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On flood protection measures for potash mines

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Development of water-soluble ore deposits is associated with the necessity to preserve water blocking strata (WBS), which separate aquifers from the mine gob. One indicator of the rate of man-induced load on WBS layers is subsidence of the earth surface, which defines the character of shift trough formation of the earth surface. The greatest threat of WBS discontinuity is posed by the areas located at the edges of a shift trough.

From the perspective of Upper Kama deposit of potassium and magnesium salts, by means of mathematical modelling methods authors demonstrated that in the capacity of threat indicators of WBS hole destruction it is possible to use the following parameters of a shift trough: edge length scaled to the depth of mining operations and maximum subsidence of the earth surface. Critical combination of these factors is responsible for the discontinuity at the edges of water blocking strata. These parameters of a shift trough can easily be controlled by instrumental procedures and can be included in the basics of a general monitoring system of WBS state at potash mines.

In order to protect the mine from the inrush of fresh water, it is necessary to form softening zones at the edges of mined-out areas near permanent or temporary borders of mining operations. Authors review different options of softening zone formation. Numerical tests have demonstrated that the most efficient way to protect water blocking strata is the formation of softening zones by means of backfilling the stopes of the workable seam or its exclusion from mining operations.

Key words: mathematical modelling; destruction; water blocking strata; shift trough; subsidence; softening zone

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Introduction. Specific nature of water-soluble ores development is associated with the necessity of a guaranteed preservation of water blocking strata (WBS), which separate aquifers from the mine gob [19]. This is ensured by using room-and-pillar mining system and supporting the WBS with barrier pillars. One indicator of the rate of man-induced load on WBS layers is subsidence of the earth surface, which defines the character of shift trough formation of the earth surface. The greatest threat of WBS discontinuity is posed by the areas located at the edges of a shift trough [2].

In order to reduce the subsidence gradient at permanent or longstanding borders of mining operations, mine-engineering protective measures are used in the form of softening zones, the presence of which allows to reduce deformation of WBS rocks. Formation of softening zones can occur by means of adjusting parameters of room-and-pillar mining system, backfilling the stopes or excluding one of the workable seams from stoping. Ways of forming softening zones at the boundaries of mining operations by adjusting the width of barrier pillars are reviewed in the studies [11, 13]. The efficiency of backfilling as a protective measure against mine flooding has been explored in numerous works [7, 11, 12, 18, 20, 21]. At the same time it has been observed that backfilling of the mined-out area with wastes of potash production allows to minimize negative impact of mineral extraction on the environment [14, 17]. At some sites it is also possible to form softening zones by means of extracting protective pillars. Implementation of these measures can decrease the concentration of mining pressure and ensure a homogenous character of WBS layer deformation [5, 6]. At the same time it remains a relevant task to select the most efficient way and substantiated parameters of softening zone formation for specified mining and geological conditions. Only in this case timely implementation of additional protective measures will permit

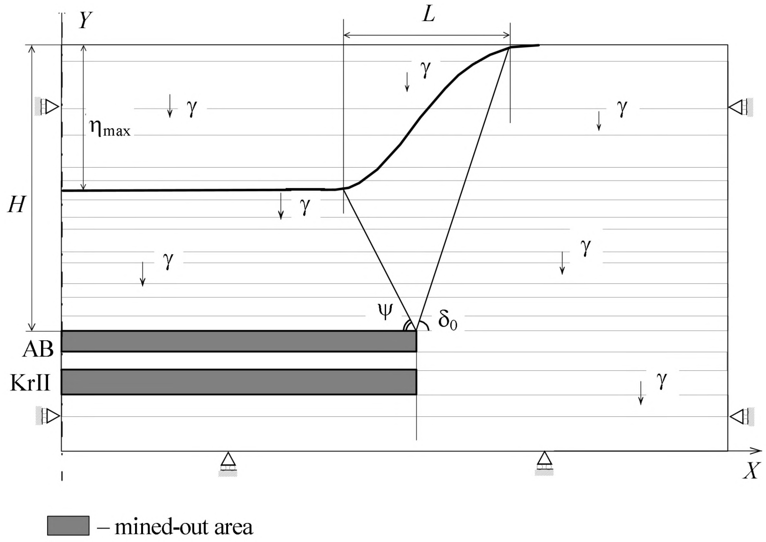

Fig.1. Calculation diagram of mathematical modelling

successful management of mining pressure, ensure safety of mining operations and optimal extraction of potassium ore from the subsoil.

Calculation method. Efficiency of applying different ways of softening zone formation is associated with the character of undermined rock mass deformation, reflected in the conditions of shift trough formation.

Shift trough of the earth surface can be determined by the following parameters: length of its edge L, scaled to the depth of mining operations H, and maximum subsidence of the earth surface η_{max} in the fully undermined zone (Fig.1).

Condition of full undermining for productive potassium layers, according to [15], is expressed by the ratio:

$$\chi = D / H \geq 1.4, \tag{1}$$

where D – size of the mined-out area in the examined principal cross-section of the shift trough.

Values of χ parameter are specified in the principal cross-sections of the shift trough in accordance with the following expressions:

$$\chi_{11} = D_{11} / H, \tag{2}$$

$$\chi_{12} = D_{12} / H, \tag{3}$$

where D_{11} – length of the examined area in the principal cross-section of the shift trough, located parallel to extraction galleries; D_{12} – width of the examined area in the principal cross-section of the shift trough, located orthogonally. In the partially mined-out area ($\chi < 1.4$) shift trough edge depends on the size of the mined-out area.

In case of horizontal occurrence of workable seams, edge area of the shift trough L is constrained by the full shift angle ψ and boundary angle δ_0 (Fig.1). Calculated length of the shift trough edge in case of full undermining is obtained using a formula [15]:

$$L = H(\operatorname{ctg}\delta_0 + \operatorname{ctg}\psi), \tag{4}$$

where $\psi = 55°$, $\delta_0 = 50°$. At Upper Kama potassium salt deposit (UKPSD) relative length of the edge area in the zone of full undermining equals $L / H = 1.54$.

The value of maximum earth surface subsidence by the end of shift process is calculated as follows:

$$\eta_{max} = 0.9 m_0 \omega p, \tag{5}$$

where m_0 – extracted thickness of the workable seam; ω – estimated coefficient of ore extraction; p – parameter, taking into account the influence of mined-out area backfilling. Extraction coefficient for the stoping of one seam is estimated as follows:

$$\omega = \frac{S_0}{m_0 l}, \qquad (6)$$

where S_0 – cross-section area of the stope; l – center distance. Parameter p takes into account the influence of mined-out area backfilling on final subsidence of the earth surface:

$$p = 1 - A(1 - B), \qquad (7)$$

where A – rate of laying the stopes with a filler; B – shrinkage coefficient of the filling mass. In the absence of filler $p = 1$.

Mathematical modelling of WBS stress-strain state, depending on the length of shift trough edges, has been performed in a 2D elasto-plastic formulation for the conditions of plain strain. To estimate the change in the state of WBS and the entire underworked rock mass over time, in the process of mining operations rheological approach has been used [1], which was based on the developed modification of the method of variable elastic moduli [3], when variable moduli only characterize the deformation of undermined seams instead of all elements of the geological section. Estimation of integral rheological parameters of the undermined rock mass has been performed by means of mathematical processing of actual or predicted patterns of increasing earth surface subsidence.

Quantitative estimation of the change rate of WBS state in the process of shift advancement was based on the analysis of a potential possibility of subvertical fracturing occurring in the rock mass [4]. For the analysis of discontinuities in WBS layers in the compression area, a Coulomb-Moor criterion in the form of a parabolic envelope has been used [9]:

$$\tau_{\max} = \tau_{\text{pr}} = \sqrt{(\sigma_{\text{ten}} + \sigma_n)[2\sigma_{\text{ten}} - 2\sqrt{\sigma_{\text{ten}}(\sigma_{\text{ten}} + \sigma_{\text{comp}})} + \sigma_{\text{comp}}]}, \qquad (8)$$

where σ_{comp} and σ_{ten} – ultimate compression and tension strength, σ_n – normal stress in the plain of maximum shear $\tau_{\max}$. In the tension area, ultimate stress was limited by the ultimate tension strength:

$$\sigma_1 = \sigma_{\text{ten}}. \qquad (9)$$

In calculations strength characteristics of the rocks, which constitute the strata, were adjusted taking into account stress-rupture coefficients for saline rocks and structural weakening for rocks of the overlying strata. It was assumed that the localization of plastic deformations in WBS layers was conditioned by their discontinuity. A forecast of formation of subvertical man-induced discontinuity zones in WBS layers has been made with regard to time dependency up to reaching the final subsidence of earth surface. Calculation have been performed using the standard scheme of finite element displacement method [22] with discretization of the area in question into triangular elements of the first order. Solution of elasto-plastic problem was based on initial stress method [10, 16].

Estimation of the influence of shift trough edge length on the character of WBS rock destruction. The authors examined room-and-pillar stoping of two sylvinite seams AB and KrII with the following parameters: AB seam – room width 3.2 m, barrier pillar width 5.8 m; KrII seam – room width 6.1 m, barrier pillar width 2.9 m (center distance l = 9 m). Extraction height was assumed to be 3.5 m (KrII seam) and 2.4 m (AB seam). The depth of mining operations was 320 m. The calculation diagram of the problem is reflected in Fig.1.

Geomechanical research has been carried out from the perspective of a typical geological section for the conditions of Upper Kama salt deposit [8] (Fig.2). In the calculations it has been assumed that average physical and mechanical properties of seams and strata, composing the undermined rock mass, remain constant in the lateral direction. The state of undermined strata has been estimated relying on the intensity of WBS layer destruction, expressed in the formation of subvertical man-induced discontinuity zones. Analysis of WBS stress state is carried out at the moment of reaching maximum subsidence of the earth surface.

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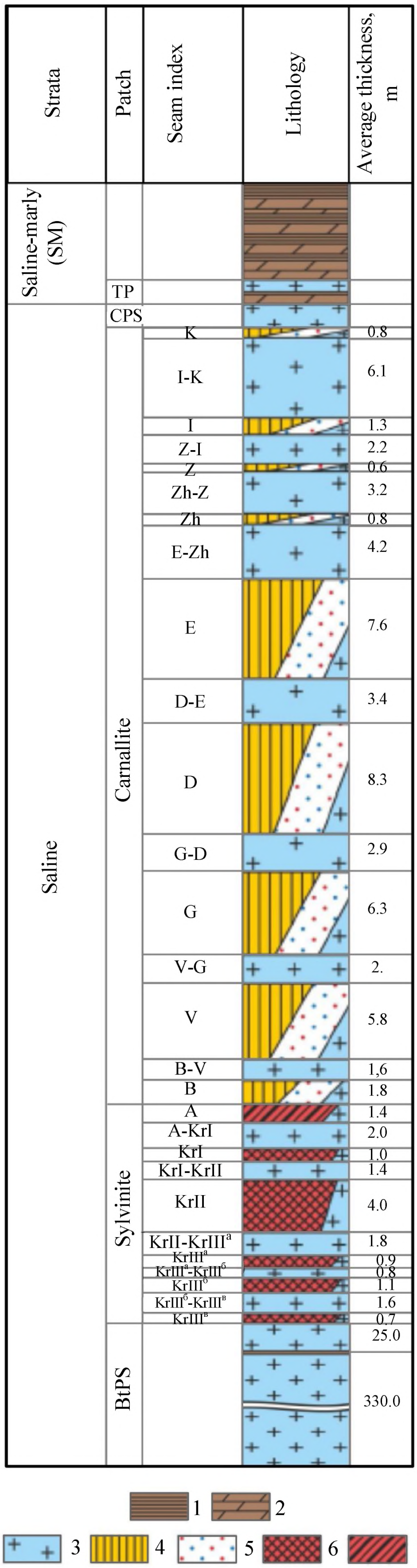

Fig.2. Typical section of saline strata at UKPSD

1 – clay; 2 – marl; 3 – rock salt; 4 – carnallite rock; 5-7 – sylvinite: 5 – speckled, 6 – red, 7 – banded

The character of WBS destruction for the conditions of full undermining $L/H = 1.54$ are illustrated in Fig.3 and 4. Under maximum subsidence of the earth crust ($\eta_{max} = 2.2$ m) development of shift fracture zone along WBS section is limited by its lower interval (see Fig.3, *b*). Carnallite seams (V, G, D, E, Zh, Z, I) and rock salt seams in the lower WBS area (B-V, V-G, G-D, D-E) are subject to discontinuity. WBS preservation is ensured by the integrity of transition patch (TP) and capping potash salt (CPS), as well as seams of interlayer rock salt in the middle area (E-Zh, Zh-Z, Z-I, I-K). In this scheme there is no need in applying additional protective measures.

An increase in maximum earth surface subsidence unmistakably characterizes elevated man-induced stress on WBS-forming seams. Under full undermining conditions ($L/H = 1.54$) and final subsidence $\eta_{max} = 3.8$ m (Fig.4, *a*) hole destruction of WBS edge occurs (Fig.4, *b*), which dictates the need to apply additional measures for its preservation.

In the context of research on destruction processes in the undermined rock strata, it is shown [2] that reduction in the relative length of shift trough edge causes a decrease in ultimate subsidence of earth surface, associated with complete WBS destruction. Therefore, edge length of a shift trough is an important factor, which determines the risk of WBS discontinuity and the need to apply additional protective measures.

Mathematical modeling of WBS state in the zone of partial undermining has been performed similar to Fig.3 for maximum final earth surface subsidence $\eta_{max} = 2.2$ m and varying relative length of the shift trough edge. Variation of shift trough edge length has been achieved by reducing the size of mined-out area and modelling conditions of partial undermining. In case of preserved maximum earth surface subsidence this leads to a decrease in shift trough edge length L (Fig.5, *a*). Under partial undermining conditions ($L/H = 1.22$) all carnallite seams (V, G, D, E, Zh, Z, I, K) and seams of interlayer rock salt in the lower and middle area of WBS lose their integrity. In the upper WBS area (interval TP and CPS) rock-salt seams also lose their stability. TP interval is characterized by cleavage cracks. Such significant rate of man-induced load on the undermined rock mass implies the necessity to apply additional measures of WBS protection.

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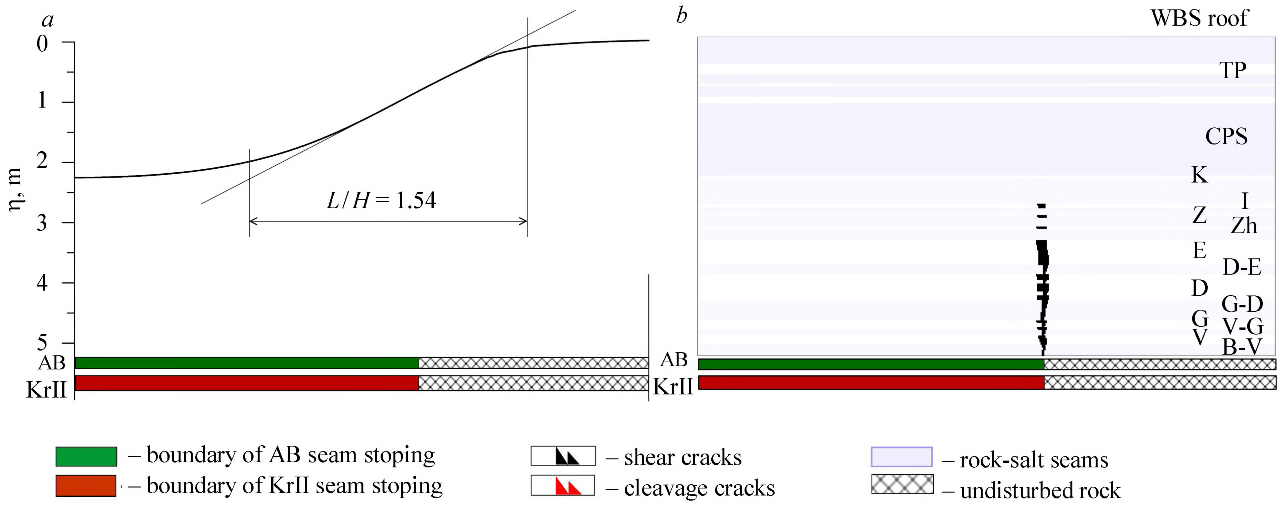

Fig.3. Calculated earth surface subsidence (*a*) and character of WBS discontinuity (*b*) in the full undermining zone under $L/H = 1.54$ ($\eta_{max} = 2.2$ m)

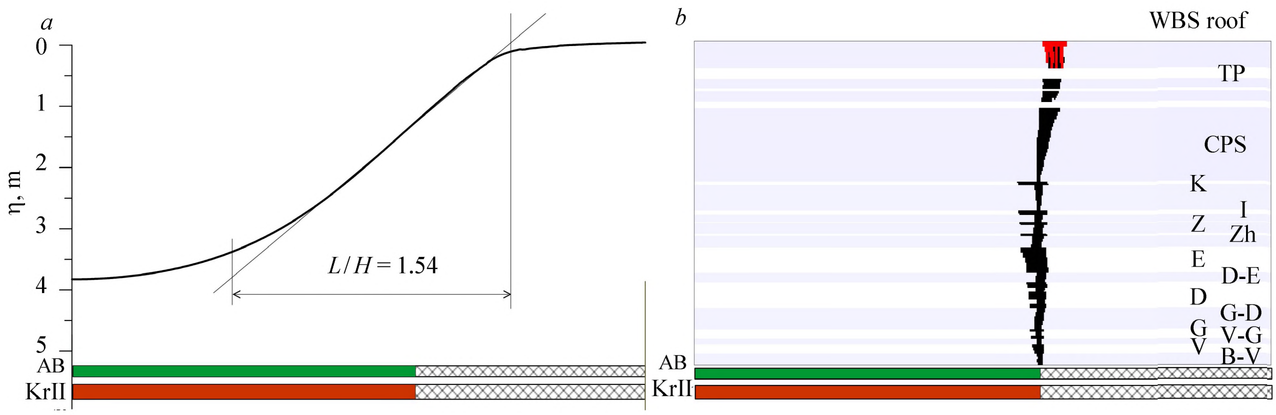

Fig.4. Calculated earth surface subsidence (*a*) and character of WBS discontinuity (*b*) in the full undermining zone under $L/H = 1.54$ ($\eta_{max} = 3.8$ m)

For legend keys see Fig.3

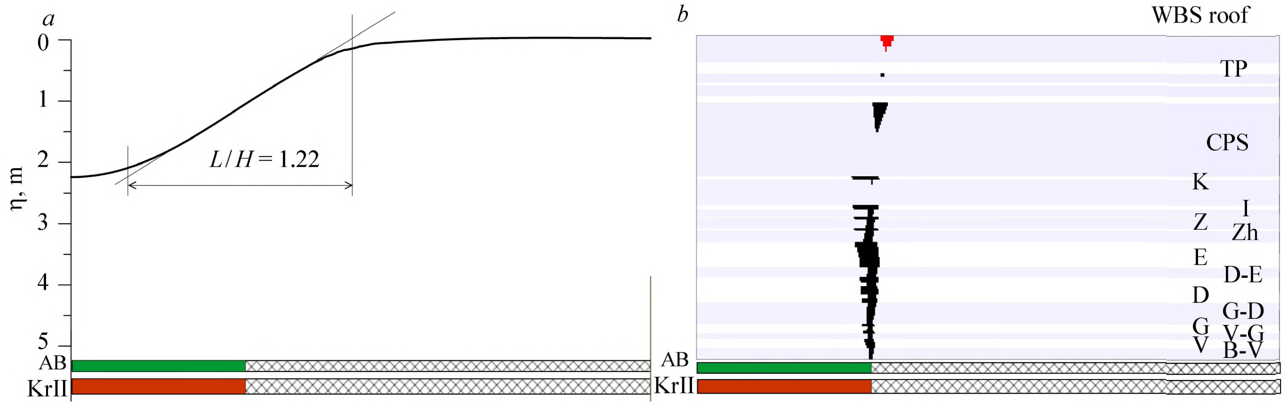

Fig.5. Calculated earth surface subsidence (*a*) and character of WBS discontinuity (*b*) at the boundaries of mining operations in the zone of partial undermining, $L/H = 1.22$

For legend keys see Fig.3

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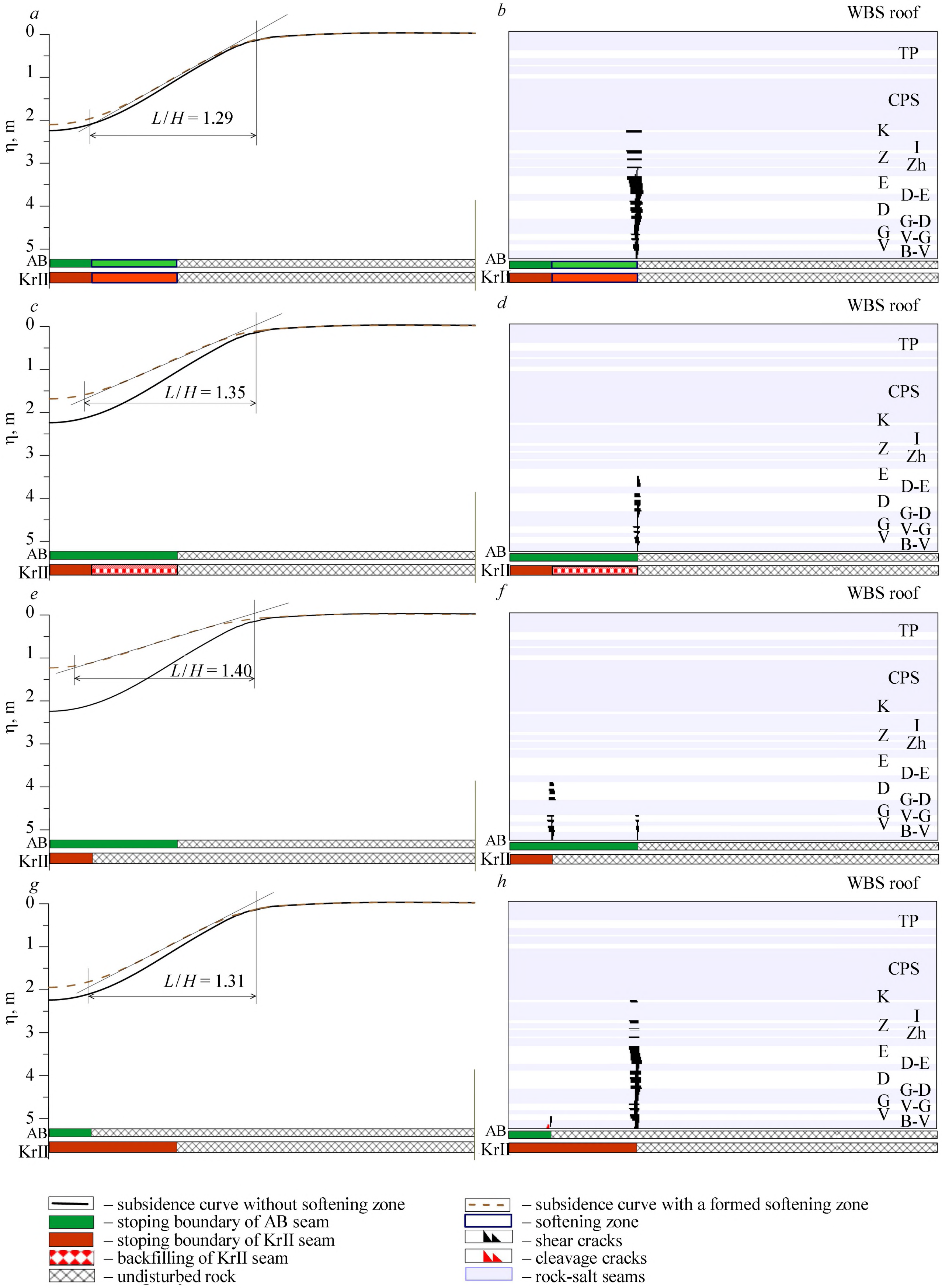

Fig.6. Calculated earth surface subsidence and character of subvertical discontinuity zone formation in case of softening zone creation by means of: adjusting parameters of room-and-pillar mining system (*a*, *b*); backfilling of the mined-out area along KrII seam (*c*, *d*); exclusion of KrII seam from mining operations (*e*, *f*); exclusion of AB seam from mining operations (*g*, *h*)

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Hence, an increase in earth surface subsidence and reduction of shift trough edge length are indicators of WBS discontinuity risk. Specific combination of these parameters requires application of additional measures to protect the mines from flooding by means of softening zone formation at permanent or temporary borders of mining operations.

Efficiency analysis of softening zone formation in the edge areas of undermined saline mass. Efficiency assessment of various approaches to softening zone formation was based on the formulation described above under the conditions of partial WBS undermining ($\eta_{max} = 2.2$ m; $L/H = 1.22$). The length of softening zone was taken to be 200 m. Geomechanical calculations analyzed the following options of softening zone formation:

1. Formation of a softening zone due to changes in the parameters of room-and-pillar mining system by increasing a center distance $l = 10.5$ m (pillar width: seam AB – 7.3 m, seam KrII – 4.4 m) and reducing the loading of barrier pillars in the zone.
2. Backfilling of stopes in the sylvinite seam KrII with a filling coefficient $A = 0.8$.
3. Formation of a softening zone due to exclusion of one workable seam (AB or KrII) from mining operations.

Calculation results of changes in shift trough configuration and WBS rock destruction for different options of softening zone formation are presented in Fig.6. Similar estimations without a softening zone are shown in Fig.5

Comparative analysis demonstrated (Fig.6) that all the considered options of softening zone formation caused certain flattening in the edge area of shift trough, while L/H ratio increased from 1.22 (absence of a softening zone) to 1.40. The most intensive flattening is registered in case the softening zone is formed by backfilling the stopes of the lower workable seam KrII ($L/H = 1.35$) or by excluding it from mining operations ($L/H = 1.40$). As expected, descending gradients of earth surface subsidence are directly reflected in the character of WBS discontinuity. Compared to the calculations without any additional measures of WBS protection at mining borders (see Fig.5), not a single option of softening zone formation (Fig.6) demonstrated localization of man-induced discontinuity zones in the transition patch (TP) or capping potash salts (CPS). From the position of efficiency, similar to estimations of displacement process development, it is preferable to form a softening zone by backfilling the stopes of KrII seam. In this case, other conditions being equal, only saline seams in the lower WBS area are subject to destruction (Fig.6, *d*).

Maximal reduction of man-induced load on WBS layers is achieved, when KrII seam is excluded from mining operations (Fig.6, *f*). In this case the area of man-induced subvertical fractures «gets split» into two zones: the first one is formed at the edge of the mined-out area along KrII seam, the second one, less distinct – at permanent or longstanding borders of mining operations. Destruction is limited to the interval of carnallite seam D and the lowest seams of rock salt B-V, V-G.

Thus, additional protective measures in the form of softening zones at permanent or temporary borders of mining operations result in intensity reduction of man-induced load on WBS. The greatest protective effect is achieved by changing the conditions of mining operations in the lowest workable seam.

Conclusions. An indicator of WBS discontinuity risk is a critical combination of shift trough parameters: maximum subsidence of the earth surface and its edge length. These parameters can easily be controlled by instrumental procedures and can be included in the basics of a general monitoring system of WBS state at potash mines.

In order to ensure safety of WBS undermining conditions in the areas of permanent or longstanding mining borders it is necessary to form softening zones. The most efficient way of forming a softening zone is backfilling of the lower workable seam or its exclusion from mining operations.

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