Substantiating and Assessing the Stability of the Underground System Parameters for the Sawn Limestone Mining: Case Study of the Nova Odesa Deposit, Ukraine

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Abstract

Due to the russian federation aggression against Ukraine, the infrastructure of many settlements has undergone significant destruction, so in the post-war period, limestone can become a reliable and useful resource for its reconstruction. A significant number of limestone deposits in southern Ukraine are suitable for the production of wall (block) stone, but the geotechnical conditions of many mining sites require the use of an underground mining method. To study the mining system parameters of the Nova Odesa sawn limestone deposit, analytical and calculation methods are used based on known and proven hypotheses of stable spans and pillars, as well as verification by numerical modeling based on the finite element method in the SolidWorks software package. It has been determined that with a change in the ceiling thickness by 50% (from 0.8 to 1.2 m), the safe width of the chamber in the absence tensile stresses in the sawn limestone roof, under given mining-geological and mining-technical conditions of mining operations, increases by 22%. It has been revealed that the area of 25.0 m² corresponds to the required safety factor of the square-shaped supporting pillar. It has been shown by numerical modeling that under the conditions of the Nova Odesa deposit, the load on a 5×5 m supporting pillar will reach 26% of its load-bearing capacity, and the extraction chamber ceiling is in a stable state without the formation of tensile stresses. The research results are useful for substantiating and assessing the stability of the room-and-pillar mining system elements with supporting pillars in the underground mining of sawn limestone or other mineral deposits.

Keywords: *mine, sawn limestone, extraction chamber, supporting pillar, ceiling*

1. Introduction

The rapid growth of the world's population has led to a natural increase in resource consumption, where an important role is played by mining of various types of minerals. A wide range of minerals is used in metallurgy, electronics, information technology, medicine, military and space technology, agriculture, and in the construction industry, since intensive population growth requires the civil infrastructure development [1, 2]. Important types of building materials are wall blocks made of natural stone – limestones, volcanic tuff, chalk, marl, gaize and tripoli [3]. They are characterized by uniform composition, low hardness and are easily sprayed onto blocks for wall materials [4-6]. The use of limestone has become the most widespread in the world. It can be used in the form of lump limestone, crushed stone, artificial (sawn, wall) and crushed stone, facing slabs, mineral chips, crushed sand, mineral powder, mineral wool, and limestone powder [7].

Due to the russian federation aggression against Ukraine, the infrastructure of many settlements has undergone significant destruction, which will require reconstruction in the post-war period [8]. The strategic direction is to intensify the mining of building material deposits for the construction of new and reconstruction of destroyed industrial and civil infrastructure facilities [9]. An important building material will be limestone, which is a valuable in many countries around the world [10-12].

As of 2021, the balance limestone reserves in Ukraine, mined at 31 deposits, are estimated at 1.0 billion m³. Natural sawn limestones are widely distributed within the Black Sea Depression, the Volyn-Podilsky Plate, the Pre-Carpathian Depression, the Trans-Carpathian Trough, the Crimean Fold-Thrust Belt, the Donetsk Folded Structure, and the southwestern slope of the Ukrainian Shield [13]. Most of the limestone deposits in Ukraine are suitable for the production of wall stone. The sawn limestone is mostly mined by a surface method, but underground mining is also used. Mining processes are mechanized, and the rock is cut into large wall blocks and standard wall stone [14, 15]. The geotechnical conditions in

Fig. 1. Overview map of the Nova Odesa sawn limestone deposit location
Rys. 1. Mapa poglądowa lokalizacji złoża wapienia Nowa Odesa

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Rys. 1. Mapa poglądowa lokalizacji złoża wapienia Nowa Odesa

Depth of occurrence		Thickness, m	Lithology description
from	to		
0.0	0.3	0.3	Soil and vegetation layer
0.3	13.5	13.2	Clay is motley – yellowish-gray, greenish-gray, brownish-gray, viscous, sometimes sandy. In the range of 9.0-13.5 m, there is a clay-limestone stratum, in which limestone debris are bound by limestone-clay material.
13.5	14.5	1.0	Limestone is yellow, shell-detrital, sometimes detrital, lighter, yellowish-gray, destroyed, fractured.
14.5	24.0	9.5	Sawn limestone is of layered color: yellow-gray, light gray, sometimes brownish-yellow. The limestone composition is predominantly shell-detrital, slightly cavernous.
24.0	24.8	0.8	Limestone is gray, yellowish-gray, recrystallized, shell-detrital, strong.

which many deposits are mined require the use of an underground mining method, the accumulated experience of which is not enough today [16, 17].

The uniqueness of underground mining of sawn limestone deposits is in the fact that it is possible to achieve waste-free production cycle. Mined full-sized, non-full-sized wall stone and crushed stone will always be used in construction, and relatively cheap production waste, which sometimes reaches 50% of the mined rock mass, is a valuable carbonate raw material. This raw material is suitable for additives in a range of building materials, concrete, as a component of the solid backfill for the mined-out areas, feeding for animals and poultry, for soil deoxidation, etc. [18-21].

To date, various scientists in the world have conducted enough research to substantiate the rational and stable parameters for the chamber system and room-and-pillar system for mining various types of mineral deposits [22-26], that it becomes efficient and geometrically expedient to prepare the reserves of the mine field [27]. However, the issues of research into the optimal parameters of underground mining of sawn limestone deposits, which can ensure the rock mass stability for a long time of mining operations at the mine field, as well as create safe working conditions for underground workers, are not sufficiently covered.

The presented research is aimed at substantiating the rational and sustainable parameters of the underground mining of Nova Odesa sawn limestone deposit, which will additionally provide Ukraine with valuable mineral raw materials for the infrastructure reconstruction in the post-war period.

2. Study area

The sawn limestone deposit at the Nova Odesa site with an area of 27.8 ha is located on the southeastern outskirts of the city of Nova Odesa, Novoodeskyi administrative center, Mykolaiv Oblast. The minefield has the shape of a parallelogram, which is adjacent to (Fig. 1):

- in the west – at a distance of 1.0 km from the deposit, the Highway Ulyanivka-Mykolaiv was laid, and closer to the mine field, there is a depleted Novoodeske limestone deposit;
- in the north – the outskirts of the city of Nova Odesa;
- in the east – agricultural lands;
- in the southwest of the deposit, there is an old closed sawn limestone quarry;
- in the southeast – the Kashperivske limestone deposit (TOV Kashperivske Rodovische), which was mined by a quarrying method and is currently mothballed.

Geologically, the Nova Odesa deposit is located on the northern flank of the Black Sea Depression, and its structure involves Quaternary and Neogene sedimentary rocks. The sawn limestone minerals are confined to the coarse-layered stratum of the Upper Sarmatian. They constitute a continuous sheet-like deposit of nonuniform internal composition. Sawn limestones are confined, as a rule, to the middle and lower part of the deposit, with a thickness of 4.5 to 10.2 m, averaging 7.5 m. The deposit is not water-flooded. The piezometric level of the main aquifer lies below the Upper Sarmatian limestone stratum or is confined to its lower part. The thickness of the rocks that overlie the mineral varies from 14.2 to 35.0 m, averaging 20.0 m.

A preliminary geological and economic assessment of the limestone reserves at the Nova Odesa deposit became a prerequisite for choosing a method for its mining. This is conditioned by the significant thickness of overburden rocks from 14.5 m to 25.3 m. The absence of groundwater is also a favorable prerequisite for underground mining. They occur below the level of deposit mining.

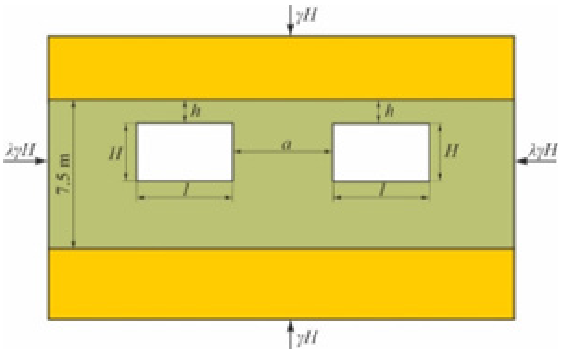


Fig. 2. Calculation schemes for modeling the stability of the chamber width and ceiling (a), as well as the supporting pillar (b): h – the ceiling height; l – the chamber width; H – the chamber height, a – the supporting pillar width

Rys. 2. Schematy obliczeniowe modelowania stateczności szerokości i stropu komory (a) oraz filaru nośnego (b): h – wysokość stropu; l – szerokość komory; H – wysokość komory, a – szerokość filaru nośnego

Tab. 2. Physical-mechanical rock mass properties

Tabela 2. Fizyczno-mechaniczne właściwości górotworu

Factor name	**Limestone thickness**
Elasticity modulus E, MPa	6000
Poisson's ratio, μ	0.3
Density γ, kg/m^3	1760
Compressive strength, σ_c, MPa	3.1
Tensile strength, σ_t, MPa	0.43

When conducting preliminary geological and economic assessment, 11 geological exploration wells have been drilled to a depth from 24.3 to 34.7 m. And during the initial experimental-industrial mining of the deposit, 184 meters of underground mine workings have been conducted. The stratigraphic section for one of the wells is presented in Table 1.

In the process of experimental-industrial mining, when tunnelling and conducting drifts in the sawn limestone body, the following fracture systems are noted: vertical and steep-dipping slightly inclined (90-70°) fractures, usually uneven, wavy with a strike azimuth of 330-350° with frequent small feathering fissures that penetrate the entire thickness of the limestone deposit. Perpendicular to these fractures, the fractures with a strike of 40-60° (vertical and inclined – 90-70°), uneven, wavy, are noted. The width of fractures varies from a few millimeters to 1.0-2.0 cm, rarely up to 7-8 cm (open fissure). In places of intersection of these fracture systems, there were also inrushes both along the walls of the mine workings and in the roof. However, the inrushes were of a local nature and did not affect the stability of the mine working ceiling. The output of marketable products – full-sized and non-full-sized wall stone is 31.75%, and together with crushed stone it is 50.95%, which indicates the influence of fracturing. The waste is 49.05%.

The technical and economic feasibility of the quality requirements has determined that, based on current limestone underground mining technologies, the maximum limestone thickness that can be mined in the first place is 3.0 m. The balance reserves of the deposit in B+C1 category, calculated and approved by the State Committee on Reserves for a mineral thickness of 3.0 m, within the limits of a special permit is 777.1 thousand m^3, and with an undetermined industrial value of C1 category – 1295.0 thousand m^3 (calculated for a thickness from 3.0 to 7.5 m).

The sawn limestones of the deposit are suitable for the wall stone production in accordance with the requirements of DSTU B V.2.7-246:2010 "Curbstones and wall stones from rocks". Based on the results of conducted physical-mechanical studies, the sawn limestones of the Nova Odesa deposit meet the requirements of the normative document in all parameters. To date, the development of geomechanically stable parameters of the sawn limestone underground mining system for this promising deposit remains a relevant issue, which is directly studied further.

3. Research methods

The experience of underground mining of sawn limestone deposits indicates the spread of the most optimal mining method – a chamber system with leaving square pillars, intended to support the overlying roof rocks [28, 29]. With this mining method, it is important to determine rational parameters, such as the chamber height, the chamber width, the ceiling thickness, and the size of the pillars [30-32]. The rock mass stability and the safety of mining operations depend on the determination of these rational parameters [33, 34].

3.1. Analytical Calculation Methods for Determining the Sawn Limestone Mining System Parameters

The extraction chamber height depends on the technological parameters of stone-cutting mining machines [35]. Therefore, to substantiate it, the existing mining equipment for the sawn limestone underground mining and the experience of its use, especially for deposits with similar mining-geological conditions, is studied. Analytical and calculation methods are used to determine the parameters of the sawn limestone underground mining:

- stable span (width) of the drift or chamber, which ensures the absence of tensile stresses in the roof, is determined based on the V.D. Slesarev calculation method [36, 37];
- stable parameters of inter-chamber supporting pillars in sawn limestone mines are determined based on the Turner – Shevyakov methods [38].

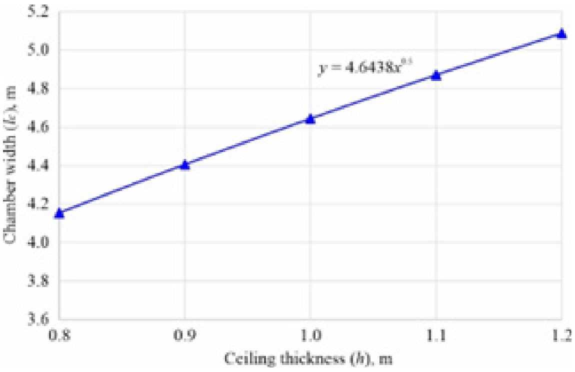
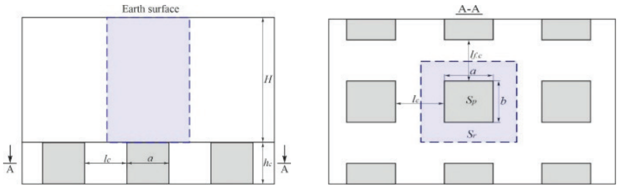


Fig. 3. The influence of the extraction chamber ceiling thickness on its width

Rys. 3. Wpływ grubości stropu komory na jej szerokość



(a) (b)

Fig. 4. The scheme for determining the sizes of the supporting pillars: (a) – view in section; (b) – top view

Rys. 4. Schemat wyznaczania wymiarów podpór: (a) – widok w przekroju; (b) – widok z góry

The main parameters for determining the above-mentioned mining system elements are the density of overlying rocks from the earth's surface (t/m^3), the sawn limestone material density (t/m^3), the mining depth (m), the compressive strength of limestone (MPa), the tensile strength of limestone (MPa), and safety factor. Further, when performing analytical research, the actual and calculated mining-geological and mining-technical mining system parameters are substituted into the mathematical expressions of the system parameters for deposit mining in order to determine the stable mining system elements.

3.2. Numerical Modeling of the Stability of the Sawn Limestone Mining System Elements

It is intended to test the sawn limestone mining system parameters determined by analytical and calculation methods using numerical modeling based on the finite element method. Numerical modeling has been widely used for studying the state of geotechnical systems, adequately reflecting the development of geomechanical processes operating in the rock mass during mining operations [39-41]. The SolidWorks software package is used to assess the stability of the predetermined thickness of the ceiling and supporting pillars in the chamber system for the sawn limestone seam mining, which provides safe conditions for mining operations. The software product is designed to study the physical processes characterizing the stress-strain state of solid bodies [42, 43].

A rock mass area of 25x15 m is modelled, containing a sawn limestone layer, as well as laminated limestones in the roof and bottom. The geomechanical problem is solved in an elastic formulation, the obtained stress values are compared with the maximum permissible rock strength values. The maximum normal stress criterion, also known as the Mohr-Coulomb criterion, based on the maximum normal stress theory, is chosen as the failure criterion [44]. According to this theory, failures occur when the maximum principal load reaches the material's strength level. The criterion is used for brittle materials, which are limestones. It is believed that if the resulting stresses exceed the maximum permissible, the material is destroyed.

The calculation schemes for modeling the stability of the mining system parameters according to their analytical and calculation values are shown in Fig. 2.

Initial data for modeling: the average rock mass structure containing minerals according to geological sections in wells (a mineral of an average thickness 7.5 m – sawn limestone, the roof and bottom are laminated limestone); average mining depth is 27 m; the extraction chamber width is determined from analytical calculations (m); the supporting pillar width and length are determined from analytical calculations (m); the ceiling thickness is conditioned by the mining experience and analytical calculations (m); the value of the load applied to the model is 0.38 MPa (with an average overlying rock density of 1.8 t/m^3). Physical-mechanical rock properties are presented in Table 2.

The main attention is paid to the stresses arising precisely in the sawn limestone mass when driving the extraction chambers, because the main mining system elements (the chamber width and height, the ceiling thickness, the supporting pillar parameters) are laid directly in the sawn limestone layer. Using the Simulation probing function in SolidWorks, it is possible to measure stresses at any point of a model. Particular attention is paid to the stressed state of the ceiling and the vertical wall of the supporting pillar.

4. Results and discussion

4.1. Substantiating the extraction chamber height

The sawn limestone deposit balance reserves in the amount of 770.0 thousand m^3 have been calculated and approved for a mineral thickness of 3.0 m (with an average seam thickness of 7.5 m). Therefore, the sawn limestone mining

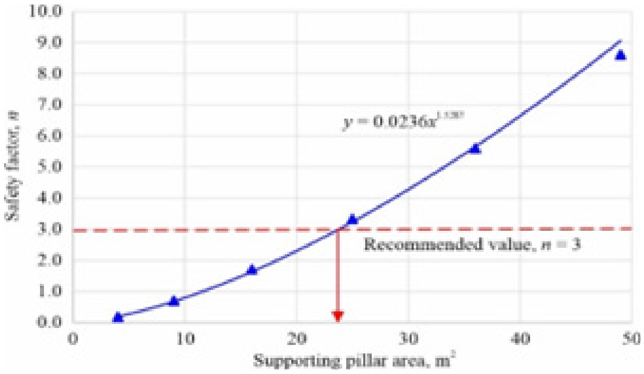


Fig. 5. Dependence of the change in the calculated safety factor of a square-shaped supporting pillar on its area

Rys. 5. Zależność zmiany obliczonego współczynnika bezpieczeństwa kwadratowego filara nośnego od jego powierzchni

is primarily assumed in one layer. According to the normative document NPAOP 0.00-1.77-16, from the condition of single-layer sawn stone mining, the face height should not exceed 3 m and should not be less than 2.2 m [45]. The extraction chamber height during single-layer mining is determined by the parameters of stone-cutting machines.

For cutting wall stone from a sawn limestone seam in the conditions of deposits within the former Soviet Union countries, stone-cutting machines of MKD-1, MKD-2 and KMAZ-188 types have been widely used [46]. When using a MKD-type stone-cutting machine, according to the technical specifications, the chamber height is no more than 2.6 m, with KMAZ-188 – 2.54-2.7 m.

In addition, the face height must be combined with an integer number of wall stone rows cut along the height of the chamber and, together with the thickness of the cuttings, must be a constant value, which will make it possible to cut a certain integer number of rows of stone with a standard height. The size of the wall stone from the sawn limestone seam, cut by the mentioned stone-cutting machines according to [47] is 390 mm×190 mm×188 mm, and the average cutting width of the working body is 27 mm. Thus, given the height of the cut wall stone, as well as the cutting width, 12 units of wall stone are cut along the extraction chamber height. In this case, the extraction chamber height will be 2.6 m. For the rational conducting of mining operations in the extraction chambers and face cuts, driven perpendicular to them with leaving the square-shaped supporting pillars, the same height of mine workings of 2.6 m is recommended for the operation with MKD-1 and KMAZ-188.

Further, with a detailed additional exploration of the deposit reserves with an uncertain commercial value of the C1 category, which is 1295.0 thousand m³, it is expedient to consider mining of the lower layer of the sawn limestone seam. In this case, when planning the mining of the lower layer, it is necessary to take into account the extraction chamber height of the upper layer, the height of ceiling left, and also the inter-horizon pillar. The total value of these parameters will make it possible to select the deposit areas where it is possible to use multilayer mining over the mine field area, because the seam thickness of the sawn limestone material ranges from 4.5 to 10.0 m.

4.2. Determining the width and thickness of the extraction chamber ceiling

The specificity of sawn stone underground mining, unlike other minerals, is in the fact that mining operations are planned in such a way as to obtain as many block products as possible from the mined rock mass. This is complicated by the increased sizes of the extraction chamber width, as a result of which the intensity of the rock pressure manifestation increases, and the rock mass is broken by fractures, both in the roof of the drift and on the surface of the mining face. Therefore, determining the rational size of the extraction chamber width by the geomechanical factor is of great importance.

The size of the extraction chamber width is significantly influenced by the strength properties and thickness of the ceiling left to ensure the chamber stability. If a strong and dense recrystallized limestone occurs above the sawn limestone seam, then the ceiling cannot be left, since a strong roof is a reliable ceiling. The presence of a strong roof reduces the loss of mineral resources.

Under the conditions of the Nova Odesa sawn limestone deposit, the roof of the sawn limestone seam is represented by slab limestone, shell-detrital, densely destroyed, fragmental, fractured, clayey, layered limestone with a thickness of 0.6-5.4 m. Given the slab limestone structure and its fracturing in the conditions of the deposit, it is recommended to leave the ceiling in the sawn limestone seam. The stable span (width) of the drift or extraction chamber of rectangular section, which ensures the absence of tensile stresses in the roof, is determined based on the V.D. Slesarev calculation method:

$$l_k = A\sqrt{\frac{R_t \cdot h}{\gamma_c \cdot n_s}}\text{, m} \qquad (1)$$

where A – a coefficient taking into account the manner in which the roof is clamped on the bearings (for an elastic beam);

h – the accepted ceiling thickness, m. The thickness of the ceiling left in the mine workings (h), given the operational experience of sawn limestone mines, ranges within 0.75-1.0 m, and in some cases 1. m – when conducting long-term capital workings.

R_p – the ultimate tensile strength of ceiling rocks parallel to bedding, t/m². The ultimate tensile strength of ceiling rocks is correlated with the ultimate compressive strength of limestone and is determined by the expression:

$$R_t = 0.1R_c + 0.12 = 0.42\ MPa \qquad (2)$$

γ_c – unit specific gravity of ceiling rocks, t/m³. According to the data of laboratory tests, the average unit specific gravity value of the sawn limestone deposit is 1.76 t/m³.

R_c – the ultimate compressive strength of rocks, MPa. According to the data of laboratory tests, the average compressive strength value of the sawn limestone deposit is 3.1 MPa.

n_s – safety factor;

The safety factor is determined as follows:

$$n_{s=}n_1 \cdot n_2 \cdot n_3 \qquad (3)$$

n_1 – a coefficient taking into account the range of variation when determining the average sample strength, is accepted within 1.3-1.6. According to the results of laboratory tests of 10 samples taken from the well core, the limestone compressive strength ranges within 2.2-4.1 MPa with an average value of 3.1 MPa. According to the analysis of the variation in the limestone strength indicators in the sample, $n_1 = 1.4$ is taken.

n_2 – a coefficient taking into account the structural mass weakening due to the presence of macro- and microfracturing, as well as the impact of the time factor, is accepted within 1.4-1.9. The coefficient value n_2 is mostly determined by the mining depth H. When H is up to 60-70 m, the n_2 value in the conditions of a fractured mass can be taken within 1.0-1.5, but with H more than 70 m, it is 1.5-2.0. Given the average mining depth of 30 m and limestone fracturing, $n_2 = 1.5$ is taken.

n_3 – a coefficient taking into account the decrease or increase in the chamber deflection compared to the design ones, as well as the presence of technological cuttings, is accepted within 1.0-1.1. It is taken $n_3 = 1.05$.

The calculated safety factor for the chamber makes 2.2 (according to formula 3).

In sawn limestone mines, the safety factor is in the range of 1.5-2.5. Typically, the safety factor is chosen in the range of 1.5-2.0, and in difficult mining-geological and mining-technical conditions – 2.5. Given the insignificant mining depth, water-free state of the deposit, a safety factor of 2.0 is finally accepted. In the analytical calculation according to expression (1), to determine the degree of influence of the ceiling thickness on the extraction chamber width, its value is varied with an increment of 0.8; 0.9; 1.0; 1.1 and 1.2 m, which is presented in Fig. 3.

Analysis of Fig. 3 shows that when the value of ceiling thickness is changed by 50% (from 0.8 to 1.2 m), the safe chamber width, at which there are no tensile stresses in the sawn limestone roof under given mining-geological and mining-technical conditions, increases by 22% according to the power-law dependence by the expression (1). The extraction chamber width, determined analytically in the range of 4.15-5.1 m, is a safe range and can be accepted for mining the Nova Odesa sawn limestone deposit with a single-layer mining of sawn limestone reserves.

Depending on the options for mining all the Nova Odesa deposit reserves, some peculiarities in determining the ceiling thickness are possible:

a) with an approved single-layer mining of the sawn limestone deposit reserves up to a certain seam mining height of 2.6 m (p. 4.1) and, taking into account variations in the sawn limestone seam thickness within 4.5-10 m, any ceiling thickness in the range of 0.8-1.2 m can be accepted, thus assuming a safe chamber width in the range of 4.15-4.5 m.

b) when considering in perspective multilayer mining of sawn limestone deposit reserves, the ceiling thickness (interlayer pillar) and, accordingly, the width of the chambers can vary within each mining layer, while observing safety in order to achieve the maximum mining of its reserves through its entire thickness, which varies in the range of 4.5-10 m.

Since the balance Nova Odesa deposit reserves are approved for a thickness of 3.0 m, their actual mining will be conducted with a single-layer mining. According to Fig. 3, it is recommended to take a width of 4.4 m with a ceiling thickness of 0.9 m. Similar to the extraction chamber height, its width should also be combined with an integer number of cut rows of wall stone and, together with the thickness of the cuttings, make a constant value that will allow cutting a certain integer number of stone rows of a standard height. With the wall stone size of 390 mm×190 mm×188 mm, which is cut by an average cutting width of the working body of 27 mm, the extraction chamber width of 4.4 m, determined by the analytical and calculation method, allows cutting 21 rows from the stoping face. Finally, the extraction chamber is selected and corrected in the mine in such a way as to ensure safe conditions for mining operations without the use of mine working support or its use should be minimal.

4.3. Determining the size of supporting pillars to support the overlying rock stratum

In underground limestone mining, in order to prevent collapse and rapid overlying roof subsidence, the issue of determining the rational sizes of the supporting pillars is especially relevant. In the case of a chamber system for mining the saw limestone, the use of square-shaped supporting pillars left to support roof rocks has become widespread.

To prevent collapses and rapid roof rock subsidence, the rational choice of the sizes of inter-chamber supporting pillars is of current importance. The supporting pillars must provide sufficient resistance to the overlying rock stratum pressure and must not be excessively strong, which usually leads to significant losses of the mineral in the subsoil. The sufficient size of supporting pillars depends on the physical-mechanical properties of sawn limestone and rock stratum, as well as the mining depth. The square shape of a supporting pillar is formed when, after the advance of extraction chambers, face cuts are driven perpendicular to them for mining inter-pillar sawn limestone reserves. It is recommended to take the face cut width (lf.c) and the ceiling thickness, similar to the extraction chamber, 4.4 m and, respectively, not less than 0.9 m.

To determine the parameters of the supporting pillars in sawn limestone mines, the Turner – Shevyakov method is the most optimal. The calculation scheme for determining the size of supporting pillars in the conditions of the Nova Odesa sawn limestone deposit is shown in Fig. 4.

The basic calculation equation, under the condition of stable rock equilibrium for a deposit with a flat occurrence of a sawn limestone seam, should have the following form:

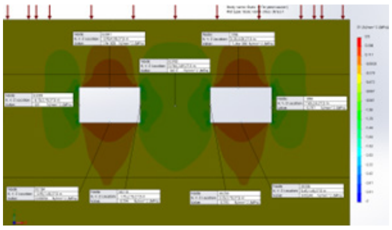


Fig. 6. Curve of vertical (SY) stress distribution in a rock mass
Rys. 6. Krzywa rozkładu naprężeń pionowych (SY) w górotworze

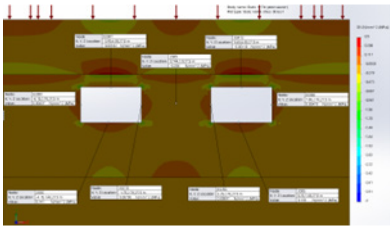


Fig. 7. Curve of horizontal (SX) stress distribution in a rock mass
Rys. 7. Krzywa rozkładu naprężeń poziomych (SX) w górotworze

$$\frac{k_e \cdot \gamma_l \cdot H \cdot S_r}{S_p} + \gamma_o \cdot h = \frac{R_c \cdot k_s}{n_s} \qquad (4)$$

Where k_e – a coefficient taking into account the influence of the size of the extraction site and the mining depth on the average load value applied to the inter-chamber pillars. It has been statistically determined that at L/H ≥ 1, a load is formed on the supporting pillars from the full mass of the overlying rock to the earth's surface. At L/H > 1, ke = 1.
γ_l – unit specific gravity of sawn limestone, t/m^3 (p. 4.3);
H – distance from the daylight surface to the chamber roof (mining depth), m (p. 4.3);
S_r – the area of the roof rocks per a pillar, m^2;
γ_o – unit specific gravity of overlying rocks, t/m^3. The arithmetic mean value of the overlying stratum rocks is $\gamma_o = 1.8$ t/m^3;
R_c – the ultimate compressive strength of rocks, MPa (p. 4.3).

Due to the fact that the output of wall stone during experimental-industrial mining is less than 60%, it is necessary to take into account the mass fracturing, which is average. The mass structural weakening factor of 0.5 is taken.
k_s – shape factor taking into account the change in the strength of the rocks that constitute a pillar at different values of the ratio of the pillar height to its width. It is determined from the expression $k_s = \sqrt{a/h}$, where a – a pillar width, m; h – a pillar height, m.
S_p – horizontal sectional area of a pillar, m^2;

If, according to the calculation scheme (Fig. 4), the chamber width is taken as l (equal to 4.4 m), the pillar width is – a, and the length is b, then for square pillars the Turner – Shevyakov equation takes the form:

$$\frac{k_e \cdot \gamma \cdot H \cdot (l+a) \cdot (l+b)}{ab} + \gamma_1 \cdot h \le \frac{R_c \cdot k_s}{n_s} \qquad (5)$$

Analytical research on determining the size of the supporting pillar is performed as follows. Based on expression (5), the calculated value of the safety factor (ns) is determined:

$$n_s = \frac{R_c \cdot (a/h)^2}{\dfrac{\gamma \cdot H \cdot (l+a) \cdot (l+b)}{ab} + \gamma_1 \cdot h} \qquad (6)$$

Further, in expression (6), the sizes of the square-shaped supporting pillar (a×b) are varied with the following increments: 2×2; 3×3; 4×4; 5×5; 6×6; and 7×7 m. Based on the result of the analytical research (6), the dependence of the safety factor on the supporting pillar area is determined. The rational area and the supporting pillar size are selected from the conditions of its compliance with the safety factor. The safety factor of the pillar is taken equal to 3-5 if the chamber is maintained for an indefinite time and 2-3 if the chamber is maintained only for the duration of mining operations. Under the conditions of the Nova Odesa deposit, long-term maintenance of pillars is supposed to support the overlying rock stratum as mining operations develop within the area of the deposit's mining field. The results of analytical calculations are presented in Fig. 5.

Analysis of Fig. 5 indicates that the safety factor of the supporting pillar for mining-geological and mining-technical conditions of the Nova Odesa sawn limestone deposit development has a power-law dependence on its area. Due to the fact that mining operations will be developed deep into the deposit over the area of the mine field and with a long time of mining the reserves, the safety factor of the supporting pillars should be at least 3.0. According to the dependence, a safety factor of 3.0 corresponds to the supporting pillar area of 24.0 m^2. With a square shape of the supporting pillar, its width and length are 4.9 m^2. It is recommended to take an integer value of the width and length of the supporting pillar 5×5.

4.4. The numerical modeling results of stability of mining system elements

Numerical modeling based on the finite element method is used to verify the results of analytical research on the stability of the chamber system elements for mining with square-shaped supporting pillars. The model consists of a sawn limestone layer of 7.5 m, laminated limestone of 4.0 m thick in the roof and bottom. The model includes chambers 4.4 m wide and 2.6 m high, as well as 5 m wide square-shaped supporting pillar with a ceiling thickness of 0.9 m. The results of modeling with obtaining curves of vertical SY and horizontal SX stresses are shown in Figs. 6 and 7.

An analysis of the vertical stress distribution curve (Fig. 6) shows that the vertical stress component forms areas of too weak stresses in the chamber ceiling that are almost equal to 0. A similar situation is in the extraction chamber bottom, where too weak tensile stresses reach 0.002 MPa. A de-stressing zone is formed in the roof and bottom of the chamber. In the extraction chamber corners, regular compressive stress concentrations up to 1.0 MPa are observed. Given the sawn limestone ultimate tensile strength of 0.42 MPa, the accepted extraction chamber ceiling thickness (0.9 m) will be in a stable state when exposed to the vertical component of rock pressure.

In the extraction chamber sides (supporting pillar mass), zones of compressive stresses are formed with values of 0.8 MPa, which does not exceed the limestone ultimate compressive strength, the value of which is 3.1 MPa. The supporting pillar is in a stable state and its loading is 26%. In the supporting pillar center, the loads are up to 0.6 MPa.

An analysis of the horizontal stress distribution curve (Fig. 7) shows that in the chambers ceiling the stress areas are close to 0 MPa. Stresses of 0.14 MPa are formed in the extraction chamber bottom. Given the sawn limestone ultimate tensile strength of 0.43 MPa, the accepted ceiling thickness (0.9 m) and the bottom of the extraction chamber will be in a stable state under the action of horizontal stresses. In the extraction chamber sides (supporting pillar mass), zones of superweak tensile stresses are formed with values close to 0. It should be noted that in the roof, in the laminated limestone layer, at the contact with the sawn limestone seam, zones of tensile stresses of 0.45 MPa appear, and in sawn limestone, compressive stresses of 0.7 MPa occur. The tensile stresses in laminated limestone reach the ultimate tensile strength of limestone, which over time will lead to fracturing and destruction. However, this phenomenon does not pose a threat, because the limestone mass is destroyed in the mass depth behind the ceiling. Analysis of curves (Figs. 6, 7) indicates that the most stressed element of the mining system due to the action of vertical stresses is the supporting pillar. If the resulting stresses do not exceed the rock ultimate strength, then there will be almost no displacements and deformations, and the chamber contour destruction will not be observed.

It should be noted that there is a sufficient convergence of analytical research and numerical modeling, because their results indicate the absence of tensile stresses in the chamber ceiling and a sufficient safety factor of the supporting pillar. Based on this, the adopted mining system parameters, namely, the extraction chamber width is 4.4 m, the extraction chamber height is 2.6 m, the ceiling thickness is 0.9 m, and the supporting pillar size is 5x5 m will ensure the rock mass stability and the safety of mining operations. Determining the mining system rational parameters makes it possible to further develop a scheme for mining and preparing the Nova Odesa deposit mine field.

5. Conclusion

As a result of research on the substantiation and assessment of the stability of the elements of the sawn limestone underground mining system, the following results have been determined using the example of a specific promising deposit:

1. The peculiarities of mining-geological and mining-technical conditions for mining a promising Nova Odesa sawn limestone deposit have been generalized and analyzed. It is noted that the balance reserves have been approved for the primary mining of a limestone layer of 3.0 m with a thickness variation of 4.5-10 m through the deposit, which indicates the prospects of multilayer mining in the future. A deposit is of flat occurence, water-free, with a developed mineral fracturing system, which is suitable for wall stone production.
2. It is proposed to use a combined scientific and methodological approach together with analytical and calculation research to substantiate and assess the stability of the sawn limestone mining system elements on the basis of known and proven hypotheses for the stability of spans and pillars with substantiation of all constituent elements and verification by numerical modeling based on the finite element method.
3. The rational value of the extraction chamber height (2.6 m) is substantiated, influenced by the permissible parameters of single-layer limestone seam mining, the technological parameters of stone-cutting machines and the need to observe the integer number of wall stone rows cut along the height of the chamber.
4. It has been analytically determined that when the ceiling thickness value is changed by 50% (from 0.8 to 1.2 m), the safe chamber width, at which there are no tensile stresses in the sawn limestone roof under given mining-geological conditions, increases by 22%. The rational value of the chamber width and ceiling (4.4 and 0.9 m respectively) has been substantiated.
5. It has been analytically determined that the safety factor of the supporting pillar for mining-geological and mining-technical conditions of the Nova Odesa sawn limestone deposit development has a power-law dependence on its area. It has been determined that the required safety factor of a square-shaped supporting pillar corresponds to an area of about 25.0 m^2, and the value of the width and length of the pillar will be 5×5 m.
6. It has been found by numerical modeling that under the conditions of the Nova Odesa deposit, the load on a 5×5 m supporting pillar will reach 26% of its load-bearing capacity, and the extraction chamber ceiling is in a stable state without the formation of tensile stresses.

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Uzasadnianie i ocena stabilności parametrów systemu podziemnego dla wydobycia wapienia: studium przypadku złoża Nowa Odesa, Ukraina

W wyniku agresji federacji rosyjskiej na Ukrainę infrastruktura wielu osiedli uległa znacznemu zniszczeniu, dlatego w okresie powojennym wapień może stać się niezawodnym i użytecznym surowcem do jej odbudowy. Znaczna liczba złóż wapienia na południowej Ukrainie nadaje się do produkcji kamienia ściennego (blokowego), jednak warunki geotechniczne wielu miejsc wydobywczych wymagają zastosowania metody urabiania podziemnego. Do badania parametrów systemu wydobywczego złoża wapienia Nowa Odessa stosowane są metody analityczne i obliczeniowe oparte na znanych i sprawdzonych hipotezach stabilnych przęseł i filarów oraz weryfikacja poprzez modelowanie numeryczne w oparciu o metodę elementów skończonych w pakiecie oprogramowania SolidWorks. Stwierdzono, że przy zmianie grubości stropu o 50% (z 0,8 na 1,2 m) bezpieczna szerokość komory przy braku naprężeń rozciągających w stropie, w danych warunkach górniczo-geologicznych i górniczo-technicznych działalności wydobywczej wzrasta o 22%. Stwierdzono, że powierzchnia 25,0 m² odpowiada wymaganemu współczynnikowi bezpieczeństwa kwadratowego słupa nośnego. Modelowanie numeryczne wykazało, że w warunkach złoża Nova Odesa obciążenie filaru nośnego o wymiarach 5m×5m osiągnie 26% jego nośności, a strop komory wydobywczej jest w stanie stabilnym bez powstawanie naprężeń rozciągających. Wyniki badań są przydatne do uzasadnienia i oceny stateczności elementów systemu urabiania komorowo-filarowego wraz z filarami oporowymi w podziemnym wydobyciu wapienia lub innych złóż kopalin.

Słowa kluczowe: *kopalnia, wapień, komora wydobywcza, filar nośny, strop*