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Technological Features of the Interaction between a Flexible Traction Element and Extracting Unit during the Development of Solid Mineral Resources of the Seabed

Igor A. Korolyov[a] and Sergey A. Lavrenko[a]

[a]Department of Mechanical Engineering, Electromechanical Faculty, Saint-Petersburg Mining University, Vasilevsky Island, 21th Line, 2, 199106, Saint-Petersburg, Russia
** Corresponding author*

[a]Scopus ID: 57188845000. ORCHID : 0000-0003-0337-3999

Abstract

This paper carries out the research on the continental mining of solid minerals and on the search of the alternative solutions of raw material's procurement for leading industries. A value of conducting underwater operations for extraction of shelf zone's ferromanganese nodules is specified. Schematic diagram of conducting mining operations is submitted. The construction of a mining complex for mining ferromanganese nodules of the Baltic Sea with the possibility of its separation partial enrichment on the seabed during the process of production is proposed. An analytical model of the system with bottom device and flexible traction element is given. The interaction between a flexible traction element and a bottom-mining unit allows to define the character of relative motion and also to describe the position of the flexible traction element as it moves in the aquatic environment. Specific conditions for steady operation of the complex for its inseparable moving on a seabed-are presented.

Keywords: ferromanganese nodules, solid minerals, subsea extraction, subsea production complex, partial enrichment, diagrams of mining operations, flexible traction element.

INTRODUCTION

The idea to develop ore resources of the ocean arose on the basis of advances in research of the ocean floor, conducted by the leading countries in the second half of the XX century. Ore potential of the ocean is determined by the need in manganese and cobalt as a strategic raw material for many heavy industries. It was found that the world ocean has huge deposits of mineral raw materials in the form of dissolved chemical elements, as well as gold, diamond, tin and other placers and nodules located on the seabed.

All industrial leading countries carry out an active research in the field of technology development for mining offshore zones and the ocean deep-bottom. The main areas of research are studying the geology of the seabed. It identifies promising areas of the development of subsea fields, researches geomorphological features of underwater deposits, as well as the development of advanced technologies and techniques and continued work in the field of special shipbuilding. Most of today's researches are devoted to seabed geology; engineering and technological information and environmental side of the issue [9, 10, 11, 15].

Lack of mainland mineral resources for the needs of modern industry and the steady growth of interest in the development of offshore fields can be explained by several factors, such as:

— a growth in economic efficiency by conducting mining operations on the bottom due to the exclusion of the technological cycle of blasting and auxiliary operations, crushing the ore mined stage. All of the above is going to increase in the long term environmental friendliness and efficiency of the production process;

— a higher concentration of minerals in the offshore compared with continental deposits, which reduces the cost of its production;

— the almost complete absence or insufficient number of solid minerals in mainland of some countries with significant mineral potential offshore.

For example, after the collapse of the USSR, the Russian Federation has become a major importer of manganese concentrate which was required in the steel industry. Shortage and strategic importance of manganese forced to intensify the construction of mining enterprises, additional exploration and the search for new unconventional sources of manganese ore.

It is planned due to national program called «The concept of development of deep-water forces and means of the Russian Federation for the period until 2021» to perform geological and geophysical research and experimental development of the field of ferromanganese nodules on a seabed in the Clarion-Clipperton Zone of the Pacific Ocean dedicated to Russian Federation and also in the Atlantic Ocean which contains resources of deep-polymetallic sulphides to identify large concentrations of non-traditional types of minerals (natural gas hydrates, ores island arcs, etc.) and to produce their preliminary geological assessment [5, 12, 13]. Implementation of the program in terms of the development of seabed resources will prepare inventories of ferromanganese nodules. In this case they will provide exploitation of deposits for five years with an annual production capacity of 3 million tons of the concretion. Exploration for deep sea polymetallic sulphides allows to delineate ore fields of deep sea polymetallic sulfides and to prepare resources of the amount up to 25 million tons of ore.

This underwater mining experience shows significant advantage of this method compared to the methods of conducting mining and mining on the continental part of the land. The development of subsea fields can be carried out in a shorter time with much lower specific investments compared to the land's construction of mining.

Ore formations are complex raw material in which there are manganese, cobalt, nickel and copper, the associated components are - molybdenum, platinum and rare earth elements group. Manganese nodules occurring on the surface of the seabed of the continental shelf of the Russian Federation and, above all, the Baltic Sea have also a practical interest. Feasibility studies have shown a high return on their development.

Shelf (continental shallow) is defined as part of the coastal seabed to a depth of 180-200 meters. The slopes of the seabed within the shelf are small and do not exceed 1.5-2º. The geological structure of the shelf is different from the structure of the continent [3, 4].

There are currently explored and put on the government balance 4 deposits of ferromanganese nodules, which are parts of one of the East Finland ore district. State Reserves Committee of the Russian Federation recognized the opening of a new manganese industrial type deposits. The total reserves of wet ferromanganese nodules on these deposits are over 4.5 million tons [4].

BACKGROUND AND PROBLEM DEFINITION

Subsea production systems must ensure not only the extraction (collection, recovery and primary processing) nodules with depth, but their transportation from the place of production to shore and unloading on land near these enterprises.

The sequence of mining activities for ferromanganese nodules is divided into many independent operations, for every of which it is necessary to develop and establish appropriate technical equipment and systems. For underwater mining the following process steps are distinguished:

— extraction of minerals from the array field;
— transporting ore from the dredge to a floating device or fixed assets (vessel, barges, platform);
— primary conversion of ore (separation, washing, etc.);
— storage and transportation to the shore for the further metallurgical processing.

Mining technology is determined by the fact that the nodules freely lie on the bottom surface, and there is no need for work or pre-crushing (destruction) of the rock mass. Therefore, all options are being developed for producing devices designed to capture nodules from the seabed and their subsequent transport to the surface.

Underwater mining of ferromanganese nodules is complicated by the fact that it is unique, with its own characteristic mode of occurrence. In particular, among the characteristics of future systems for subsea processing equipment nodule deposits should include the following:

— small power productive layers and the uneven distribution of iron-manganese nodules in them;
— aggregate performance of the basic principle of manufacturing operations and a combination of several equipment modules in the same complex technical means for collecting and lifting from the bottom of nodules. Depending on the system design, the order of blocks in the mining deposits may be a variety of combinations of units in the complex of equipment;
— a high level of automation of technological processes should be carried out in the absence of people at all levels of production. The automation system must provide flexible tracking of the changes in geological and mining conditions in deposits, equipment performance and meteorological situation.

Analysis of patents and development experience shows that there are many solutions of complex's creation for production of ferromanganese nodules from the seabed. But so far they are not fully tested and, moreover, economic efficiency, which can be evaluated by comparing competing proposals, has not yet been determined [3, 4].

The most interesting solutions and concepts approved in the last 25 years are:

— hydraulic system using an air-lift pump and recovery options; it includes separate subsystems for the collection of nodule and lifting them to the surface;
— mechanical (cable-ladle or cable-winch) system, which is able to collect and lift nodules;
— system of autonomous remote-controlled shuttle vehicles, to collect and lift nodules in continuous mode.

Bottom technical tools have a number of design features due to the nature of production of manganese ore, geomorphological parameters fields and, more importantly, the depth of location. In addition, the considered mechanisms, in a simplified form, can be used to open the passage of underwater exploration workings and implementation of large-volume sampling of unconsolidated sediments.

PROPOSED TECHNOLOGY AND DESIGN

During the study of modern scientific foundations in the field of the development of equipment for the mining of solid minerals of seabed (SMS) two trends are identified in the mechanization of production:

— the use of facilities such as walking devices with paddle wheels and caterpillar machines and screw, which allow to mine on the shelf at a depth of 60 meters. Tests have shown that during the working there is a strong turbidity of water, accompanied by a deterioration of visibility and complexity of the process control [7, 8, 14];
— the use of dredges and chair-scraping units that allow deep-sea dredging. This process is quite simple and it is an effective method of development of the surface in case of a shallow sea. Underwater deposits which are located in close proximity to the beach or are a continuation of onshore can be successfully developed by cable-scraper devices. A clear disadvantage of the rope-bucket device is poor filling of buckets and poor quality of working off the bottom sections of the field [1, 3, 9].

A construction of a mining complex for mining ferromanganese nodules of the Baltic Sea lying at a depth of 30-50 meters was proposed by collective of Saint-Petersburg Mining University [1, 2, 16]. A feature of this complex is the possibility of ferromanganese nodule's separation and their partial enrichment of the seabed in the process of production.

Complex for the extraction and enrichment of solid minerals in the seabed consists of boat (pos. 1) with a receiving device for solid minerals, dividing on hopper (pos. 2) and the transferring conveyor (pos. 3) for nodule loading on barge (pos. 4); drum hoisting winch (pos. 5) and winch scraper double drum (pos. 6), which are kinematically connected with mining unit (pos. 10) through the tool (pos. 11) and the hook (pos. 12) by the two head (pos. 7) and the tail ropes (pos. 8, 9) (Fig. 1, 2).

Tail ropes (pos. 8, 9) round the diverting pulleys (pos. 13, 14) which are fixed to the anchors (pos. 15, 16). Flexible elements (pos. 17) are associated with buoys on the sea surface (pos. 18). There is a portal (pos. 20) on the hinge (pos. 19), the free end of which is mounted a deflection unit (pos. 21) for the head rope (pos. 7) and diverting pulleys (pos. 22, 23) for a tail rope (pos. 8, 9). Mining device (pos. 10) is configured as a rigid spacer frame (pos. 24) (Fig. 1, 2), which is a straight parallelepiped with a square cross section perpendicular to its longitudinal axis. Frame mining unit is formed by longitudinal profiles (pos. 25), which are performing the role of supporting skis sliding along the bottom and connected into a single structure with square frames (pos. 26, 27) in its grounds and (pos. 28, 29) in the middle. For the convenience of assembly of the device, these frameworks have flanges for connecting the symmetric parts of the frame into a single unit.

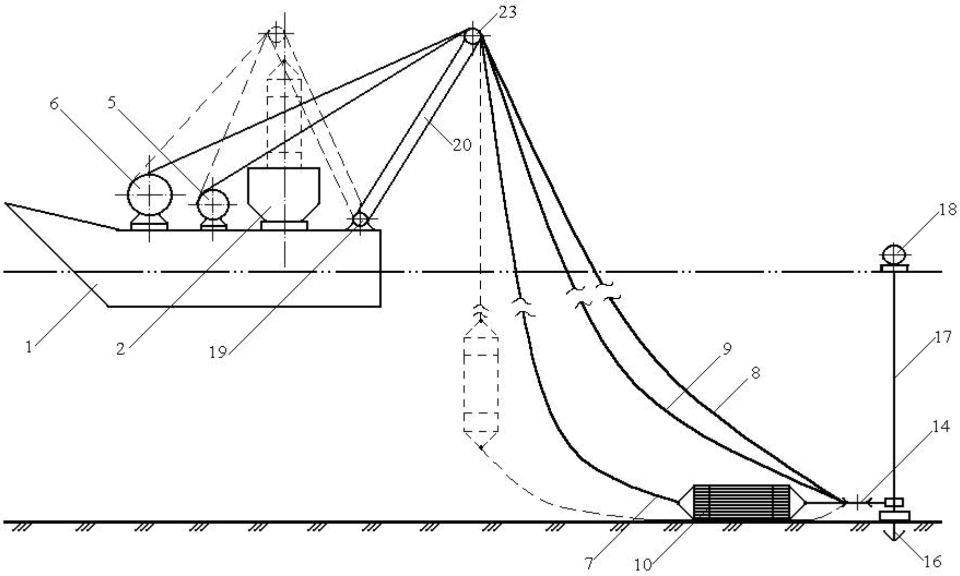

Figure 1. Complex for the extraction of solid mineral resources of the seabed.

The boot guide cones (pos. 30) from the inside are attached to the square frames (pos. 26, 27) and the outside of the loops flat flaps (pos. 31) are installed. They are made in the form of an isosceles trapezoid, connected at their bases with transverse frames (pos. 26, 27), which are controlled by levers (pos. 32). At the closing of the valves quadrangular pyramid with a square base on both sides of the mining unit is formed. Tops of the pyramids are located on the longitudinal axis of symmetry of the device.

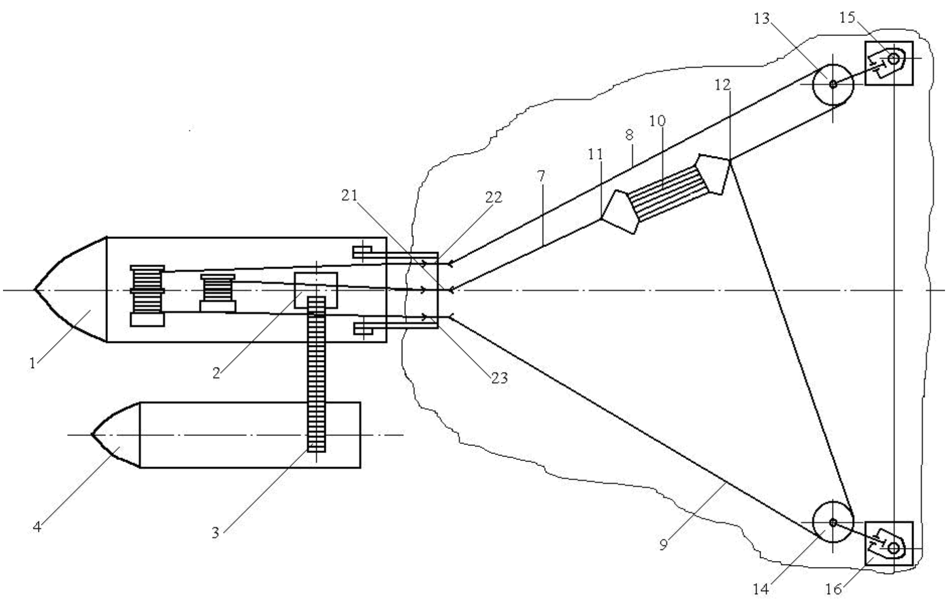

Figure 2. Complex for the extraction of solid mineral resources of the seabed.

Inside the frame at the corners of frames (pos. 26, 27) on brackets (pos. 33) rollers (pos. 34) are mounted, rotating on axes (pos. 35). Inside the frame (pos. 24) tackles (pos. 36) are mounted at the corners of frames with collars fixed and movable blocks enclosed in the guide box.

Washing and concentrating of nodules during the extraction are carried out in a drum-din, which has a cylindrical shape. Such shape is formed by longitudinal rods laid along the generatrix of the cylindrical surface and fixed to the annular shroud to form longitudinal gaps between them.

Production system works the following way: flotation device installs in the area of occurrence of solid minerals, barge moored to it. On the seabed anchors are installed with the diverting pulleys. Location anchors are determined by the position of buoys on the surface of the sea. The device is lowered to the bottom in a vertical position on the rope winch (dashed lines in Fig. 1). When the device touches the bottom of the sea and locates into the unstable equilibrium, with further weakening of the rope it falls down on any of its edges for the production's start.

By the inclusion of a drum scraper winch cooperated with the disabled drum lifting winch mining unit (Fig. 1, 2) moves along the mine site from water craft, cutting off the bottom layer containing nodules, filling drum rumble. Downloaded nodules with host rocks during the rotation of drum rumble are washed and then solid minerals are separated from the waste. Mining is lifted on the boats and unloaded into the hopper (Fig. 1, 2) for the overload on the barge. Presented mining equipment complex can work with successive portions of the bottom moving across the seabed and will enable production area of occurrence.

DESIGN CRITERIA

Operating principle of the production system is based on the functioning of the flexible traction element and the bottom of the mining unit. When the vessel is at a certain speed flexible traction element has its own weight, occupies a certain position in water, creates a tension force for the movement of the bottom of the mining unit. Mining equipment being under the influence of the horizontal component of the thrust moves along the bottom, overcoming the resistance movement in the total system. The stable behavior of the mining device`s motion is provided when the value of the horizontal component of the thrust of the flexible traction element is less than the vertical component of attached conditions. In this case the bottom of the mining unit moves inseparably from the seabed. In the case of the separation production process is disrupted. The flexible traction element sags under gravity, the path slack chain line is described by the equation in accordance with the Bernoulli equation.

Description of the analytical model of the functioning of the flexible traction element with a bottom-mining unit was made with the following assumptions:

— watercraft bottom and a mining unit are located in one plane of motion;

— the chain is inextensible and uniform, deliberately it is not considered the option of elastic deformations in the flexible traction element, the weight is evenly distributed over the entire length of the element;

— the urging force acts to the mining device lying on the bottom.

Case of homogeneous chain slack and derivation of the catenary sag are based on the trajectory, in which one of the points of the chain is pinning points below its ends. In the concept of mining complex slack chain forms a special case in which the point of connection of the flexible traction element-mining unit is the lowest point of the trajectory.

During transportation of the bottom device its mass is not constant over time and increases as the container is filled with sediment scraper, traction element changes its position in the plane of motion. The motion of the scraper is carried out by removing the craft, the length of the traction element is not changed [17]. The flexible traction element has a significant influence on the nature of the motion of the bottom of the device, on its efficiency in terms of performance and ecology.

RATIONALE

A heavy homogeneous string is taken up in this research [9]. This string is suspended at points A and B, which may be at different heights (Fig. 3). The equilibrium of an arbitrary small element of a string which has length Δs is considered. The gravity forces on the current allocation of this element:

$$\Delta P = \rho g \Delta s, \tag{1}$$

which are: ρ − the bulk density of the string material, g − acceleration of gravity, $T(x)$ and $T(x+\Delta x)$ – tensile forces at the points (x) and $(x+\Delta x)$ respectively.

The equilibrium conditions of the selected with the length Δs in the long projections on the axes OX and OY can be described by a system of equations in the form:

$$\begin{cases} -T(x)\cos\alpha(x) + T(x+\Delta x)\cos\alpha(x+\Delta x) = 0 \\ -T(x)\sin\alpha(x) + T(x+\Delta x)\sin\alpha(x+\Delta x) - \Delta P = 0 \end{cases}. \tag{2}$$

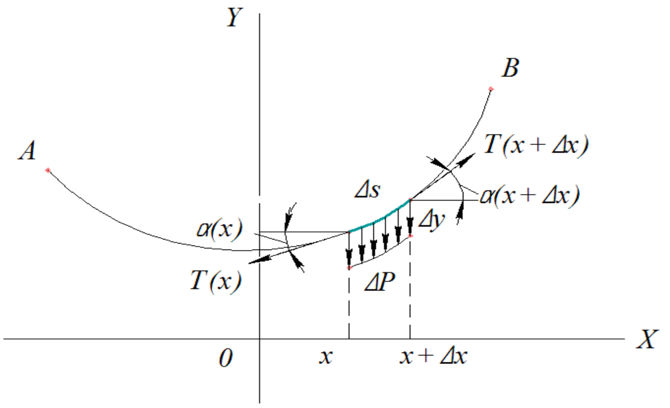

Figure 3. Sag of homogeneous heavy chain suspended at two points arbitrarily.

From the first equation one conclusion can be done:

$$T(x)\cos\alpha(x) = T_0 = const. \tag{3}$$

The second equation can be written in form:

$$d(T(x)\sin\alpha(x)) = dP(x). \tag{4}$$

Because of $T(x) = \dfrac{T_0}{\cos\alpha(x)}$, the output follows:

$$d(T_0 tg\alpha(x)) = dP(x) \text{ or } T_0 d(tg\alpha(x)) = dP(x).$$

According to $tg\alpha(x) = \dfrac{dy}{dx} = y'$, the equation (4) can be written in the following form:

$$T_0 d(y') = dP(x) = \rho g A ds. \quad (5)$$

The length Δs of the elementary section is given by the following form:

$$ds = \sqrt{1+(y')^2}\,dx. \quad (6)$$

As a result, the differential equation of the catenary is given:

$$T_0 \frac{dy'}{dx} = \rho g A\sqrt{1+(y')^2} \text{ or } T_0 y'' = \rho g A\sqrt{1+(y')^2}. \quad (7)$$

The current equation is represented as a first-order differential equation:

$$T_0 z' = \rho g A\sqrt{1+z^2}. \quad (8)$$

The solution of this equation is obtained by separation of variables:

$$T_0 dz = \rho g A\sqrt{1+z^2}\,dx \Rightarrow \frac{dz}{\sqrt{1+z^2}} = \frac{\rho g A}{T_0}dx \Rightarrow \int\frac{dz}{\sqrt{1+z^2}} = \frac{\rho g A}{T_0}\int dx. \quad (9)$$

Then, the equation takes the form:

$$\ln(z+\sqrt{1+z^2}) = \frac{x}{a} + C_1,\ a = \frac{T_0}{\rho g A} \quad (10)$$

The equation takes the form:

$$z+\sqrt{1+z^2} = \exp\left(\frac{x}{a}\right) \Rightarrow z = \frac{\exp\left(\frac{x}{a}\right)-\exp\left(-\frac{x}{a}\right)}{2} = sh\frac{x}{a} \Rightarrow y' = sh\frac{x}{a}. \quad (11)$$

An expression for the shape of a catenary, which is described by the hyperbolic cosine, can be obtained by integration of this equation:

$$y = a\cdot ch\frac{x}{a}. \quad (12)$$

Mathematical modeling task is to find relationships between the main force and kinematic parameters of the system «bottom device - a flexible traction element» (Fig. 4).

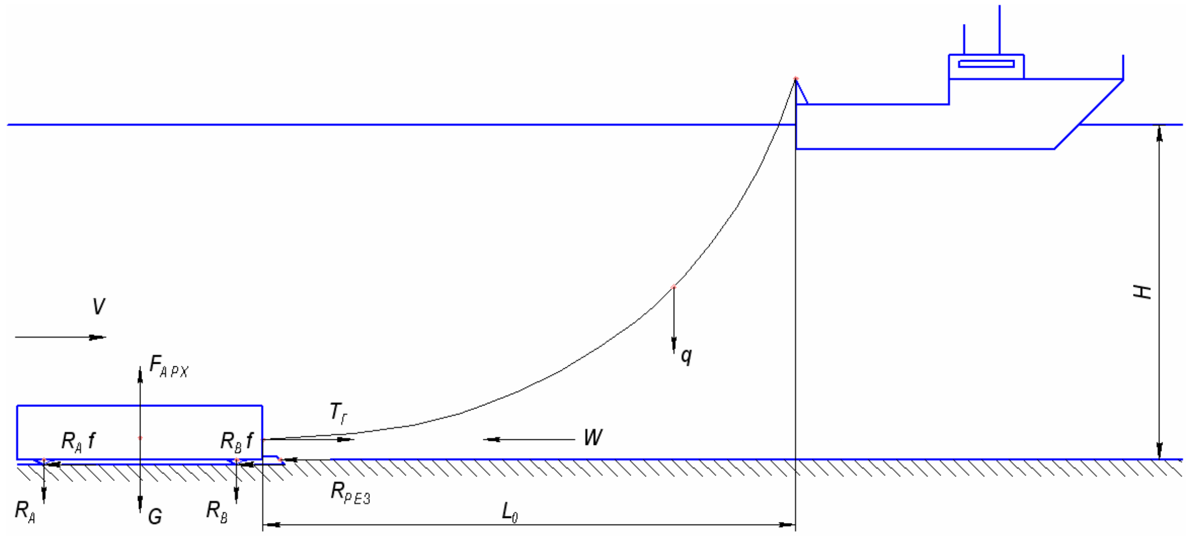

Figure 5. Scheme of the production system.

In the description the following designations are given: H - the depth of immersion (meters); $M_C(t)$ – the mass of the trapped ferromanganese nodules (kilograms); M_A – the mass of the bottom unit (kilograms); ρ_A – device's material density (kilograms per cubic meters); ρ_0 – chain's material density (kilograms per cubic meters); L_0 – removing the bottom of the mining unit from boat (meters); ρ_C – ferromanganese nodule's density (kilograms per cubic meters); ρ_B – water's density (kilograms per cubic meters); f – friction coefficient; k_B – resistance coefficient of water; k_{PK} – resistance coefficient of the cutting edge; S – midship section (square meters); S_{PK} – area of the face of the cutting edge (square meters); R_B – resistance force of water;

$$R_B = g\cdot k_B\cdot S\cdot \upsilon^2; \quad (13)$$

which is: R_{TP} – friction force;

$$R_{TP} = f\cdot N, \quad (14)$$

which is: N – normal reaction of supports; R_{PK} – resistance force of the cutting edge;

$$R_{PK} = k_{PK}\cdot S_{PK}\cdot g. \quad (15)$$

which is: Q_A – the buoyant force acting on the bottom device;

$$Q_A = \rho_B \cdot \frac{M_A}{\rho_A}. \tag{16}$$

which is: Q_C – the buoyant force acting on ferromanganese nodules;

$$Q_C = \rho_B \cdot \frac{M_C}{\rho_C}. \tag{17}$$

The normal reaction of the support can be given by the expression:

$$\begin{aligned} N &= M_A g + M_C g - M_A \frac{\rho_B}{\rho_A} g - M_C \frac{\rho_B}{\rho_C} g - T_Y \\ &= g\left[M_A\left(1-\frac{\rho_B}{\rho_A}\right) + M_C\left(1-\frac{\rho_B}{\rho_C}\right)\right] - T_Y \end{aligned}. \tag{18}$$

To exclude transient driving mode of the bottom device a value of the speed and depth must be selected to comply with the condition:

$$T_Y^1 + Q < Mg \text{ or } tg\alpha_0(t) \geq Arth\left(\frac{H}{1+2(Mg-Q)}\right) + \gamma,$$

$$Q = \rho_{\text{B}}\left(\frac{M_A}{\rho_A} + \frac{M_C}{\rho_C}\right) \tag{19}$$

Calculation of the parameters of the system ends when the device is full bottom ferromanganese nodules (the volume of bottom mining unit and the volume of extracted ferromanganese nodules are equal).

CONCLUSIONS

Based on the concept of conducting mining operations during the production of ferromanganese nodules, the theory of flexible traction element with a bottom-mining unit was created. This theory describes the process of the movement in case of the constant length of the traction element when boats are in motion.

In the description of the process of interaction the possibility of changing the length of the flexible traction element when it is stationary condition is not taken into account. The extraction process should be conducted in a steady operation [17].

According to the results of the theoretical research of the function of the flexible traction element with a bottom-mining unit, basic parameters of algorithmization for further mathematical modeling are received and the analysis of the parameters of the mining complex is done.

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