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Theoretical substantiation of water inflow into the mined-out space of quarries mining hard-rock building materials

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Abstract. This paper covers topical issues of groundwater and surface water inflow depending on the quarry field spatial dimensions, which leads to an increase in the costs of dewatering and drainage. The spatial dimensions of a quarry field are one of the key indicators in determining the appropriate depth of mining the deposits of hard-rock building materials. The theoretical research is performed using the following methods: statistical and analytical research method for analyzing the hydrological characteristics of non-metallic deposits and their parameters; graphic-analytical method for determining the area of the quarry walls from which water flows due to groundwater and atmospheric precipitation; technical-economic method for assessing the patterns of changes in costs for dewatering the quarry depth; and method of options for selecting the type of water drainage equipment. As a result, patterns have been obtained that characterize the change in the normative inflow of atmospheric precipitation depending on the quarry field area and the change in the unit costs for dewatering depending on the type of the studied quarry field. The practical significance of the conducted research is to use the obtained results of developed design solutions, tested and implemented in the scientific-technical (project) documentation for the mining conditions of Sofiivskyi, Mykytivskyi, Boleslavchykskyi, Chaplinskyi, and Lyubimivskyi fields of non-metallic hard-rock minerals.

1. Introduction

The global mining plays a crucial role in the extraction and processing of mineral resources [1, 2]. It encompasses various sectors, including coal, metals, industrial minerals, and precious stones. The industry is subject to fluctuations in commodity prices, geopolitical factors, and environmental regulations [3-6].

Ukraine ranks first in the world in terms of reserves of non-metallic hard-rock raw materials suitable for the manufacture of building materials, namely crushed stone products: limestones, dolomites, quartzites, sandstones, granites, migmatites, hard shale and other minerals [7-9]. There is a particularly wide variety of granites of different ages, textures and colors. Deposits of metamorphic and igneous rocks are widespread in the Zhytomyr, Kirovohrad, Dnipropetrovsk, Donetsk, Zaporizhzhia, Kyiv, and Vinnytsia Oblasts. These deposits are confined to the Ukrainian Crystalline Shield [10, 11].

Igneous and metamorphic rock deposits are distinguished by significant diversity in composition, thickness, structure, location relative to the dominating surface elevations, shape and size, approved reserves, water cut and water abundance, thickness and nature of overburden rocks [12-16]. Mentioned factors necessitate careful geological and engineering assessments when planning and operating quarries within igneous and metamorphic rock deposits, ensuring sustainable resource extraction while addressing challenges related to mineral composition, geological conditions, water management, and overburden characteristics [17, 18].

In the practice of planning quarries of hard-rock building materials within igneous and metamorphic rock fields, their economically feasible mining depth is limited by many parameters and factors: the depth of explored mineral reserves; increased water inflow, which leads to a sharp increase in the cost for dewatering; the built-up area near quarry fields, which limits their spatial dimensions; increased radioactivity of minerals with depth, small cross-sectional dimensions of the igneous rock deposit, etc. [19-21].

The determination of economically viable mining depths for quarries within igneous and metamorphic rock fields is a complex process that takes into account numerous interrelated parameters and factors [22–24]. As mining operations delve deeper, they often encounter increased water inflow from underground aquifers. Managing this water can become a significant operational expense, as deeper excavations may require more advanced dewatering systems and the associated energy costs [25]. Advances in mining technology and equipment can extend the feasible mining depth by improving efficiency, safety, and cost-effectiveness [26, 27]. New drilling methods, automation, and material handling technologies may enable deeper excavations [28-30].

Based on the analysis of the current state of mining enterprises, as well as scientific-technical [13-16] and project documentation [19-21], it has been revealed that an appropriate criterion for substantiating a rational (economically feasible) depth of mining non-metallic hard-rock mineral deposits of igneous and metamorphic origin is the economic indicator of expedient mining of a mineral (mining cost of 1 m^3 and the minimum acceptable profitability of an enterprise) [31-34].

Increased inflow of groundwater (with increasing depth) and surface water (with increasing quarry field spatial dimensions), which leads to increased costs for dewatering and drainage, is one of the key indicators in determining the expedient conduct of mining operations in the specified fields [35, 36]. Analyzing the above studies, it is possible to conclude that issues of hydrogeological specificity, namely the water inflow into the mined-out space of a quarry, relate to deposits of sedimentary origin [37-40], brown coal sections and iron-ore deposits mined at deep quarries, the depth of which reaches more than 400 m [41].

As for the deposits of igneous and metamorphic origin, which are the raw material base for mining building materials for the manufacture of crushed stone products, they are almost unexplored, as these quarries are not of great depth, which today ranges from 20 to 150 m, and on average no more than 75 m [42, 43].

In the work [12], which studies in detail the issues of groundwater inflow in non-metallic fields of Ukraine, it has been determined that the maximum permissible water inflow during mining of granite quarries, due to a combination of various factors and, first of all, to the production capacity of the quarry, should not exceed the set value for a large quarry of 2250 m^3/hour with an enterprise production capacity of 2500 thousand m^3/year.

Analyzing the above indicators of the amount of permissible water inflow depending on the quarry productivity, the maximum water inflow for an average quarry, mining raw materials for the manufacture of crushed stone products with a capacity of 200 thousand m^3/year, should not exceed 4320 m^3/day (180 m^3/hour).

Groundwater water inflow in non-metallic fields of Ukraine in this period, with a mining depth within 20-70 m, ranges from 25 to 1 200 m^3/day, and surface water (atmospheric precipitation) inflow is up to 2500 m^3/day during the rainy season.

It should also be noted that when mining non-metallic hard-rock mineral deposits, the greatest water cut is observed in the zones of tectonic faults [44-46] technogenic disturbances [47, 48] and weathering crust [49, 50]. As for the undisturbed rock mass, the water inflow in such deposits is extremely small and does not entail significant costs [51]. Examine several fields:

– Lyubimivsky granite deposit is located within the city of Dnipro [21]. The protecting pillar width between the quarry and the Dnipro River is 30-50 m, the pressure water horizon depth is observed over the entire area of the outcropped mass from the Dnipro River side. The total water inflow is 250-600 m^3/day, depending on the season;

– Malokokhnovsky granite deposit is located near the city of Kremenchuk, Poltava Oblast [19]. The pillar width between the quarry and the Dnipro River is over 350 m, the pressure water horizon depth is observed in the zones of tectonic faults, which are located in the weathering crust along the entire length of the mass from the Dnipro River side. The total water inflow is over 9000 m^3/day.

Analyzing the hydrogeological conditions of the above fields, it is possible to conclude that the mining depth of the quarry does not always affect the quantitative water inflow indicator.

The specified provisions determine the relevance of the research purpose for the theoretical substantiation of water inflow into the mined-out space of quarries mining hard-rock building materials.

2. Methods

About 117 non-metallic fields of igneous and metamorphic origin are used as research objects, systematized into groups with the identification of typical (basic) fields, the main parameters of which are given in [52, 53]. In this systematization, three main groups of quarries are distinguished by the area of the fields: large, medium and small area, and three main types that differ in the average thickness of the overburden rocks: small, medium and large.

To achieve the purpose set, the research uses the following methods: statistical and analytical method for processing the parameters of active non-metallic quarries, mining raw materials for the manufacture of crushed stone products, and analysis of the hydrological characteristics of non-metallic fields; graphic-analytical method for determining the area of the quarry walls from which water enters the mined-out space, the average daily water inflow due to groundwater and atmospheric precipitation; technical-economic method for assessing the patterns of changes in energy and unit costs for dewatering the quarry depth and determining indicators of unit costs for water discharge at typical quarries; method of options for selecting the type of pumping unit that provides effective draining of the mined-out space.

Theoretical research on substantiation of possible groundwater and atmospheric water inflow into the mined-out space of the quarry is performed with consideration of the exploration and extension of useful mineral reserves to the maximum depth without spacing the quarry walls beyond the boundaries of the contour of estimated reserves by area and intra-quarry stockpiling of overburden rocks. All this ensures the development of resource-saving technologies for mining igneous and metamorphic fields [54].

The methodology for the theoretical substantiation of a possible water inflow into the mined-out space of the quarry is as follows:

The water inflow into the mined-out space is determined by the expression [55,56]:

$$Q_w = Q_d + Q_a, \tag{1}$$

where Q_d is average daily water inflow due to groundwater in fractured zones of crystalline rocks, m^3/day; Q_a is normative inflow from atmospheric precipitation, m^3/day.

$$Q_d = S_{o.a} \cdot q, \tag{2}$$

where $S_{o.a}$ is the outcropped area of the quarry walls from which water flows into the mined-out space, m^2; q is rock filtration rate, m/day;

$$S_{o.a} = \sum_{i=1}^{n} S_i = S_{o.a}^{I} + S_{o.a}^{II}, \tag{3}$$

$$\begin{gathered} S_{o.a} = \left[\left(L_q - H_i \cdot ctg\alpha_P^{I}\right)H_3 + \left(B_q - H_i \cdot ctg\alpha_P^{I}\right)H_i\right] \cdot 2 + \\ + \left[\left(L_e - H_a \cdot ctg\alpha_P^{II}\right)H_a + \left(B_a - H_a \cdot ctg\alpha_P^{II}\right)H_a\right] \cdot 2 \end{gathered}, \tag{4}$$

where $S^{I}_{o.a}$ is the area of outcropped quarry walls of approved reserves, m^2; $S^{II}_{o.a}$ is the area of outcropped quarry walls of added reserves, m^2; L_q is quarry length, m; H_i is depth of internal dump formation, m; α^{I}_{p} is the resulting wall slope angle when mining the approved reserves, deg; B_q a quarry width, m; L_e is quarry length with extension of reserves, m; H_a is the depth of added reserves, m; α^{II}_{p} is the resulting wall slope angle when mining the added reserves, deg; B_a – a quarry width of added reserves, m.

$$Q_a = S_q \cdot H_p, \tag{5}$$

where: S_q is the quarry surface area, m^2; H_p is the average daily amount of precipitation per calendar year, mm/day.

Electricity consumption for drainage is calculated by the formula [14]:

$$Z = C_e \cdot \frac{N_p \cdot N_e \cdot P_p \cdot K_l \cdot T_w \cdot T_d \cdot \dfrac{A \cdot S_q + S_{m.o} \cdot q}{Q_p \cdot T_o}}{\eta_C} \text{ UAH/year}, \tag{6}$$

where: N_p is the number of pumps in operating mode; N_e – number of engines on the pump; P_p is pump power, kW; K_l is pump load factor; T_w is working time per day, hours; T_d is the number of working days per year; η_c is network efficiency coefficient; C_e is cost of 1 kW·h, UAH; A is average daily precipitation, m; S_q is quarry field area, m^2; $S_{m.o}$ is the area of mineral outcrop from which groundwater is released, m^2; q is the volume of water entering the quarry from one square meter, m^3/m^2; T_o is operating time of the pump per day, hours; Q_p is pump capacity, m^3/hour.

3. Results and discussion

A detailed analysis of the geological-hydrological characteristics of non-metallic fields of mineral raw materials for the manufacture of building products (building materials) is performed using the example of the Prydniprovsk region fields. The specified fields are directly adjacent to the basin of the main artery of Ukraine – the Dnipro River with its numerous tributaries. Such fields are in the most unfavorable conditions in terms of water inflows into the mined-out space. Based on these assumptions, further research is conducted, taking into account complex geological-hydrogeological conditions in the presented non-metallic fields.

The structure of these deposits includes rocks of the Konsko-Verkhovtsevska series of the ultrametamorphic formation, confined to the rocks of the upper suite of the Aul series of Archean age, intrusive formation, rocks of the weathering crust and rocks of the Quaternary system. The field area is a low-lying, slightly undulating, rather unevenly dissected plain. The lowest surface elevations are observed along the Dnipro River valley and its tributaries. The field minerals (disturbed by weathering and fresh rocks) are part of the Crystalline Massif with an uneven surface.

The average daily annual inflow is 250-1500 m^3, which depends significantly on the hydrogeological conditions, mining depth, and location (distance to the coastline) [53, 56]. The crystalline rock water saturation is determined by the degree of fracturing and the fracture state. The groundwater mirror lies below the roof of crystalline rocks, groundwater is non-pressure.

The aquifer thickness ranges within 30-75 m, the average thickness in the mined part of the fields is 50-60 m. The filtration rate of crystalline rocks and their weathering crust ranges within 0.17-0.001 m/day. For gravel and crushed stone, according to experimental data from hydrogeological studies, it varies from 0.1 to 5-10 m/day.

According to data in [57], the average amount of precipitation per year ranges from 250 to 2200 mm/year, and averages 550-600 mm/year. As for the steppe zone, where non-metallic deposits of hard-rock minerals are most widespread, this indicator is 450-500 mm/year. Thus, the normal water inflow from atmospheric precipitation, depending on the quarry field area, will be (Fig. 1).

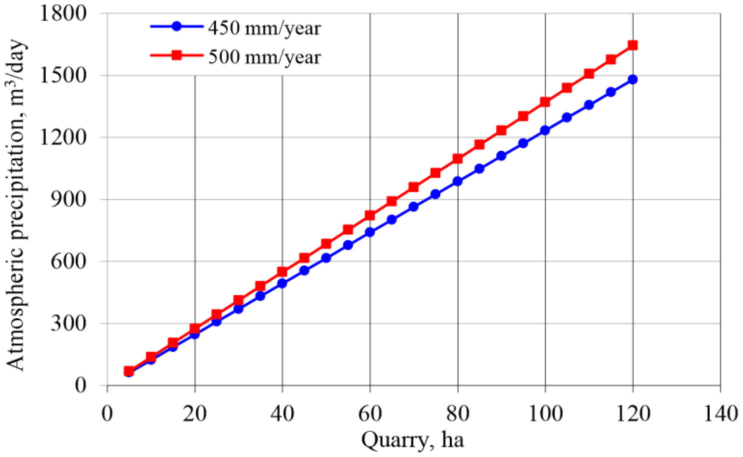

Figure 1. Dependency graph of the normative atmospheric precipitation inflow on the quarry field area

Analyzing the obtained results, it can be concluded that the dependence of the normative atmospheric precipitation inflow on the quarry field area varies according to equation:

$$Q_A = 12.67 S_q - 7 \cdot 10^{-13}, \tag{7}$$

The resulting regression equation can be used to determine the amount of atmospheric precipitation at the base quarries with the approximation accuracy R = 0.997. Indicators of water inflow from atmospheric precipitation at typical quarries are presented in Table 1.

Table 1. Indicators of water inflow into quarry from atmospheric precipitation.

Quarry group	Quarry type	Average quarry field area, ha	Water inflow, m^3/day
I	1	92.7	1180
	2	86.8	1100
	3	92.2	1170
II	4	30.8	385
	5	31.5	400
	6	33.4	415
III	7	13.4	170
	8	14.6	185
	9	15.3	195

As noted earlier, q is the rock filtration rate, which for rocks of igneous and metamorphic origin with an undisturbed texture (practically impermeable or waterproof rocks) is 0.001 m/day, and for rocks with capillary fracturing (poorly permeable rocks) it can be 0.00-0.01 m/day [58]. The practice of mining deposits of igneous and metamorphic origin shows that in zones of tectonic faults and weathering crust this rate can reach 0.025-0.17 m/day [19-21]. Indicators for calculating the average daily water inflow due to groundwater at typical quarries are given in Table 2.

As a result of the research, a graph of a change in the average daily groundwater inflow depending on the depth of deposit mining at typical quarries has been obtained (Fig. 2). As can be seen from the results obtained, the largest water inflow is from the groundwater inflow with a sharp increase in the quarry depth to 130 m. This significant increase in groundwater inflow at a depth of 130 meters is a critical finding that warrants further investigation and management considerations for quarry operations. Understanding the relationship between mining depth and groundwater inflow is essential for ensuring the safety and sustainability of quarrying activities.

Table 2. Average daily groundwater inflow into the quarry.

Quarry group	Quarry type	Quarry depth, m	Quarry field length, m	Quarry field width, m	Area of outcropped quarry walls from which water flows into the mined-out space, m^2	Water inflow, m^3/day
I	1	388	1198	774	913955	15537
	2	355	1263	690	784772	12556
	3	327	1197	770	680222	10203
II	4	230	615	493	305054	4118
	5	205	711	446	317936	3815
	6	203	700	471	287867	3454
III	7	156	426	311	141126	1623
	8	153	465	313	142787	1571
	9	134	509	300	137720	1377

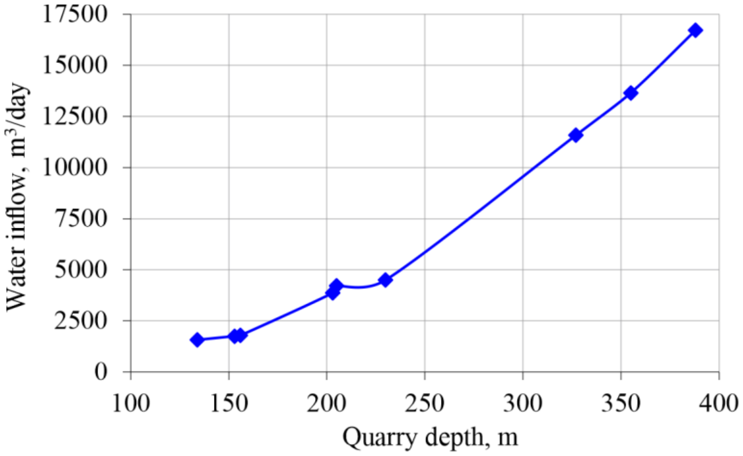

Figure 2. Graph of changes in the total average daily groundwater and atmospheric water inflow depending on the quarry mining depth.

The specified indicators (Fig. 2) are approximated in the form of the following analytical dependence:

$$Q_d = 0.0002H_q^3 + 0.0067H_q^2 + 12.664H_q - 1029.5 \tag{8}$$

The resulting regression equation can be used to determine the amount of average daily groundwater inflow at the base quarries with the approximation accuracy R = 0.9984. The error in calculating the expected water inflow does not exceed 1%. Analyzing the obtained data, showing the change in the average daily water inflow into the quarry from atmospheric precipitation and from groundwater, estimating the hourly water inflow for each type of quarry, the authors of the research have selected the necessary pumping station that will pump out the volume of water from the maximum quarry depth. The water pressure is calculated taking into account the quarry depth, the resulting wall slope angle of the quarry, along which the drainage pipeline is laid, and also taking into account the resistance forces arising from contact with the pipe walls and at the angles of its rotation [59]:

$$H_{w.p} = H_h + \sum_{i=1}^{n} h_h \tag{9}$$

where: H_h is geometric lift height, m; $\sum_{i=1}^{n} h_h$ is the sum of hydraulic losses due to friction and in local support bearings (depends on the length, diameter and layout of the pipeline system), m.

The type of pump station is selected according to the passport (graphic characteristics of the pumps), the results are shown in the Table 3. The calculation results of the patterns of change in energy consumption for water drainage depending on the quarry depth have the dependence shown in Figure 3.

Table 3. Selection of the type of pumping unit for typical quarries.

Quarry group	Quarry type	Quarry depth, m	Total water inflow, m^3/hour	Pump type	Pump power, kW	Required pump number, units
I	1	388	697	TsNS 850-420	1250	1
	2	355	569	TsNS 300-360	425	2
	3	327	483	TsNS 180-340	225	3
II	4	230	188	TsNS 105-245	110	2
	5	205	176	TsNS 180-212	140	1
	6	203	161	TsNS 180-212	140	1
III	7	156	75	TsNS 60-198	65	1
	8	153	73	TsNS 60-198	65	1
	9	134	66	TsNS 60-165	55	1

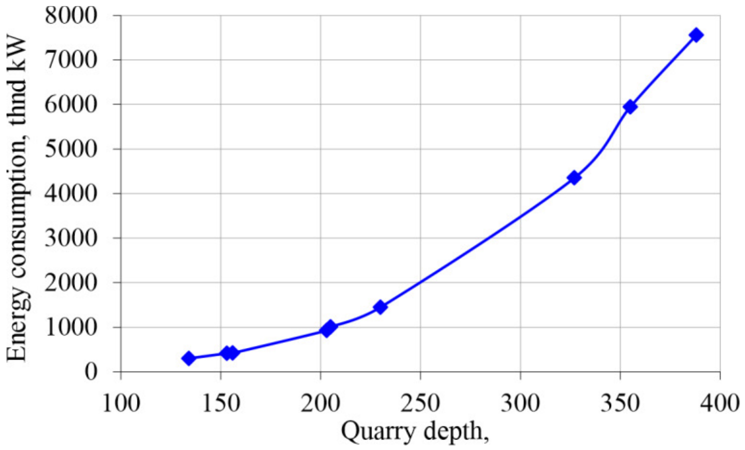

Figure 3. Patterns of changes in energy consumption for drainage depending on the quarry depth.

The electricity spent for water drainage is calculated by formula (6), the calculation results are shown in Figure 4 (the cost of 1 kW is considered within 2019-2023 for mining enterprises).

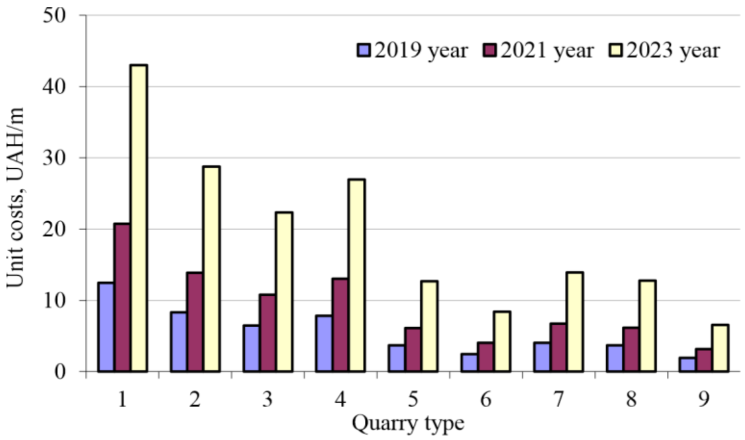

Figure 4. Indicators of unit costs for dewatering at typical quarries.

Analyzing the obtained results shown in Figs. 3 and 4, it can be concluded that with an increased depth of mining the field, there is an increase in the indicators of water inflow into the mined-out space, which is reflected by a sharp increase in the quarry depth to 130 m. The dynamics of change in the unit costs for groundwater and atmospheric water drainage from a quarry has a proportional growth with an increase in the cost of energy resources for mining enterprises and has a significant growth in recent years, which has led to an increase in the share of water drainage costs in the total cost of mining building materials, and leads to a decrease in the enterprise profitability.

Further research in this direction could focus on several important aspects to enhance our understanding and improve the management of water inflow in quarries of igneous and metamorphic origin mining hard-rock building materials. Given the observed increase in energy-related costs, research can delve deeper into optimizing energy-efficient water drainage methods. This might involve the use of renewable energy sources, energy-efficient pumps, and monitoring systems to minimize energy consumption. A better understanding of the geological aspects can aid in predicting and managing water inflow more effectively, so the geological factors that influence water inflow, including the porosity and permeability of rocks, fault lines, and groundwater flow patterns should be studied in-deep. Establishing long-term monitoring programs to track changes in water inflow, water quality, and costs over extended periods can help refine models and improve decision-making.

By addressing these research direction, future studies can contribute to more sustainable and efficient water management practices in quarries, ultimately benefiting both the mining industry and the environment.

4. Conclusions

The paper conducts researches in the direction of theoretical substantiation of possible water inflow into the mined-out space of quarries of igneous and metamorphic origin for mining hard-rock building materials. As a result of the research, the dependence of the possible water inflow into the mined-out space on the quarry field spatial parameters and the mining depth has been determined. In addition, an analysis has been performed of the dynamics of changes in unit costs for water drainage works in recent years of operation of the specified fields, which shows a significant increase in losses from the increase in the cost of energy resources.

The practical significance of the conducted research is to use the obtained results of the developed design solutions, tested and implemented in the scientific-technical (project) documentation for the mining conditions of Sofiivskyi, Mykytivskyi, Boleslavchykskyi, Chaplinskyi, and Lyubimivskyi and other fields of non-metallic hard-rock minerals.

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