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FORECASTING SAFE CONDITIONS FOR DEVELOPING COAL BED SUITES UNDER AQUIFERS ON THE BASIS OF GEOMECHANICS OF TECHNOGENIC WATER CONDUCTING FRACTURES

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Studies of the processes of displacement of rock massif layers in the course of their initial underworking indicate that their maximum curvature tends to decrease in the inverse proportion to squared distance to coal bed from the layer in question. It manifests itself in the distribution of vertical extension deformations: these are the largest in the vicinity of the coal bed and decrease towards the surface. Such is the consequence of the mechanism of bending the massive layers: the curvature of underlying layers is higher than that of overlying ones.

In the zone of complete underworking the maximum curvature of each layer of the repeatedly underworked bedded formation is equal to the maximum curvature of the surface, that is the curvature of the overlying layer repeats the curvature of the underlying one. Hence, the maximum curvature of any layer in the massive is inversely proportional to squared depth of the coal bed suite. Note that the distribution of vertical deformations of the massive differs in both its quality and quantity from that of the initially underworked massive: vertical deformations are an order of magnitude fewer and their distribution is presented by alternating deformations of extension and compression. Such is the consequence of the mechanism of layer bending in case the massive is underworked repeatedly and it explains why the height of the zone of water conducting fractures does not grow in such conditions with respect to the one formed during the excavation of the initial layer of the suite.

The technique of forecasting the development of zone of water conducting fractures developed on the basis of such geomechanical processes makes possible safe excavation of coal beds under aquifers.

Key words: delamination fractures, layer separation, normally secting fractures, boundary curvature, initial and repeated underworking, zone of water conducting fractures.

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Introduction. Extracting mineral resources from earth entrails entails perturbing the natural tensed state of rock massive which results in their displacements and deformations. In the course of such processes the geomechanical state of the underworked massive changes considerably (its strength characteristics deteriorate, fractionation and water permeability of rocks increase). In case an aquifer appears to lay within the zone of underworking, it endangers mining activities on the one hand, while on the other it may be unacceptable from the point of protecting that aquifer itself.

When doing mining under aquifers a special geomechanical and hydro-geological forecast shall be produced of violating the natural state of the rock massive, serving as a foundation for stipulating safe conditions of excavating coal beds from earth entrails that would exclude formation of hydraulic links between the mining excavations and aquifers which would result in unacceptably high water penetration or even its breakthrough into the mine.

Aquifers are understood not only as surface water runs (rivers, creeks, canals) and basins (lakes, water reservoirs, industrial waste dumps), but aquiferous strata and complexes, major aquified tectonic faults and fractionation zones, drowned mines, unplugged survey, hydrogeological, water level lowering and other technical wells [2, 16]. Therefore, in conjunction with the problem at hand, aquifer is to be understood in a wide meaning of the word as a natural or artificially produced water collection that may potentially serve as source for water breakthrough into the mines.

Development and formation of normally transecting fractures, delaminations and separation cavities. In the course of excavating coal beds the natural equilibrium of rock massive is perturbed, so that the massive deforms and displaces [1, 14, 17]. A cave-in zone forms immediately above the worked out cavity of the coal bed. Rocks in that zone are subject to heaviest deformations, so that they disintegrate into separate pieces and blocks of irregular sizes that avalanche disorderly into the excavated cavity. Apparently, water would penetrate unobstructed through such a technogenic zone. The parameters of that zone may be approximately assessed using the Prof. S.G. Avershin [1] formula

$$h = m/[(k-1)\cos\alpha], \tag{1}$$

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where h – is the height of collapse zone; m – is the excavated thickness of the coal bed; k – is the factor of rock volume expansion (varying from 1.1 to1.5 for coal rocks); α – is the slope angle of the coal bed.

Propagating towards the surface the collapse zone transforms into the zone where the layers have not lost their continuity. In that zone the maximum curvature of the layers decreases in inverse proportion to squared distance from the coal bed to the considered layer. Following that distribution the underlying layer bends stronger than the overlying one, which promotes delamination and the formation of separation cavities (Fig.1). Delaminations result in the massive losing its tightness. The maximum loss of tightness (with delamination cavities opening up) is observed near the coal bed (Fig.1a) while it gradually decreases towards the surface (Fig.1b). Cross-sections removed from the stall towards the excavated space demonstrate certain closure of delaminations, and the massive tightens back partially. Delaminations per unit thickness of the massive in the vertical are characterized by the distribution of vertical deformations, as retrieved along the well axis by its depth benchmarks. These are presented as respective profiles in the scheme (Fig.2) ε_1. As seen from those profiles, the maximum loss of tightness (extension deformations in the vertical) is observed in the vicinity of the coal bed and diminishes gradually towards the surface. Cross-sections removed from the stall towards the excavated space demonstrate certain closure of delaminations, and the massive tightens back partially. As a rule, deformations ε_1 occurring during the initial underworking are all positive, since, as mentioned above, the curvature of the underlying layer is always larger than that of the overlying one [3, 5, 18]. Further progress of the stall brings the negative curvature to zero, roughly.

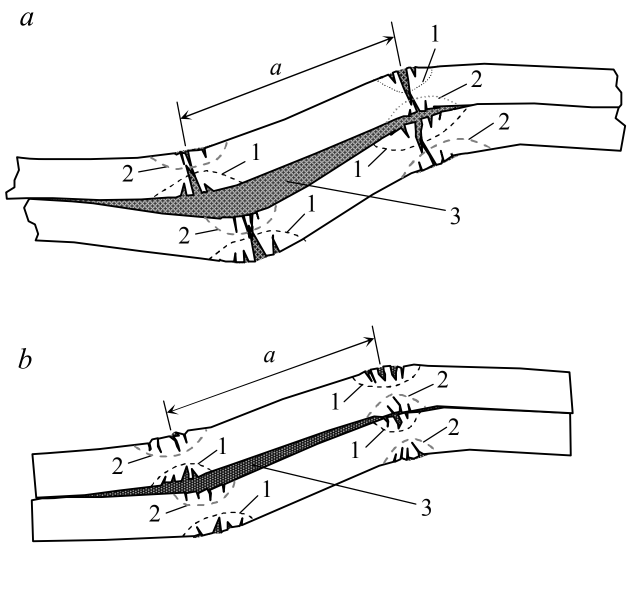

Fig.1. Scheme of technogenic fractures forming in the layers lying in the vicinity of the coal bed (*a*) and at some distance from it (*b*)

1 – extension zone; 2 – compression zone; 3 – delamination cavity; *a* – is the size of the block

When the layers above the collapse zone bend, initially one and the same section of any layer bends with a positive curvature and then goes into the bend of the negative curvature. Positions of the maximum curvatures develop fractures transecting the layer normally. The curvature being positive the upper part of the stack of layers bending together (we will call it a layer for simplicity hereunder) undergoing an extension has the fracture formed and opened, while the lower part of the stack is compressed (Fig. 1). Next, as the stall progresses that section of the layer undergoes a negative curvature bend. Now extension deformations form in the lower part of the layer with normal transecting fractures opening there, while fractures in the upper part of the layer close and a compression zone forms there. Therefore the process of developing a normally transecting fractures goes from both the top and the bottom of the layer to meet each other halfway. A block of size a forms between the neighboring normally transecting fractures (Fig. 1). Further progress of the stall brings the negative curvature to zero, roughly (a flat bottom of the mold forms). Such a process of sign alternating bends is repeated in the layer at distance a.

Formation of the zone of water conducting fractures. In the vicinity of collapse zone where curvature deformations are large, the normally transecting fractures growing towards each other break the layer to its full depth (Fig. 1a). As the distance from the coal bed towards the surface increases, i.e. with the layers curvature diminishing, penetration and opening of fractures diminish proportionally. In the result, there appears a layer at a certain distance $H_т$ along the normal to the coal bed, in which such fractures fail to penetrate that layer completely [7]. With respect to its underlying layers such a layer retains its waterproof properties and the upper boundary of ZWRF is associated with it. The maximum curvature of the layer associated with the upper boundary of ZWRF is called *the boundary curvature* [2]. Below that layer lies the zone of water conducting fractures itself, which consists of two hydraulically linked systems of technogenic fractures: delamination fractures and throughput normally transecting

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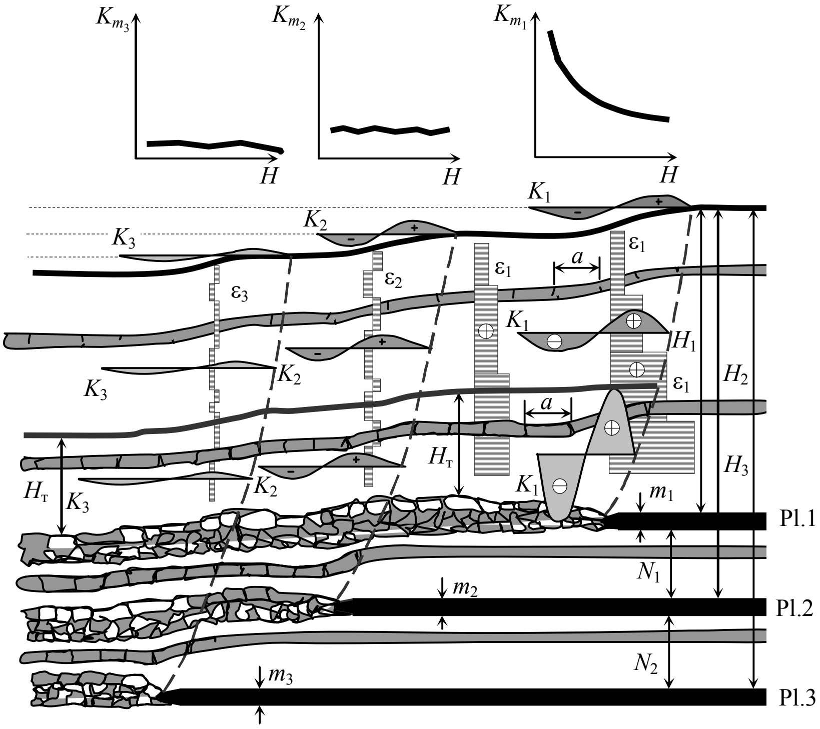

Fig.2. The geomechanical scheme of forming technogenic fractures due to deformation of the massive of rock layers goes like this:

K_1, K_2, K_3 and ε_1, ε_2, ε_3 – are, respectively, the profiles of curvature and vertical deformations for coal beds 1,2,3; a – is the block in the layer; H_1, H_2, H_3 – are, respectively, the depths of coal beds 1, 2, 3; N_1, N_2 – are the depths of coal bed partings; K_{m_1}, K_{m_2}, K_{m_3} – are, respectively, the maximum curvatures of the layers

fractures, as follows from the above [2, 5, 8]. In case the upper boundary of ZWRF reaches the lower boundary of aquifer, water starts penetrating the excavated cavity via these channels. Since the level of fractionation of the zone grows from the layer at the upper boundary of ZWRF to coal bed, then, depending on how much higher the upper boundary of ZWRF is than the lower boundary of aquifer, water will either filter through to the mining cavity or break through into it.

Curvature deformations in the layers above the ZWRF remain smaller than the boundary curvature, normally transecting fractions do not penetrate the full depth of the layer so that there remains a middle layer with a section unperturbed by the normally transecting fractures (Fig. 1b). As the distance from the coal bed increases the degree of penetration by main fractures becomes drops off, so he thickness of unperturbed watertight section becomes larger. So, despite the fact that delaminations and the separation cavity form here as well due to layer bending (though not as large as those in the ZWRF), no hydraulic link develops between the overlying and the underlying delaminations. That is how the zone of water conducting fractures forms in the course of excavation of the initial layer of the suite, i.e. in the course of the initial underworking [2, 16, 18].

ZWRF development in the course of repeated underworking of rock massive. In the course of underworking the second layer of coal bed suite under a massive of such structure in the zone of full displacements of the first layer deformation processes will develop the following way. Partings of thickness N_1 deform the same way they do during the initial underworking. Layers above the worked out coal bed 1 are subjected to repeated bending but field observations demonstrate [4, 5, 16] that the curvature distribution appears to be qualitatively different from that produced during the initial underworking. Within the limits of the repeatedly underworked depth the curvature remains constant (see curves K_2 in Fig.2) and equal in its absolute value to the curvature obtained on the surface from both field observations and the existing computational technique [12]. The distribution of vertical deformations (curve ε_2 in Fig.2) also differs from those obtained in the course of the initial underworking:

– in their absolute value deformations are an order of magnitude smaller than those from the initial underworking;

– the curve looks as a sequence of positive and negative vertical deformations.

Such a distribution of deformations indicates that no opening of delamination cavities takes place. Layers blend with each other during bending without any suspension. Similar picture is observed during the excavation of coal bed 3 (Fig. 2). The only difference then is that the maximum curvature values and vertical deformations are smaller than those during the excavation of coal bed 2, since $H_3>H_2$.

According to [12], the maximum curvature of the layer at the upper boundary of ZWRF during the excavation of coal bed 1, called the boundary curvature, is defined by the expression

$$K_{\text{г}} = \frac{c_1 m_1 F'(z)_m}{H_{\text{т}}^2(\text{ctg}\psi_3 + \text{ctg}\delta_0)^2}, \tag{2}$$

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where c_1 - is the factor accounting for the mining technology of coal bed 1 excavation; m_1 - is the excavated mass of coal bed 1; $F'(z)_m$ - is the maximum value of typical curve for the given conditions; $H_т$ - is the distance from coal bed to the layer at the upper boundary of ZWRF (height of the zone of water conducting fractures); ψ_3, δ_o - are, respectively, the angle of complete displacements and the boundary angle [12].

After suffering both the positive and negative curvatures of such value the layer evens out at the curvature close to zero. In the areas of maximum curvatures the normal transecting fractures open up in proportion to $\sqrt{K_г}$. Such a dependence is retrieved from the analyses of field observations of displacements of rock massive [1, 9], following which one may write that

$$\delta_1 / \delta_2 = H_2 / H_1 ;\; K_1 / K_2 = \left(H_2 / H_1\right)^2 \text{ или } H_2 / H_1 = \sqrt{K_1 / K_2}\,, \tag{3}$$

where δ_1 and δ_2 – are the openings of the normal transecting fractures in the layers removed to distances H_1 and H_2 from the coal bed in the vertical; K_1 and K_2 – are, respectively, the curvatures of layers removed to the same distances from the coal bed in the vertical.

It follows from (3) that

$$\delta_1 / \delta_2 = \sqrt{K_1 / K_2}\,, \tag{4}$$

in other words the opening of the fractures is proportional to square root of the curvature of that layer.

Meanwhile, as noted before, the layer on top of the ZWRF retains its waterproof properties (normally transecting fractures do not penetrate the full depth of the layer). During repeated underworking (coal bed 2 excavation) that layer is subjected to sign alternating curvature deformations. Since for every layer the maximum curvature in the repeatedly underworked massive is equal to the respective maximum deformation of land surface, the latter defined by excavation of the coal bed in question, one may assess numerically the maximum curvature of the layer at the upper boundary of ZWRF [2, 5, 13], calculating it the same way it would be done for the land surface after the available technique [12]:

$$K_{m2} = \frac{c_2 m_2 F'(z)_m}{H_2^2 (\mathrm{ctg}\psi_3 + \mathrm{ctg}\delta_0)^2}\,, \tag{5}$$

where c_2 – is the factor accounting for the mining technology of excavation of coal bed 2; m_2 – is the excavated mass of coal bed 2; H_2 – is coal bed 2 stratification depth.

Starting with formulas (2) and (5) one may claim that the value K_{m_2} is less than the value $K_г$ $H_2^2 / H_т^2$ – fold, provided all the other conditions remain equal. Respectively, the normally transecting fractures that remained after the excavation of coal bed 1 and stayed closed in the zone of complete excavation of that coal bed, open up again to the value proportional to $\sqrt{K_{m_2}}$, i.e. the opening of these fractures will be $H_2^2 / H_т^2$ times less than their opening at the moment when coal bed 1 was excavated. Therefore, there will be no conditions for further penetration of the normal transecting fractures into the considered layer. Besides, such layers have undergone multiple bendings above the zone of water conducting fractures, and their areas of maximum curvatures have developed the so-called «fluidity hinges». It means that the throughput normal transecting fractures in such layers may only be formed at the values of K exceeding $K_г$ by 40 % minimum [5]. After coal bed 2 is fully excavated, normal transecting fractures close down.

Similar to the process of excavating coal bed 2, during the excavation of coal bed 3 the maximum curvature of the layer at the upper boundary of ZWRF, positioned at distance H_T from coal bed 1, shall be,

$$K_{m_3} = \frac{c_3 m_3 F'(z)_m}{H_3^2 (\mathrm{ctg}\psi_3 + \mathrm{ctg}\delta_0)^2}\,, \tag{6}$$

where c_3, m_3, H_3 are, respectively, the factor accounting for the mining technology of excavation, the excavated mass and stratification depth of the coal bed 3.

Since $H_3 > H_2$, $K_{m3} < K_{m2}$, that is the layer at the upper boundary of ZWRF gets even a smaller bend than the one it received due to excavation of coal bed 2. Respectively, the opening of normal transecting fractures will be smaller than the one resulting from excavating coal bed 2 by a factor of approximately H_3^2 / H_2^2, and still smaller than that resulting from excavating coal bed 1 (by approximately $H_3^2 / H_т^2$ – fold). After the complete excavation of coal bed 3 the normal transecting fractures close completely in the zone of full displacements too. Fractures themselves remain there, but they are fully closed. Further growth of fractures through the layer is only possible in case their new opening due to excavation of the next coal bed exceeds their initial maximum opening (due to excavation of coal bed 1).

The ensuing excavation of coal beds 4, etc. of the suite will not bring any significant changes into the geomechanical process reviewed above.

The mechanism of deforming the layers of rock massive and of developing technogenic fractures in them was reviewed in application to such mining conditions when each sequential coal bed is excavated in the zone of full displacement over the overlying worked out coal beds.

When the boundaries of different faces in different coal beds of the suite coincide in full or in part, the curvature of layers overlying the initially underworked first coal bed will grow in proportion to the degree of coincidence of such face boundaries, and, respectively, the value of the boundary curvature will shift from layer to layer receding from the coal bed. One may suggest with quite a substantiation that the upper boundary of ZWRF will keep receding respectively. It follows then that to define the height of ZWRF during repeated underworking it would be enough to retrieve the distance to which the points of boundary curvature shift.

Forecasting the height of ZWRF penetration on the basis of the mechanism of formation of technogenic fractures in the layers of the initially and repeatedly underworked massive. When excavating the first coal bed of the suite of depth m_1 the boundary curvature $K_г$ will be found in the layer distanced by $H_{т1}$ from it, which may be expressed the following way [5]:

$$K_г = 4m_1 / H_{т_1}^2 . \tag{7}$$

When excavating the second coal bed of depth m_2 of the suite (underlying the first one), the common curvature of layers above the first coal bed worked out before increases so that the level of the boundary curvature shifts to the layer that lies further along the normal from the first coal bed. Respectively, the upper boundary of ZWRF shall move over and its elevation above the first coal bed shall reach the value $H_{т2}$. The latter may be retrieved from the condition of accumulation of curvature deformations at the upper boundary of that zone in dependence of the mutual positions of lower (upper) boundaries of mining operations at the first and second coal beds:

$$K_г = 4m_1 / H_{т_2}^2 + 4a_2m_2\left(S_2 - S_2' / S_2\right)/\left(H_{т_2} + N_1\right)^2 . \tag{8}$$

When excavating the third coal bed of the suite the condition of accumulation of deformations at the upper boundary of ZWRF may follow the analogy with (8) to be written as:

$$K_г = 4m_1 / H_{т_3}^2 + 4a_2m_2\left(S_2 - S_2' / S_2\right)/\left(H_{т_3} + N_1\right)^2 + 4a_3m_3\left(S_3 - S_3' / S_3\right)/\left(H_{т_3} + N_1 + N_2\right)^2 . \tag{9}$$

After excavating the n^{th} coal bed

$$K_г = 4m_1 / H_{т_n}^2 + 4\left[\sum_{i=2}^{n} a_i m_i \left(S_i - S_i' / S_i\right)\right] / \left(H_{т_n} + \sum_{i=1}^{n-1} N_i\right)^2 , \tag{10}$$

where $K_г$ is the boundary curvature that may be defined independent of formula (2) from the content of clay in rock composition and the depth distribution of layers in the underworked massive [5, 6, 11]; $H_{Тn}$ is the ZWRF elevation above the topmost coal bed remaining after the excavation of n coal beds; $a_i = q_i / q_1$, is the factor accounting for the activation of displacement process when coal beds two, three, etc. of the suite are excavated; q_i is the relative maximum settling of the ground surface due to excavation of the i^{th} coal bed of the suite; q_1 is the same value related to the excavation of the first coal bed of the suite. S_i is the distance between the lower (upper) boundaries of mining zones of the first and the i^{th} beds, such that no extra curvature is added to the boundary curvature; S'_i is convergence or divergence of the lower (upper) boundaries of the initial and i^{th} coal beds within S_i [5]; $m_1, m_2, \ldots, m_n$ are the excavated masses of coal beds of the suite; $N_1, N_2, \ldots, N_{n-1}$ are the depths of coal bed partings.

It appears impossible to solve equation (10) exactly with respect to $H_{Тn}$. Therefore $H_{Тn}$ may be retrieved either using interpolation functions [2] or taking a particular solution for certain adopted initial conditions. In particular, if we adopt $\sum_{i=2}^{i-1} N_{i-1} = 0$ (a condition of layer excavation of the coal bed) for equation (10), then the solution of that equation with respect to $H_{Тn}$ will look as follows:

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$$H_{\text{т}_n} = 2\sqrt{\left[m_1 + \sum_{i=2}^{n} a_i m_i \left(S_i - S'_i / S_i\right)\right] / K_{\text{г}}} \,. \tag{11}$$

To retrieve the elevation of ZWRF with respect to excavated coal bed 1, 2, 3, …, *n,* one needs to account for the thickness of partings (Fig.2):

$$H_{\text{в}_n} = H_{\text{т}_n} + \sum_{i=2}^{n-1} N_{i-1} \,. \tag{12}$$

Hence, according to [2, 5], the safe depth of mining activities under an aquifer for coal beds 1, 2, 3, …, *n* shall be defined by the following relationship:

$$H_{\text{б}n} = H_{\text{в}_n}. \tag{13}$$

Conclusions. Following the above, the condition most favorable for underworking aquifers is pillarless mining of coal beds of the suite, which provides for fitting the aquifer within the zone of complete displacements.

Decreasing the depth of underworking below aquifers is only possible by way of such mutual positioning of stope boundaries in different coal beds, that their maximum cumulative computational curvature [2, 8, 10] at the lower contour of aquifer due to excavation of the current and previously excavated coal beds does not exceed the value of the boundary curvature ($K_{\text{г}}$). It may be achieved varying the value of S'_i in equation (10) or (11). That would provide for decreasing the losses in sill pillars under aquifers and mitigating the detrimental effect of technogenic processes on geological environment.

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