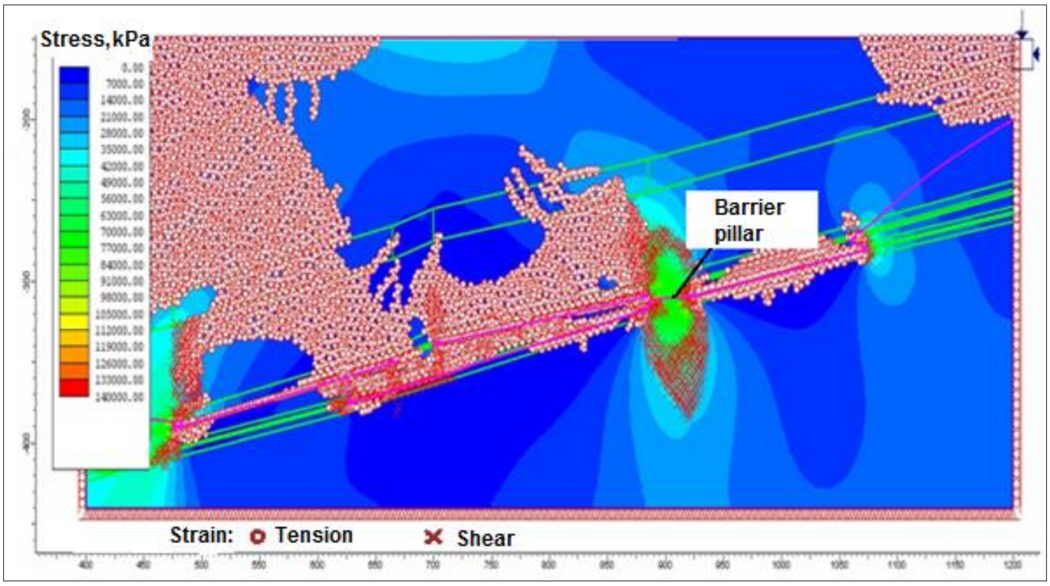
Within the barrier pillar, progress of out-of-limit deformation zones is observed in the range of the edge areas of the coal seam at the depth of down to 10.0 m; closure of the zones takes place when the barrier pillar is less than 20.0 m. thus, out-of-limit deformation zones and subsequent increase in the barrier pillar permeability happen if its width is less than 20.0 m.

In the context of the numerical model, effect of out-of-limit deformation on the filtration processes through a barrier pillar has been estimated by means of 2 to 10 times increase in the coal seam permeability to compare with its natural permeability [14–16].

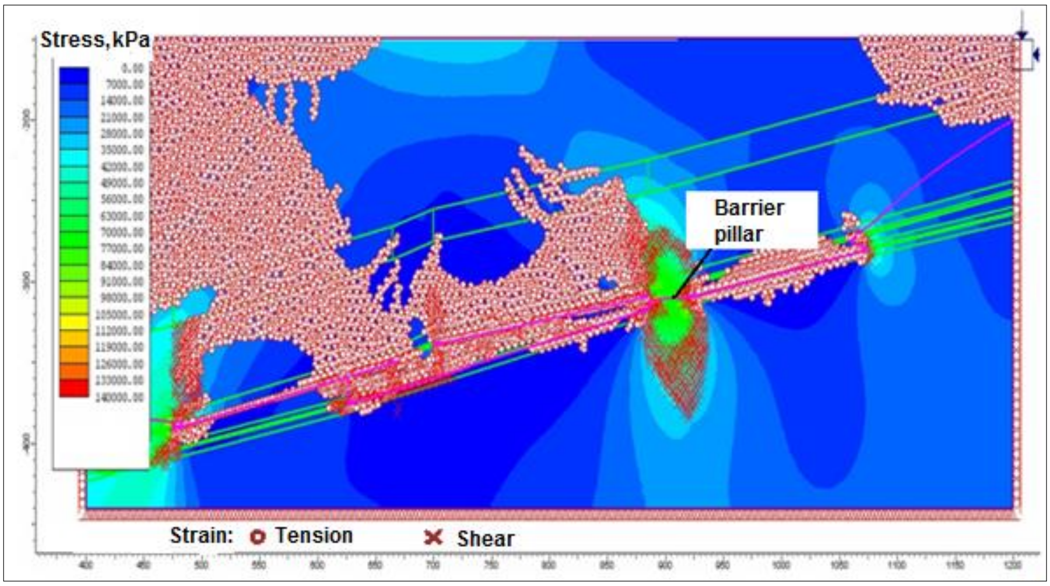
Fig. 3 demonstrates the results of calculations, concerning water inflows formed through the barrier pillar depending upon its permeability values (filtration coefficient is 0.07, 0.14, and 0.7 m/day).

It should be noted that if permeability of the barrier pillar is maximal, decrease in its width (Fig. 3) cannot result in significant water inflow increase. That is connected with maximum consumption of a resource of the formed water inflows from the flooded belt road of the southern longwall 1 of seam l_2^1.

Availability of unfilled flooded cavities, containing free water, within a junction area of previously mined-out southern longwalls 1 and 2 of seam l_3a is source of additional water inflow to a line of the projected ventilation drift within seam l_2^1 [17–20].



a



b

Fig. 2. Forming zones of out-of-limit deformation of coal rock formation if barrier pillar width is 35 (a) and 5 (b) meters

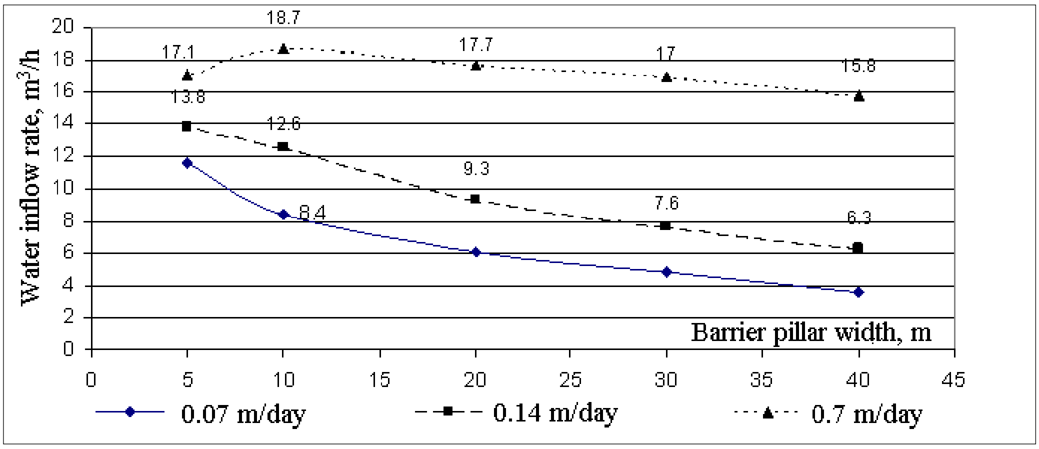


Fig. 3. Forming prognostic water inflows in terms of different widths of the barrier pillar and its permeability levels

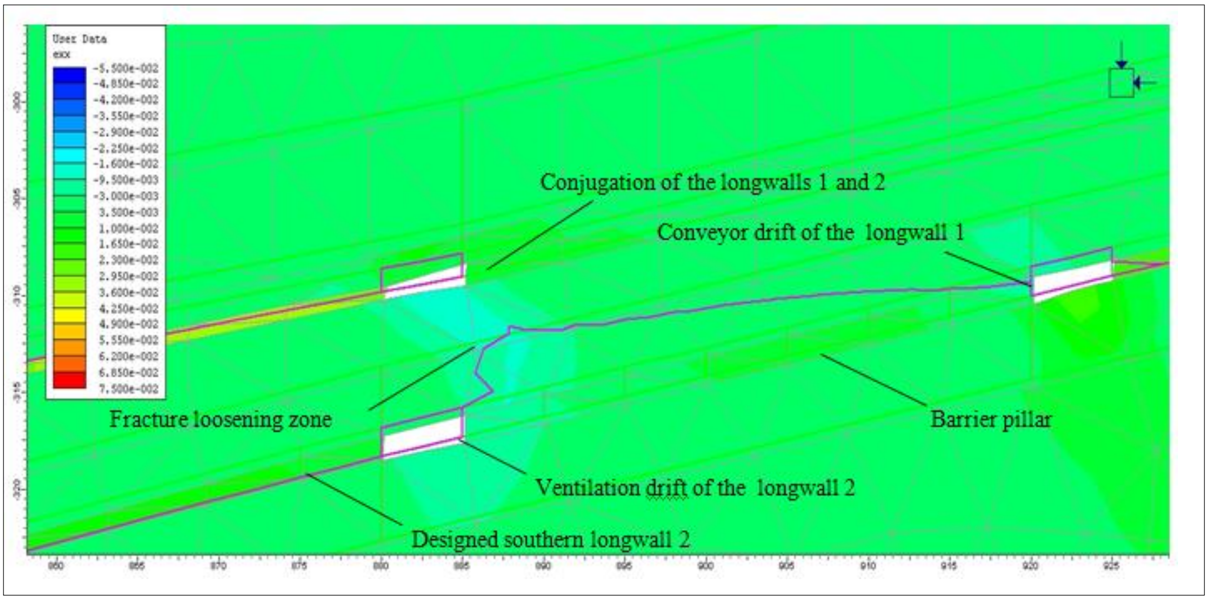


Fig. 4. The field of relative horizontal deformations when conjugation site of the 1st and 2nd southern longwalls of l3 seam is undermined by the designed 2nd southern longwalls, as a fraction, barrier pillar width 35.0 m

Under the conditions, the progress of out-of-limit deformation, followed by the formation of aquiferous fissures within undermining site at the boundary of southern longwalls 1 and 2 of l_3 seam, is the key factor determining formation of water inflows to the projected mine working.

Analysis of stress-strain state modeling, in terms of various relative positions of boundaries of southern longwalls 1 and 2 of l_3 seam, and ventilation drift of the southern longwall 1 of l_2^1 seam shows that location of zones of the most intensive fracture loosening within interval of rock parting is characterized by 10 to 15 m zone under the junction area (Fig. 4).

Location of the projected ventilation drift of the southern longwall 2 of l_2^1 seam out of the area of the most intensive fracture loosing is one of the conditions to decrease formation of water flows in the context of the determined effect of junction boundary of the southern longwalls 1 and 2. That can be achieved by the development and extraction of oblique longwall providing free outflow.

Conclusions. When the model of nonstationary filtration in finite differences was brought into coincidence with the profile finite-element hydrogeomechanical model of discrete medium, it has become clear that both mined-out and flooded field of mine workings exerts long-term drainage influence on coal rock mass developing lowered water pressure values within the mined-out sites; moreover, permeability parameters of the caved rocks approach natural values during their during their 25-year gravitational compaction. If pillar width is 20 and 5 m then water inflows from the flooded field are of subordinate value being 8 to 17 % of total drainage by a new projectable longwall. In this context, water inrush risk from stratified areas of a contiguous coal seam roof is possible where zones of the most intensive fracture softening are formed. That may be prevented while developing and mining of oblique longwalls with standard slope for water discharge.

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Садовенко І.О., Загриценко А.М., Тимощук В.І., Деревягіна Н.І. ГІДРОГЕОМЕХАНІЧНІ ПАРАМЕТРИ БЕЗПЕЧНОГО ВІДПРАЦЮВАННЯ ВУГІЛЬНИХ ПЛАСТІВ В ЗОНІ ВПЛИВУ ЗАТОПЛЕНИХ ВИРОБОК

В статті обґрунтовані раціональні розміри бар'єрного цілика на прикладі реальної гірничо-технічної ситуації біля затопленої 1-ї південної лави пласта l_2^1 південного ухилу шахти «Добропільська» ПСП «ШУ Добропольське» для безпечного проведення вентиляційного штреку суміжної 2-ї південної лави пласта l_2^1.

На основі синтезу моделей нестаціонарної фільтрації методом кінцевих різниць і профільної кінцево-елементної гідрогеомеханічної моделі дискретного середовища кількісно оцінені параметри стійкості цілику і ризик фільтраційного прориву води з урахуванням зміни фільтраційно-ємнісних і геомеханічних властивостей гірського масиву в часі.

З використанням чисельного моделювання процесів нестаціонарної фільтрації в кінцевих різницях визначені прогнозні водопритоки в виробку, що знаходиться в зоні впливу відпрацьованих і затоплених ділянок. Оцінка напружено-деформованого стану порід бар'єрного (або охоронного) цілика в зоні впливу затоплених виробок виконана на профільній моделі ділянки шахтного поля, де використані результати рішень задач планової фільтрації з формування поля напорів навколо гірничих виробок.

Встановлено, що відпрацьоване і затоплене поле очисних виробок має тривалий дренуючий вплив на вуглепородний масив, створюючи знижені значення напорів в межах відпрацьованих ділянок, а параметри проникності зрушених порід наближаються до природних значень в процесі їх гравітаційного ущільнення протягом 25 років. При розмірах цілика шириною 20 і 5 метрів водопритоки з боку затопленого поля мають другорядне значення і становлять 8 … 17 % від загального притоку до нової лави. При цьому ризики прориву води існують з розшарованих зон покрівлі зближеного вугільного пласта, де в інтервалі породного міжпластя на сполученні підготовчих виробок формуються зони найбільш інтенсивного тріщинного розпушення.

Ключові слова: *гідрогеомеханічні процеси, затоплення, бар'єрний цілик, моделювання, водоприток, деформації.*