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DETERMINATION OF RATIONAL TECHNOLOGICAL CONDITIONS FOR THE USE OF PUMP DREDGER SUCTION HEADS

Purpose. Development of theoretical foundations for determining rational technological conditions for the use of pump dredger suction heads in underwater mining of unconsolidated minerals.

Methodology. In calculating the volume of complex geometric figures formed by the intersection of cones of different heights, whose vertices lie in the same plane, a standard method of integration was applied.

Findings. The feasibility of using funnel technology in underwater soil mining has been substantiated. An analysis of technological schemes for the use of pump dredger suction heads intended for underwater mining of unconsolidated minerals has been performed. As a limiting criterion for selecting the layout scheme of mining funnels, it is proposed to use the dimensionless coefficient of mineral recovery. For comparative analysis, the most suitable schemes for moving pump dredger suction heads with final positions of funnel centers were proposed – referred to as the square-nest and triangular-nest schemes. Graphic representations of the mined space of the underwater quarry using the funnel method with square-nest and triangular-nest layouts are provided. Based on the analysis, it is assumed that during the mining of unconsolidated soil using a single suction pipe, the extraction funnel will take the shape of a cone. It is proposed to determine the volume of soil extracted from such a funnel by calculating the sum of volumes of the following geometric figures: parallelepiped; a complex figure obtained by cutting off the volume of a truncated cone with planes parallel to its axis; and cone.

Originality. For the first time, it is proposed to determine the volume of soil extracted from an underwater dredging site of a suction dredger using the integration method. Theoretical dependencies were obtained to determine the extraction coefficients when applying square-nest and triangular-nest schemes for repositioning the suction head during funnel-type underwater mining operations.

Practical value. The calculated values of extraction coefficients for the square-nest and triangular-nest schemes of repositioning the suction head will enable efficient use of the funnel mining method. The technological feasibility of applying the triangular-nest scheme has been established according to the criterion of the mineral extraction coefficient from the underwater mining site.

Keywords: *suction head, underwater mining, extraction coefficient, technological conditions*

Introduction. The use of suction dredgers in underwater mining of unconsolidated soils is accompanied by their free suction, i.e., the separation of solid soil particles from the mass and their transfer to the suction pipe. This action is accompanied by the movement of water flow along the surface of the bottom under the influence of the pressure difference between the water surface in the reservoir and the inlet to the impeller of the centrifugal soil pump. That is, the suction of soil particles in an underwater pit, by its physical nature, is a process of erosive soil erosion and its transfer to the suction pipe [1, 2]. Such movement of loose soil particles is accompanied by the formation of an underwater funnel in the shape of a

cone. The apex of such a cone is located at the suction point, i.e., at the point where the suction pipe is installed [3]. At the same time, the geometric parameters of such a pit will be influenced by the physical, mechanical, and rheological properties of the soil, as well as the installation level of the suction pipe of the suction dredger [4].

Literature review. For underwater mining of unconsolidated soils, the following suction modes are usually used: surface, deep, and mixed [5, 6]. The surface suction mode is used when the suction pipe is installed on the surface of the underwater bottom. In this case, a suction area is formed under the suction pipe within a certain distance from the pipe to the bottom. The deep suction method involves the preliminary immersion of the suction head into the soil layer to form a sub-bottom

face [7, 8]. This mining method ensures maximum efficiency of the suction process due to the maximum concentration of slurry [9]. It is known that such a mining process can be implemented using structurally and technologically complex mining systems that are used in specific mining conditions [10, 11]. The mixed method is implemented when suction heads are immersed in loose soil to a shallow depth and can be considered intermediate between surface and deep modes. Examples of practical implementation of these methods of unconsolidated soils suction indicate the prospect of using the deep suction method, for example, in the mining of the Samara deposit of construction sand (Dnipro), which, however, required the design and implementation of specialized mining equipment [12, 13]. The implemented technology made it possible to carry out comprehensive measures and ensure the mining of minerals located under a layer of environmentally hazardous man-made sludge without preliminary stripping operations. Despite its high efficiency and minimal environmental impact, this technology was unable to withstand technological and economic competition during times of uncertainty and economic crisis, with a technologically simpler and more affordable technology that implements surface suction mode [14, 15].

Unsolved aspects of the problem. A characteristic feature of the above modes of suction of loose soils is the use of a funnel-shaped method of working movements of the suction head. Compared to fan and trench methods, this method of working movement does not require the use of a complex rope and anchor system with underwater ledge height control. It is known that in underwater mining of loose soils, thanks to the simplicity of the suction head design and means for working movement, the funnel method has become widely used [1, 16]. Examples of the use of the funnel method in underwater soil mining using a marine hopper and a river sand loader are shown in Figs. 1–2.

It should also be noted that the use of jet agitation systems for loosening of soil is particularly advisable, as they significantly accelerate the soil mining process and increase its efficiency [17, 18].

Objectives of the article. The aim of the study is to develop theoretical foundations for determining rational technological conditions for the use of pump dredgers suction heads accompanying underwater mining of unconsolidated soils.

To achieve the set goal, the following research tasks were formulated and solved in the work:

- to perform modeling of the location of mining funnels during underwater soil extraction;
- to obtain analytical dependencies for determining the extraction coefficient of a mineral resource using the funnel method;
- to calculate the values of the extraction coefficients for different models of the location of the centers of mining funnels.

Methods. To solve the research problems, the standard integration method was used in calculating the volume of complex geometric figures formed by the intersection of cones of different heights, whose vertices are located in the same plane.

Results. Deposits of ore and non-ore sands found in Europe as a whole and in Ukraine are usually of eluvial,

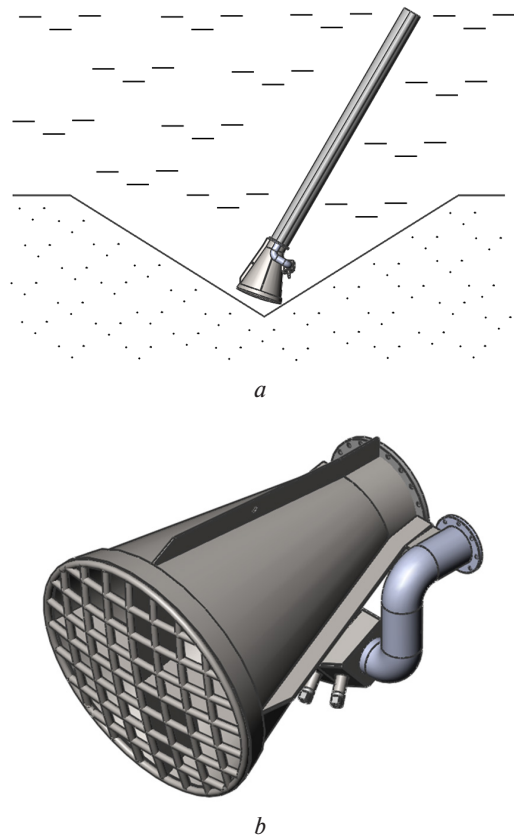


Fig. 1. Use of a soil suction head on a self-propelled marine hopper in funnel-type mining operations: a – suction head in a funnel-type pit; b – suction head

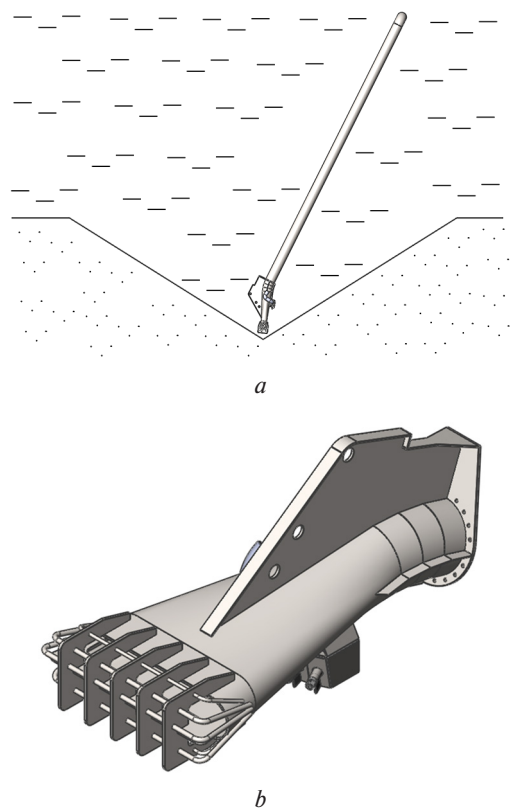


Fig. 2. Use of a soil suction head on a river sand loader in funnel-type mining operations: a – suction head in a funnel-type pit; b – suction head

alluvial, deluvial, and proluvial origin and are formed in the form of marine, river, lake, marsh, glacial, and dune deposits. Sand deposits located in Ukraine are usually found in formations similar to strata with linear deposits. There are also lens-shaped deposits with a significant content of clayey sands. The body of such mineral deposits are usually completely or partially located under the groundwater table. A significant number of sand deposits are classified as alluvial, located in the beds and floodplains of modern rivers. There are also deposits lying at the bottom of the Black Sea, the Sea of Azov, and bays. A characteristic feature of generic sands is the thickness of the mineral deposit. It is known that for most such deposits, the thickness of the sand layer rarely exceeds 10 m [19, 20]. A comparative description of well-known sand deposits based on the thickness of the mineral layer is provided in Table 1.

The funnel method of mining is accompanied by the use of the most acceptable schemes for the movement of the pump dredger suction head with the final location of the centers of the mining funnels, which can be called: square-nest (Fig. 3) and triangular-nest (Fig. 4).

We will analyze the layout of mining funnels in underwater sand mining order to improve the efficiency of extraction operations [21, 22] by substantiating the parameters of the mineral extraction coefficient.

Solid modeling of the surface of the mined area of an underwater quarry, performed with the vertices of the mining funnels located in square-nest and triangular-nest schemes, shows that such mining methods can be fully implemented thanks to modern means of positioning the pump dredgers suction heads in an underwater quarry [23]. However, the criteria for the expediency of their selection and implementation remain unclear.

The criterion for selecting of the model of location of the centers of mining funnels should be the extraction coefficient of the mineral, which is a well-known and important economic and social criterion. For certain patterns of mining funnels locations, the coefficient value will vary. Accordingly, the difference between these values depends on the relative step of the suction head rearrangements (compared to the thickness of the mineral deposit) [24]. It should also be noted that in order to determine the extraction coefficient of a mineral resource, with different parameters of technological schemes for underwater mining, it is necessary to focus

Table 1

Comparative characteristics of sand deposits by mineral deposit thickness

The name of the sand deposit	Average thickness of mineral deposit layer, m
Oleksandrivske deposit, Pivdenna section	7.24
Prybuzke deposit	6.6
East Bug deposit	10.15
East Bug 2 deposit	10.22
Voznesenske deposit	9.62
Velunske deposit of construction sand	13.27
Novo-Ukrainian sand deposit	10.9

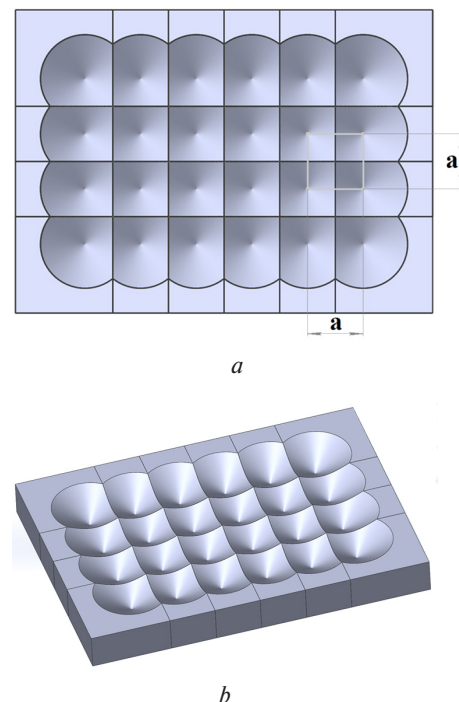


Fig. 3. The square-nest scheme of mining funnels vertices location:

a – view of the surface of the extracted space of an underwater quarry in plan; b – the solid model of the extracted space of an underwater quarry

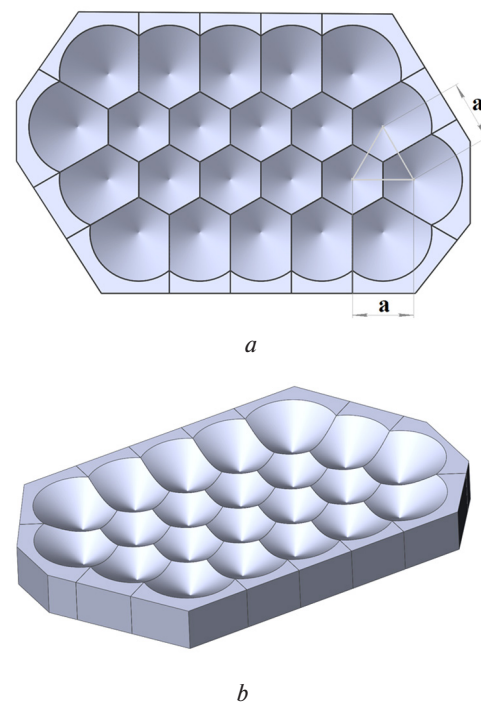


Fig. 4. The triangular-nest scheme of mining funnels vertices location:

a – view of the surface of the extracted space of an underwater quarry in plan; b – the solid model of the extracted space of an underwater quarry

on analyzing the parameters of intersection of the forming extraction funnels in the underwater quarry field [25]. It should be noted that when extracting soil with a single suction pipe, the extraction funnel is cone-shaped. In this case, the volume of soil extracted from such a fun-

nel should be considered as the sum of the volumes of three figures: parallelepiped; a complex figure obtained by cutting off the volume of a truncated cone with planes parallel to its axis, and cone. The scheme for determining the volumes of these figures is given in Fig. 5.

To determine the specified parameters of such figures in the work, a theoretical task was solved concerning the volume of figures obtained as a result of cutting off part of a cone with a plane parallel to its axis [26, 27].

Let us introduce the designation of the natural slope angle for wet sand – α . In order to present the calculation results in a dimensionless form, we introduce the concept of the relative displacement step of the pump dredger suction head, which shows the ratio of the positioning step of the suction head to the depth of the funnel, i.e., to the height of the cone h .

It should be noted that when using the funnel method of mining in an underwater quarry, when mining unconsolidated sandy rocks, a stable slope is formed, which is actually the forming surface for the cone (funnel).

Reference literature and operational experience [28, 29] show that the height of the ledge during underwater mining of soil using suction dredgers is a limiting factor that affects productivity. And depending on the capacity of the mining system, the height of the ledge should be more than 2.4–6.4 m. In accordance with these recommendations, a ledge height of 10 m or even more may be not only acceptable but even recommended when using the funnel method to mine an underwater deposit of unconsolidated sandy soils. Thus, it should be taken into account that for most known sand deposits located in Ukrainian subsoil that can be mined by underwater methods, the thickness of the mineral deposit rarely exceeds 10 m. Based on the analysis, it can be assumed that useful mineral in such deposits will be mined by deepening the suction head (Figs. 1, 2) from the roof of the seam to the floor. That is, the entire deposit will be mined in a single layer of underwater bottom faces consisting of funnels, i.e., cones.

When solving the problem of deriving analytical dependencies for determining the extraction coefficient of a mineral deposit using the funnel method, we will assume that the depth of the funnel, i.e., the height of the cone h , is equal to the thickness of the deposit H .

In this case, the relative step of positioning of the pump dredger suction head can be determined by the formula

$$b_i = \frac{a_i}{H},$$

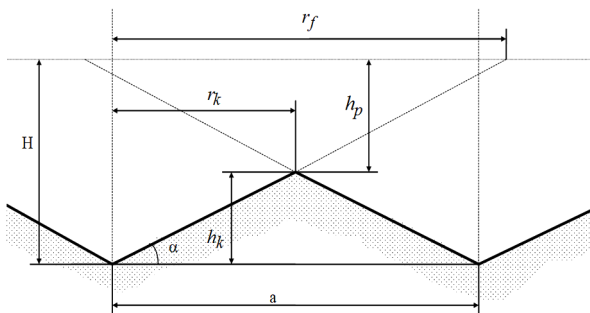


Fig. 5. Schematic representation of the underwater bottom face formed by intersecting funnels during underwater mining of minerals

where a is a step of positioning of the pump dredger suction head, m.

For illustrative purposes, calculations were performed for the following series of relative steps of positioning of the pump dredger suction head: 0.0; 0.2; 0.4; 0.6; 0.8; 1.0; 1.2; 1.4; 1.6; 1.8; 2.0; 2.2; 2.26; 2.4; 2.6; 2.77; 2.8; 3.0.

At the same time, relative steps of positioning of the pump dredger suction head $b = 2.26$ and 2.77 are given for square-nest and triangular-nest mining schemes, respectively, in which the bases of adjacent cones intersect at a single point equidistant from the axes of these cones.

The formula for calculating the radius of the cone is as follows

$$r_f = \frac{h}{\operatorname{tg}(\alpha)}.$$

Then, when $h = H$, the formula for calculating the radius of the cone will take the form

$$r_f = \frac{H}{\operatorname{tg}(\alpha)}.$$

The indicator r_f characterizes the radius of a single cone base, the formation of whose surface is not affected by adjacent mining cones, i.e., the forming cones do not intersect. This relative step of positioning of the pump dredger suction head corresponds to the values of $b = 2.26$ and 2.77 for square-nest and triangular-nest mining schemes, or greater ones. However, if the positioning step values are smaller than those specified, the calculated cone will be formed under the influence of neighboring cones. In this case, let us call this actual radius r_k .

To determine the volume of the cut-off part, we will write down a triple integral with limits: along the x -axis – the distance between the extreme points of the intersection formed when two cones intersect; along the y -axis – from the radius of the cone to the cut-off plane; along the z -axis – from 0 to the surface of the cone

$$\int_{-\sqrt{(r_f)^2 - (z_i h)^2}}^{\sqrt{(r_f)^2 - (z_i h)^2}} \int_{r_f}^{\sqrt{x^2 + y^2}} \int_0^{z_i} dz dy dx,$$

where $z_i = \frac{a_i}{2}$ is distance from the vertex of the cone to the cutting plane.

Let us convert the triple integral into a double integral

$$\int_{-\sqrt{(r_f)^2 - (z_i h)^2}}^{\sqrt{(r_f)^2 - (z_i h)^2}} \int_{r_f}^{\sqrt{x^2 + y^2}} h - \frac{h}{r_f} \sqrt{x^2 + y^2} dx dy.$$

Then we will determine the ratio of the volume of the cut-off part to the total volume of the cone

$$V_n = \frac{V_f}{V_k},$$

where V_k is the total volume of the cone, m^3 ; V_f is the volume of the cut-off part of the cone, m^3 .

We will perform transformations to obtain an analytical dependence for determining the mineral extraction coefficient in accordance with the meaning of relative step of positioning of the pump dredger suction head. Let us record the actual radius of the cone as

Table 2

The significance of extraction coefficients for square-nest and triangular-nest schemes of positioning of the pump dredger suction head

No.	The relative step of positioning of the pump dredger suction head, a/H	The extraction coefficients	
		a square-nest scheme, K_{Vch}	a triangular-nest scheme, K_{Vtr}
1	2	3	4
1	0	0	0
2	0.2	0.954	0.956
3	0.4	0.908	0.913
4	0.6	0.861	0.869
5	0.8	0.815	0.826
6	1	0.769	0.782
7	1.2	0.723	0.738
8	1.4	0.676	0.695
9	1.6	0.63	0.651
10	1.8	0.584	0.607
11	2	0.538	0.564
12	2.2	0.491	0.52
13	2.262	0.477	0.507
14	2.4	0.435	0.477
15	2.6	0.385	0.433
16	2.77	0.345	0.396
17	2.8	0.338	0.389
18	3	0.297	0.343

$$r_k = \frac{a}{2},$$

in this case, the height of the cone will be

$$h_k = r_k \operatorname{tg}(\alpha).$$

Separately, we will determine the fixed values of the radius and height of the cone for square-nest and triangular-nest positioning of the pump dredger suction head,

for a square-nest scheme

$$r_{fch} = 1.414r_k; \quad h_{ch} = 0.884r_k,$$

or a triangular-nest scheme

$$r_{fir} = 1.155r_k; \quad h_{tr} = 0.722r_k.$$

We will determine the height of the parallelepiped using the following formulas for a square-nest scheme

$$h_{pch} = H - h_{ch},$$

for a triangular-nest scheme

$$h_{ptr} = H - h_{tr}.$$

The extraction coefficient for a square-nest scheme is determined by the formula

$$K_{fch} = \frac{V_{Fch}}{a^2 h_{ch}}.$$

The volume of the figure V_{Fch} formed after the cones touch in a square-nest scheme is determined by the formula

$$V_{Fch} = V_k(h_{ch})^2 - 4V_{fch}(h_{ch})^3,$$

where V_{fch} is the volume of the cut-off part in a square-nest scheme.

The extraction coefficient for a triangular-nest scheme is determined by the formula

$$K_{fir} = \frac{V_{Fir}}{3.464r_k^2 h_{tr}}.$$

The volume of the figure V_{Fir} formed after the cones touch in a triangular-nest scheme is determined by the formula

$$V_{Fir} = V_k(h_{tr})^2 - 6V_{fir}(h_{tr})^3,$$

where V_{fir} is the volume of the cut-off part in a triangular-nest scheme.

The formula for calculating the total extraction coefficient for a complex figure formed as a result of the intersection of mining conical funnels in the quarry field of an underwater quarry, consisting of the sum of the extraction coefficients for the cone, a truncated cone bounded by planes parallel to its axis, and a parallelepiped, is written as for a square-nest scheme

$$K_{Vch} = \frac{K_{fch} h_{ch} + h_k (H - h_{ch})}{H},$$

for a triangular-nest scheme

$$K_{Vtr} = \frac{K_{fir} h_{tr} + h_k (H - h_{tr})}{H}.$$

The calculated values of the extraction coefficients for the specified square-nest and triangular-nest

schemes of positioning of the pump dredger suction head in the funnel method of mining operations are given in Table 2 in columns 3 and 4.

A graphical representation of the calculated values of the extraction coefficients for the specified square-nest and triangular-nest schemes of positioning of the pump dredger suction head is shown in Fig. 6. The numerical values obtained indicate a quantitative difference in the extraction coefficients when using square-nest and triangular-nest schemes, which increases linearly with an increase in the relative step of the pump dredger suction head positioning a/H .

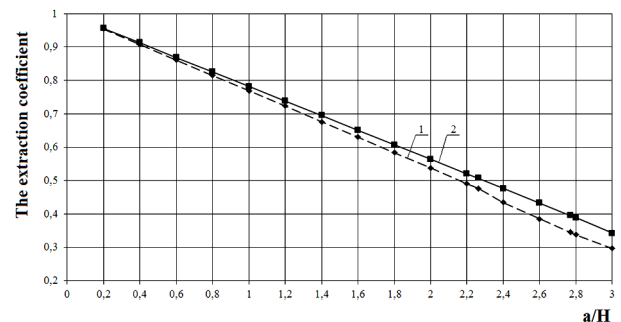


Fig. 6. Dependence of the extraction coefficient on the relative distance between the funnel vertices:

1 – for a square-nest scheme; 2 – for a triangular-nest scheme

At the same time, for example, for $b = 3$, the extraction coefficient of the triangular-nest scheme exceeds the extraction coefficient of the square-nest scheme by 15.5 %. This ratio is quite significant, indicating the feasibility of using a triangular-nest scheme for underwater mining of unconsolidated minerals.

In general, the theoretical foundations developed in this work for determining the rational technological conditions for the use of the pump dredger suction heads, in the underwater mining of unconsolidated minerals can find wide application in modern mining production, dredging and construction works. It should be noted that prior to the widespread introduction of automation and positioning systems for pump dredger suction heads in mining, especially in underwater mining, only the square-nest mining method was widely used. When implementing this method, they mainly relied on the skill of the pump dredger master. Taking into account the available modern automation systems, the implementation of the funnel method with a triangular-nest scheme for positioning of the pump dredger suction heads can show not only the previously confirmed technological feasibility but also significantly increase the economic efficiency of underwater mining and construction works.

Several companies already operate on the modern market, offering specialized solutions used for monitoring and automation of mining and dredging operations [30]. Technological leaders in the design and production of such control systems are: DSC Dredge (USA), VOSTA LMG (Netherlands), Kruse Integration (USA), Dragflow (Italy), SPE Dredging Solutions (Germany). One example is the use of the automated DSC Vision system (developed by DSC Dredge (USA), which integrates high-precision GPS (RTK GPS) and sonar images, which, in combination with software, allow the dredger master to observe the movement of the suction head in real time and control its parameters. VOSTA LMG (Netherlands) offers a wide range of automated mining and dredging management systems. Their solutions include subsea production control and monitoring, slurry pump management, and cloud-based dredger management systems. Dragflow, specializing in the production of pumps and dredgers, also offers developed automation systems that can include GPS positioning of the suction head, measurement of pulp density, remote control of equipment with data visualization, which is especially important for the safety of work in hazardous industrial conditions. Kruse Integration provides comprehensive automation solutions including GPS positioning, submersible pump control systems and dredging quality management software. The MARPO_DGPS system from SPE Dredging Solutions is a specialized solution for monitoring underwater mining and dredging operations. Differential GPS is used here for precise positioning of the suction head and visualization of the extraction process, which contributes to the implementation of the optimal mode of the deposit operation while minimizing raw material losses.

Automation systems based on GPS sensors installed on the pump dredger suction heads are a modern advanced technology, the use of which significantly increases the efficiency and accuracy of mining and dredging operations. Such systems allow for automatic move-

ment and positioning of suction heads. The principle of operation of the system is to install high-precision GPS sensors on the suction head or the boom of the pump dredger, which in some versions can be RTK-GPS (Real-Time Kinematic). Such equipment allows centimeter-level accuracy in determining the position of the suction head in real time.

Industrial application of an automation system based on GPS sensors requires preliminary preparation and programming, during which the operator creates a digital model of the underwater quarry or the area of the bottom to be developed. Such a digital model includes the initial and final boundaries of the site, depth to the top of the reservoir, reservoir thickness, depth to the bottom of the deposit, angle of natural slope, and other parameters that need to be achieved. The system involves transmitting data about the current location of the suction head via GPS sensors to a computer, which is usually installed in the dredger master's cabin. During the operation of the pump dredger, the software compares the current coordinates of the dredger with the programmed digital model of the underwater quarry. When the position deviates from the specified data, the system automatically sends commands to the drives of the working movement winches, lowering and lifting winches, and hydraulic drives of mechanisms in order to adjust the position of the suction head, boom, or other equipment. At the same time, an accurate digital map of the underwater quarry, the position of the suction head and the pump dredger are displayed on the monitor screen in the dredger master's cabin. This allows for real-time monitoring of mining or dredging operations.

The use of automated positioning systems provides significant advantages to mining enterprises. They allow reducing the influence of the human factor, which eliminates operator errors, especially when working in conditions of limited visibility or in difficult meteorological conditions, to increase the efficiency of mining operations, and to achieve high accuracy when developing an underwater quarry. Automatic positioning reduces the time required to reposition the suction head, thereby reducing downtime, increasing equipment utilization, and increasing work productivity, which helps reduce the number of required repeat passes and, thus, reduces fuel and resource consumption, and increases the service life of the equipment. Such systems are particularly useful when performing underwater construction work, namely the construction of hydraulic structures, underwater channels and fairways, and bottom preparation when laying underwater communications. Automation systems collect detailed data on the productivity of the extraction and transportation system, volumes of extracted soil, depth, etc. This allows one to effectively analyze the progress of mining operations and optimize their further planning.

Conclusions. The solid modeling of the extracted space of an underwater quarry performed in the work with the vertices of the mining funnels arranged according to the square-nest and triangular-nest schemes showed the technological feasibility of such methods of mining operations when positioning the suction head in an underwater quarry using modern means.

The theoretical studies conducted allowed us to obtain analytical dependencies for determining the extraction coefficient when using square-nest and triangular-nest schemes in underwater mining of unconsolidated minerals by the funnel method.

The performed calculations of the values of the extraction coefficients indicate the quantitative advantage of the triangular-nest scheme, for which the extraction coefficient will be greater than when using the triangular-nest scheme by 15.5 %.

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Визначення раціональних технологічних умов застосування виконавчих органів землесосних снарядів

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Мета. Розробка теоретичних основ визначення раціональних технологічних умов використання ґрунтозабірних видобувних пристроїв землесосних снарядів, що супроводжують підводний видобуток незв'язних корисних копалин.

Методика. При розрахунках об'єму складних геометричних фігур, що утворюються при перетині конусів різної висоти, вершини яких розташовують в одній площині, застосований стандартний метод інтегрування.

Результати. Обґрунтована доцільність застосування воронкової технології при підводному видобуванні ґрунтів. Виконаний аналіз технологічних схем застосування ґрунтозабірних пристроїв землесосних снарядів, призначених для підводного видобутку незв'язних корисних копалин. У якості обмежуючого критерію вибору схеми розташування видобувних воронок запропоновано використовувати коефіцієнт виймання корисної копалини у безрозмірному виді. Для виконання порівняльного аналізу запропоновані найбільш прийнятні схеми переміщень ґрунтозабірних пристроїв із кінцевим розташуванням центрів видобувних воронок, що

були названі квадратно-гніздовою й трикутно-гніздовою схемами. Приведені графічні зображення виробленого простору підводного кар'єру при його освоєнні воронковим способом із квадратно-гніздовою та трикутно-гніздовою схемами. У результаті аналізу припущено, що при видобуванні незв'язного ґрунту одиночним усмоктувальним патрубком видобувна воронка буде мати форму конуса. Запропоновано визначати об'єм ґрунту, що виймають із такої видобувної воронки, шляхом урахування суми об'ємів таких геометричних фігур: паралелепіпед; складна фігура, отримана шляхом відсікання від усіченого конуса частин об'єму площинами, паралельними його осі; і конус.

Наукова новизна. Уперше запропоновано визначати об'єми ґрунту, витягнутого з підводного вибою землесосного снаряду, методом інтегрування. Отримані теоретичні залежності для визначення коефіцієнтів виймання при застосуванні квадратно-гніздової й трикутно-гніздової схем перестановки виконавчого органу при воронковому способі підводних видобувних робіт.

Практична значимість. Отримані розрахункові значення коефіцієнтів виймання для квадратно-гніздової й трикутно-гніздової схем перестановки виконавчого органу дозволять ефективно використовувати воронковий спосіб видобувних робіт. Визначена технологічна доцільність застосування трикутно-гніздової схеми за критерієм коефіцієнту виймання корисної копалини з підводного вибою.

Ключові слова: ґрунтозабірний пристрій, підводний видобуток, коефіцієнт виймання, технологічні умови

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