Technological solutions for mining of off-balance gypsum reserves in difficult geological conditions

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Abstract. Mining technological solutions for underground mining of off-balance gypsum reserves in difficult mining and geological conditions were justified. An analysis of typical geological disturbances of gypsum seams is carried out using the Artemivsk deposit (Ukraine) as an example. Physical and mechanical properties of rocks in disturbed zones are determined. A quantitative assessment of strength characteristics of rocks during their moistening is carried out. The minimum permissible values of the width of the tape pillar and the power of the protective stack above the camera in the presence of a violation in the roof are calculated. The use of selective mining of the lower part of the seam by combines of the "Roadheader" type is recommended. The maximum width and height of the chamber are determined by the type of combine. The technology has been tested and realized at the gypsum mine of the Additional Liability Company "Siniat".

1 Introduction

Natural gypsum global production was about 150 million tons in 2018. Leading countries in this field are the USA, China and Iran, with total production of about 50 million tons per year. The production of gypsum in Ukraine has been from 1.5 to 1.7 million tons per year throughout the past 5 years. The largest deposit of gypsum in Ukraine is Artemivsk deposit and it is located in Bakhmut city, Donetsk region. This deposit has been developed by underground mining since the middle of the last century. Currently, gypsum is mined and processed by the Additional Liability Company "Siniat" of the "Etex Group" international concern. Annual gypsum production was 200 thousand tons in 2018.

The Artemivsk gypsum deposit belongs to sedimentary epigenetic deposits. Geological structure of the deposit consists of sediments of the Lower Permian, Paleogene, Neogene and Quaternary ages. Quaternary sediments are represented by deluvial reddish and brown loams with dense calcareous sediments, sands, clays and a soil-plant layer. Their total

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thickness is 40 m. Tertiary sediments are not present everywhere and are represented mainly by sand and clay interlayers with a thickness of up to 25 m. Lower Permian sediments of the Slavic Formation lay deeper and are represented by gypsum and anhydrite strata with interlayers of carbonate rocks.

There are aquifers in sandy clays, sands and sandstones within the deposit. Their effect on the inundation of workings is negligible. The river Bakhmutka, which is hydraulically connected with the karst waters of gypsum seams, has a more significant effect. Hydrogeological conditions in the deposit are generally favorable.

Gypsum deposits are confined to sediments of the Slavic Formation of the Lower Permian, in the cross-section of which ten seams are identified. Seams V, VI and VII are of industrial importance. Seam V is currently under development. Its extracted thickness reaches 18 m. The structure of the seam is presented in Table 1.

Table 1. Structure of seam V of gypsum.

Rock	Seam thickness, m	Structural element
Argillite	0.7–14.0	Seam roof
Gypsum anhydrite	2.5–4.5	Protective seam in the roof of the room
Dolomite	0.6–1.1	Upper dolomite
Gypsum	1.0–2.0	Immediate roof
Gypsum, anhydrite	5.0–7.0	Extractable layers
Dolomite	0.6–1.1	
Gypsum, anhydrite	7.0–9.5	
Dolomite	0.6–0.9	
Gypsum	0.8–1.4	Protective seam in the floor of the room
Argillite	0.5–5.0	Floor of the seam
Limestone	0.8-1.2	

A room-and-pillar mining was used in the deposit. Mining technology had been changed during the deposit development. Drilling and blasting mining method was used until 1975. The world experience had indicated that drilling and blasting technology did not provide long-term stability of goafs. Collapses at the Artemivsk mine proved insufficient long-term stability, as well as collapses at other mines of Ukraine ("Mykytivska", "Dekonska"), Bulgaria ("Koshava"), and France ("Port-Maron", "Shante-Lu"). Therefore, a combined mining technology had been used from 1975 to 2014, which assumed preparatory workings made by drill-type combines and subsequent extraction of the gypsum seam by drilling and blasting method. Mining system parameters were: the average height of the room of 15.0 – 18.0 m; room width of 8.0 – 10.0 m; the shape of safety pillars was rectangular; dimensions of safety pillars in plan of 7.0 – 12.0x30.0 m; the protective layer in the roof and in the floor of 1.0 m each.

However, the presence of vast areas of geological disturbances of karst type in the deposit did not allow using these technologies everywhere. It was difficult to ensure a stable state of room roofs and prevent rock collapse in disturbed areas. In addition, production costs increased and losses of minerals in safety pillars of irregular shape increased. Therefore, a significant amount of reserves with geological disturbances was transferred to off-balance reserves. When balance reserves started depleting, a necessity of partial transfer of off-balance reserves back to balance ones occurred. This required additional study of geological features of the deposit, as well as adjusting the parameters of development system and gypsum mining technology.

In the recent years, the problem of reserves revision has become one of the main problems for many mining regions of solid minerals [1-4]. In each case, this problem is solved individually. Therefore, the dissemination of experience in development of off-balance mineral reserves in various mining and geological conditions is very important.

The goal of the paper is to develop mining technological solutions for underground mining of off-balance gypsum reserves in difficult mining and geological conditions.

2 Methods

In order to justify the technology of mining in disturbed areas, comprehensive studies of geological disturbances of the rock massif are performed. The following methods are used: visual inspection of workings at the border of disturbed areas; exploratory drilling; laboratory determination of physical and mechanical properties of rocks.

Visual inspections are performed in mining sites during each shift according to safety rules and other regulatory documents. Position, size and descriptive characteristics of the identified anomalies are documented, in particular, an abrupt deflection of dolomite layers, clay outcrop in roof and on side surfaces of rooms, appearance of moist areas, large rock outfalls beyond design parameters, cracks in the roof.

The large-scale structure of disturbed areas is determined by drilling exploration wells from the earth's surface. The character of disturbances is specified during the mining operations by exploratory drilling of small-diameter wells ahead of the face.

In order to justify the parameters of mining system in disturbed areas, physical and mechanical properties of gypsum and associated rocks are determined in laboratory conditions. These properties are: uniaxial compression and tensile strength, density, porosity, and static Poisson's ratio. The change of properties of rocks during their moistening are also studied. Standard techniques were used [5-7].

3 Results and discussion

Analysis of comprehensive surveys of disturbed areas allows drawing conclusions about the character of geological disturbance of the rock massif. The character is associated with the manifestation of exotectonics and subsequent karst formation processes over the leaching areas of underlying seams of rock salt. This pattern of karst formation is typical for gypsum deposits [8-10]. A geological disturbance manifests in a form of replacement of the protective seam of gypsum in the room roof with clay material in the upper part of the seam, as well as in a form of vertical displacements of the seam.

The exploration work and production exploration drilling allow revealing two main types of karst: bare karst and covered one. Bare karst has the largest manifestation scales and is associated with processes of ancient underground leaching of gypsum, subsidence of overlying terrigenous rocks and filling of formed voids with terrigenous rocks. This karst develops from the upper gypsum seams and can reach the floor of seam V. The cracks are filled with gray and brown clay material with fragments of dolomite. The thickness of karst cracks does not usually exceed 0.1 m and sometimes increases to 0.3 – 0.5 m (Figure 1).

Areas of bare karst are linear and extend from bassets of the seam into the massif to a distance of 0.2 to 1.5 km. The width of areas decreases from the upper seams to the lower ones, reaching values of 30 – 250 m.

Covered karst has limited distribution scale and has almost no effect on the amount of gypsum reserves. Covered karst is connected to the leaching processes of sulfate rocks, which occurred almost immediately after seam formation, and deposition of sedimentary rocks. Covered karst is confined to the inside part of the seam and is represented by horizontally-layered, well-sorted sand and clay rocks of gray and brown color. Karst thickness is up to 3.8 m.

Fig. 1. Example of bare karst.

An analysis of the revealed disturbances within the northeastern section of the mine field indicates that with a thickness decrease or absence of a protective seam of gypsum in the room roof, there is generally no upper seam IV. In this case, the roof collapse with further formation of a subsidence cone on the earth's surface can occur unless preventive measures are taken (Figure 2).

Fig. 2. Earth's surface after mine roof collapse in 2001.

Laboratory studies have indicated that the strength of gypsum gradually decreases when approaching the karst at a distance of 3-5 meters. Strength value is approximately 30 % less on contact with karst than far away from the disturbance [11]. This feature should be considered when calculating the development system parameters in disturbed areas. It is also important to consider the humidity of rocks [12] in calculations of mine workings stability, because it reduces their strength. This is typical for areas where the karst cavity is filled with a water-clay mixture. Quantitative characteristics of the rock strength reduction during moistening are shown in Table 2. The determination procedure is given in [13].

Table 2. Decrease of strength of gypsum and related rocks during moistening.

Rock	Tensile strength, MPa at rock moisture *W*:			Compressive strength, MPa at rock moisture *W*:		
	$W = 0.5$ %	$W = 2$ %	$W = 4$ %	$W = 0.5$ %	$W = 2$ %	$W = 4$ %
Gypsum	6.2	5.0	4.1	27	19	12
Anhydride	12.2	7.9	5.2	62	45	28
Dolomite	9.1	7.8	6.2	49	47	45

Since seam IV is absent in areas of geological disturbances, the probability of encountering karst in the upper part of seam V increases. A general concept of mining operations in disturbed areas is determined from this. The concept implies a transition to selective gypsum mining using the mining combines [14, 15], development of only the lower part of the seam and transition to the "long safety pillar-gallery" system. The mining scheme in the disturbed zone is shown in Figure 3.

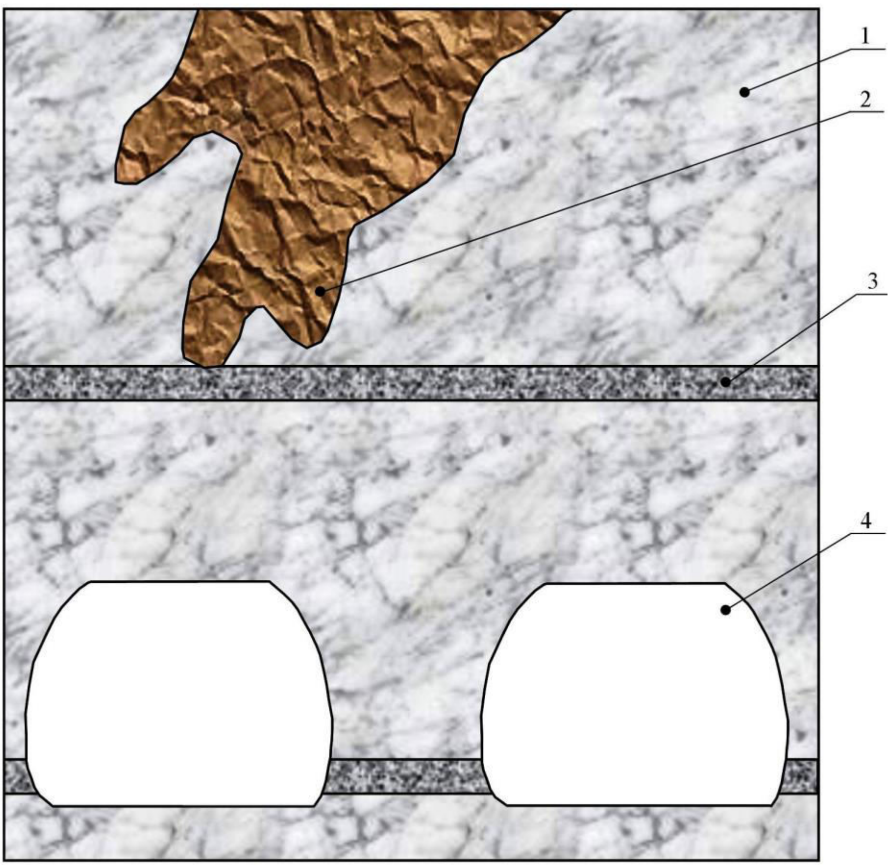

Fig. 3. Illustration of mining technology of disturbed gypsum seam: 1 – gypsum seam, 2 – karst, 3 – layer of dolomite, 4 – mine working.

The most important element of the mine working stability is its roof [16]. Calculation of the protective seam thickness *m* over the mine working is generally performed according to the most unfavorable scenario. The protective seam must support the weight of weak rocks up to the surface. This variant is illustrated in Figure 4.

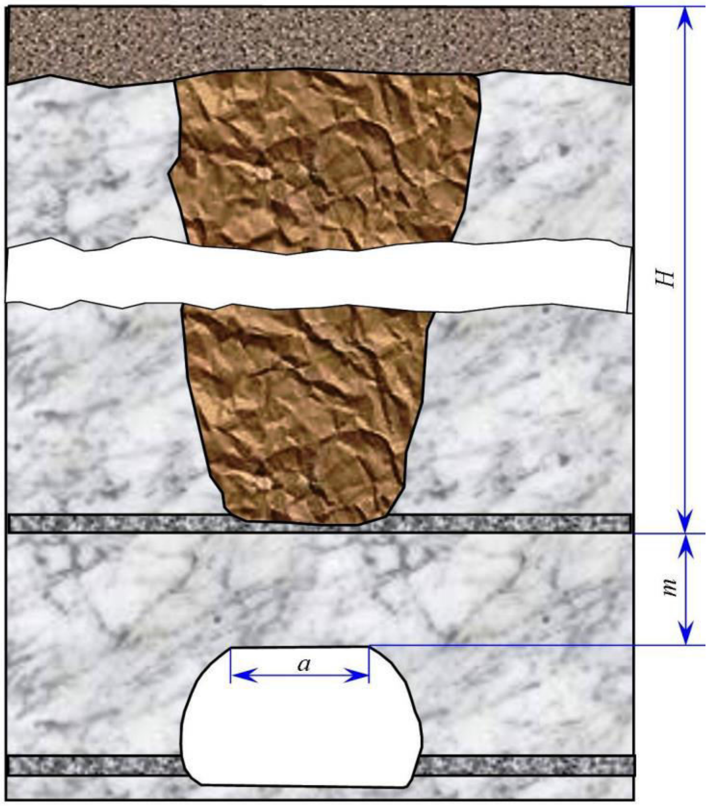

Fig. 4. To calculation of protective seam thickness in room roof for the most unfavorable scenario.

Classical formula of V. Slesarev [17] was assumed an initial expression in calculations of the stable span of the room roof flat part:

$$a \le \sqrt{\frac{4\sigma_t m}{3\gamma^*}}, \tag{1}$$

where a is span of the upper flat part of the room, m; m is the thickness of the protective seam of gypsum in the room roof, m; σ_t is tensile strength of gypsum protective seam, Pa; γ^* is the bulk weight of overlying layers, N/m^3, which is determined from the expression:

$$\gamma^* = \frac{g(\rho_1 m + \rho_2 d)}{m}, \tag{2}$$

where ρ_1 and ρ_2 are densities of gypsum seam and weak seam respectively, kg/m^3; d is thickness of weak seam, in this case, equal to the depth H, m; g is acceleration of gravity, m/s^2.

Equation of the room roof stability is obtained from expressions (1) and (2):

$$4\sigma_t m^2 - 3ga^2\rho_1 m - 3ga^2\rho_2 H \ge 0 \tag{3}$$

The positive value of the solution of equation (3) determines the required thickness m of the protective seam.

The following parameters are assumed in the calculation for the extraction area of the lower seam of gypsum of the Artemivsk deposit: tensile strength of gypsum $\sigma_t = 2.0$ MPa; density of the lower seam of gypsum $\rho_1 = 2.5 \cdot 10^3$ kg/m^3; average density of covering rocks $\rho_2 = 2.3 \cdot 10^3$ kg/m^3; roof width $a = 4.1$ m.

The indicated values vary slightly within the area with geological disturbances. Changes in the seam depth H have significant effect due to irregularities in the terrain of the earth's surface. The dependency of protective seam thickness m on depth H is almost linear and is shown in Figure 5.

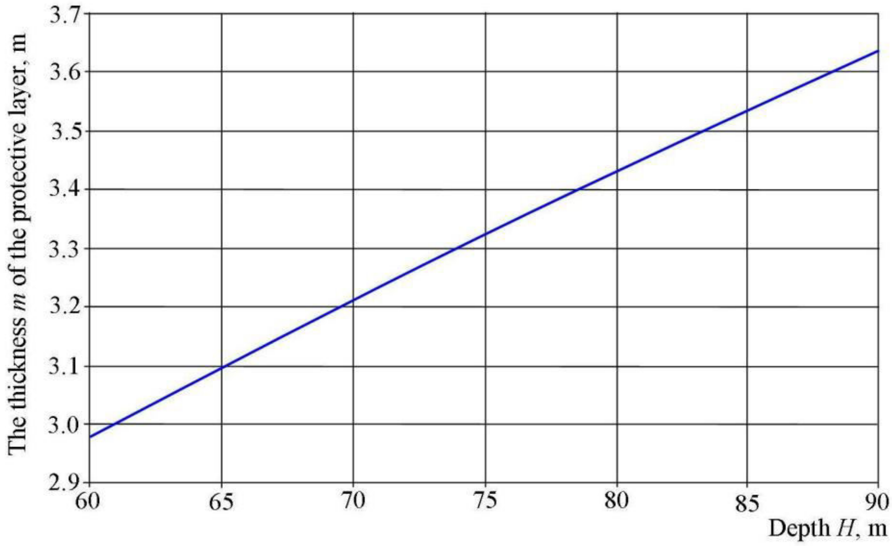

Fig. 5. Dependency between protective seam thickness of room roof on mark depth of room roof with a karst above the middle dolomite.

If the working is made along the upper part of gypsum seam and stopped when the karst appeared, then further mining of the room according to the full design height could lead to roof collapse. In this case, the coaxial mine working is made in the lower part of seam and a protective seam of thickness m_1 is left between the two mine workings (Figure 6 and Figure 7). This seam must only support its own weight, and its thickness m_1 should not depend on depth. The parameter H should be set equal to zero in expression (3). Then:

$$m_1 \geq \frac{3a^2 g\rho_1}{4\sigma_t}. \tag{4}$$

The working made in the lower part of the seam is only partially unloaded by the working located above it (Figure 7).

The situation is further reduced to the case presented in Figure 4. Because of this, it is necessary to perform an additional calculation to determine the thickness m. If condition (3) is not fulfilled, then the value of parameter m_1 is further increased. Based on the results of control drilling, the value of m_1 can be adjusted.

The calculation scheme of the long safety pillars is illustrated in Figure 8.

The equation of long-term stability of the safety pillar [18]:

$$(s+b)\rho g H n = bK_s K_w \sigma_c \frac{(1+2\nu)(1-\nu)}{\nu}, \tag{5}$$

where s is maximum room width, m; b is minimum width of long safety pillar, m; K_s is safety pillar shape coefficient; K_w is coefficient of structural weakening of rock massif; ν is static Poisson's coefficient; n is safety factor; σ_c is compressive strength, MPa.

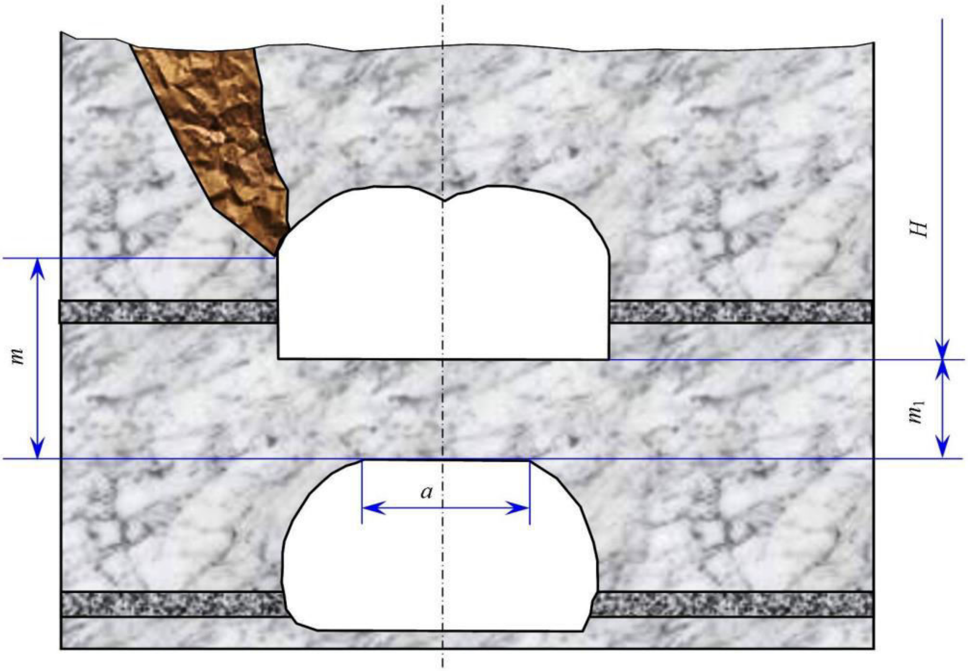

Fig. 6. Development of disturbed gypsum seam at two levels.

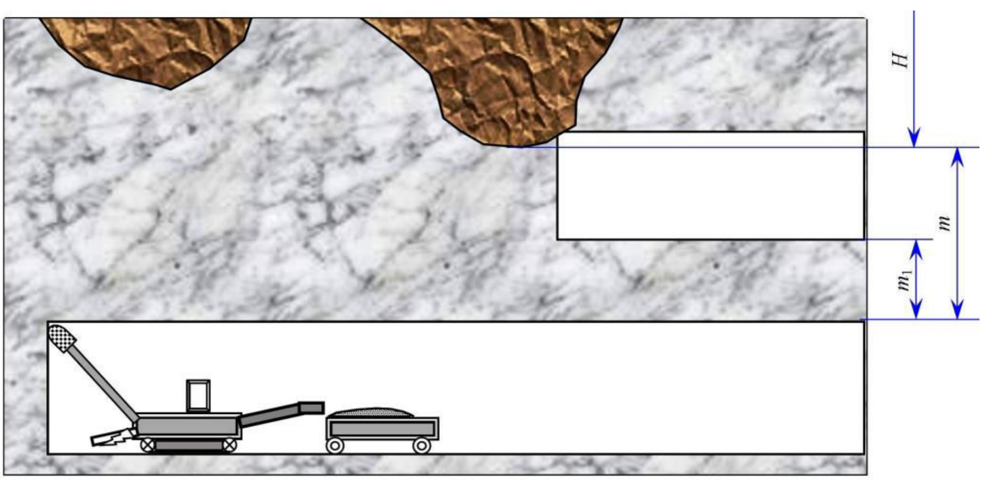

Fig. 7. Longitudinal cross-section for second development option.

There are many known formulas of safety pillar shape coefficient. Use an empirical expression, which best corresponds to the long safety pillars:

$$K_s = \frac{0.21h/b + 0.79}{0.7h/b + 0.28}. \tag{6}$$

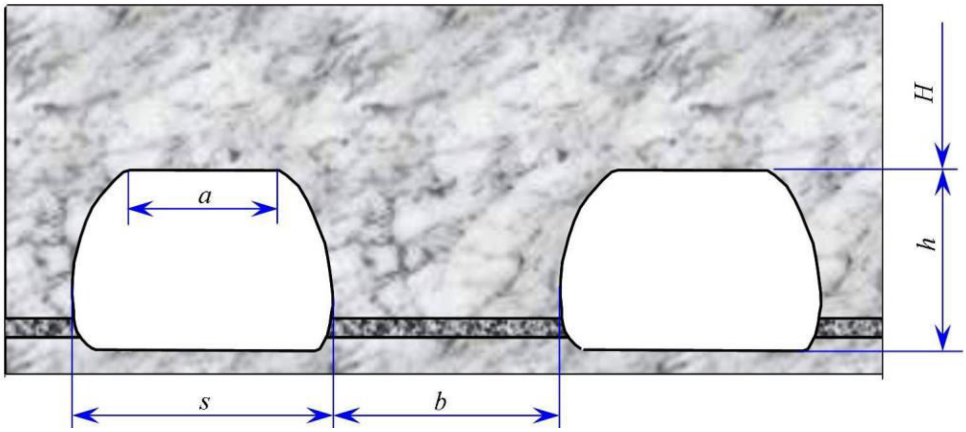

Fig. 8. To calculation of long safety pillar width.

Combined fulfillment of conditions (5) and (6) leads to an equation:

$$\begin{aligned}&(0.79K_w\sigma_t(1+2\nu)(1-\nu)+0.28\rho gHn)b^2+(0.21K_w\sigma_t h(1+2\nu)(1-\nu)-\\&-0.7\rho ghHn+0.28\nu\rho gns)b-0.7\nu\rho gh^2ns=0\end{aligned} \tag{7}$$

The positive root of equation (7) is the desired width of the long safety pillar. The minimum safety pillar width in its cross-section is from 5.7 to 8.5 m for the conditions of Artemivsk gypsum deposit in the depth range from 60 to 90 m and a working height of up to 5 m.

These technological solutions are realized at the mine of the Additional Liability Company "Siniat" when finalizing mining of gypsum seams in disturbed areas. Selective action combine Sandvik MR 340 was used for this [19]. This combine is effective in technological schemes for selective mining of minerals with a tensile strength of up to 60 MPa. Combine cutting is performed by a transverse-axial mining head, which is mounted on a swinging boom. The combine is most efficient with compressive strength of rocks of up to 25 MPa. These working conditions are common for most gypsum mines. Inclusions of more durable anhydrite are episodic. The maximum width of the mine working was 7.45 m, the maximum height was 4.87 m.

4 Conclusions

The need for a partial development of off-balance reserves occurred in the largest gypsum deposit of Ukraine, which is the Artemivsk deposit, due to depletion of reserves with favorable mining and geological conditions. Areas with significant geological disturbances of gypsum seams are assigned to off-balance areas. It is established that geological disturbances in the areas of off-balance reserves are mainly represented by karsts. It is indicated that the most disturbed area is the upper part of the seam. The physical and mechanical properties of rocks in disturbed areas and their dependency on moisture content are determined. Technological solutions for safe development of off-balance reserves are justified. A scheme with long safety pillars is recommended instead of the traditional room-and-pillar system. The minimum permissible values of the parameters of the development system (the width of the tape pillar and the power of the protective stack above the camera in the presence of a violation in the roof) are calculated. The use of selective mining of the lower part of the seam by combines of the "Roadheader" type is recommended. The maximum width *s* and height *h* of the chamber are determined by the type of combine. In our case, for the Sandvik MR 340 combine $s = 7.45$ m, $h = 4.87$ m. The technology has been tested and realized at the gypsum mine of the Additional Liability Company "Siniat".

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