Determining the Rational Immersion Depth of a Mining Complex Capsule for Underwater Mining of Ferromanganese Nodules

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Abstract

The article discusses the extraction of solid mineral resources (SMR) from the bottom, such as ferromanganese nodules (FMN) and cobalt-manganese crusts (CMC), occurring in both offshore and deep regions of the World Ocean. For separating and lifting the water surface is used mining complex, which includes a hydraulically dragheads and intermediate capsule with atmospheric pressure introduced into the of extraction process in order to increase energy efficiency through the organization of a two-stage hydroascent, the first stage is carried out by external hydrostatic pressure. To determine the optimum depth of immersion of the intermediate capsule composed mathematical model. It is based on the sustainable hydroascent provided at the first stage transport (from the bottom to capsule), and reducing power consumption slurry pump performing the second stage transport (from the capsule to the sea surface). In determining the rational immersion depth were taken into account design features of slurry pipeline, mine geological parameters, the parameters of extracted minerals, performance of dragheads, the slurry flow parameters, such as concentration, consistency, density. Presents an example calculation and determined the optimal capsule insertion depth for offshore geological environments.

Keywords: mining complex; a capsule; a mathematical model; ferromanganese nodules; the optimal immersion depth.

1. Introduction

The world's oceans are concentrated significant reserves of mineral and energy resources in the near future will be of commercial value. It's now known that the content of useful rocks underwater of solid mineral resources...
(SMR) is not inferior to similar resources of the continental reserves. The greatest interest among industrial SMR of bottom are ferromanganese nodules (FMN), cobalt-manganese crusts (CMC) and the depth poly-metal sulfides (DPS). And interest to these minerals will increase as the depletion of onshore. All the more urgent is the issue of the development of systems of underwater mineral deposits and the creation of efficient mining complexes.

For mining both shallow depths and deepwater fields, need reliable and effective means of mechanization, with sufficient performance and reliability. Among the many research facilities for subsea production, a special place is occupied by facilities, which include an intermediate capsule with a supported atmospheric pressure. [1, 2].

2. Actuality

The enormous potential of mineral resources of the ocean is confirmed by various researchers. [3, 4]. Of the existing SMR most common ferromanganese nodules, which may occur as great depths (4000-7000m), and in the coastal areas of the shelf. The largest deposit of nodules - Clarion-Clipperton Zone is located in the Pacific Ocean. Total reserves are estimated at 18 billion tonnes ore [3]. The main parameters of oceanic nodules: the average density of 2.4g/sm$^3$, however, found to 4.4-5.3g/sm$^3$; the size of the nodules 4-10 sm [5], sizes ferromanganese nodules prevail in the range of 5-10 cm [6]. Offshore reserves nodules of interest to Russia, mainly represented in the zone of the Arctic seas of the Russian Federation. The most promising for the development of the Western Arctic seas (White, Barents, Kara) [6], as well as the Baltic Sea and the Gulf of Finland [7].

Other important SMR of bottom include CMC. The main area of occurrence - the Pacific Ocean [8]. However, it can occur in other regions of world ocean [9]. The main parameters of crusts: 800-2500 m water depth [10]; density - 1800-2110kg/m$^3$; thickness of layer formed: 10-15 cm or more. Projected reserves of CMC in the oceans 300-400 million tons ore mass [8]. The third perspective view of the underwater SMR - depth polymetallic sulphides, which is the same as iron-manganese and CMC is a complex raw material [3]. The main area of occurrence - the Pacific Ocean.

To modern mechanisms for the production of underwater mining operations should include suction dredger, airlift and ejecting shells, mechanical dredge, rope-scraper installation and the combination of these mechanisms [5,10-13]. Theoretical development of complexes, which include an intermediate atmospheric pressure capsule (Fig.1), are promising, because such complexes are energy efficient by use as a power source of constant hydrostatic head (H on Fig.1), caused by the magnitude of capsule dive. Indicated feature allows to transport the nodules and other SMR in the form of slurry to the capsule without additional energy input [14].

![Fig. 1. Scheme of the complex with intermediate capsule](image)

Extraction SMR carried out by means a dredge device that may have different constructive versions available. There are developing devices with a drum executive body and driven by a multi-stage axial turbine [15, 16], but
they have a number of disadvantages, so have been proposed dredge device with the vertical orientation of the working body and driven by a positive-displacement hydraulic engine [17-20].

The capsule can in principle be submerged under the level at any value H, but not any value will provide, on the one hand - to create the necessary flow rate for transporting the nodules and other SMR from the bottom to the capsule, on the other - achieving the lowest possible energy consumption achievable by reducing the transportation length from the capsule to ore-collector. Development of a mathematical model that allows us to calculate the only possible rational depth of immersion of the capsule on the condition of achieving the critical velocity in the lower slurry pipeline nodules specified size based on various parameters hydrottransport system is an urgent task, the results of which are shown in this article.

3. Theoretical development of a mathematical model

SMR of extraction process includes the preliminary preparation of bottom mineral deposits for transportation (separation crusts from the bottom) using dredge devices and two-stage hydroascent to the sea surface in the form of slurry. The first stage - from the bottom to the capsule to a height \( H_2 \), carried out by "natural draft" caused by hydrostatic pressure \( H \). The second stage - hydrolift from the capsule to ore collector to a height \( H \), carried out by soil pumps mounted in the capsule.

In determining the rational depth of capsule immersion by condition for effective operation mode of the complex using various parameters: water depth \( H_1 \); the radius of the field processing \( R \); the length of the pipeline \( L_1 \) and \( L_2 \); the pipeline construction related to energy loss \( \Delta h_1 \), \( \Delta h_2 \); the density of the solid and seawater \( \rho_s \) and \( \rho_w \); slurry density \( \rho_{sl} \); specific charge \( q \); the nodules porosity \( m \); volume concentration \( S_v \); flow rate \( v_w \); critical velocity slurry \( v_{cr} \). Note that the mining machine performance has been assumed to be constant – \( G_m = \text{const} \).

Conditions sustainable hydroascent solids of minerals is described by the following condition:

\[
v_{w} \geq 1.1 v_{cr}
\]  

The flow rate at the bottom of the pipe section is determined as a function of the relative depth immersion of capsule \( H = H_1 / H_1 \) taking into account the loss of pressure on the resistance in the pipeline:

\[
v_w = \frac{\sqrt{2gH_1}}{\sqrt{L_1} \cdot \sqrt{\frac{\lambda}{D} + \frac{\xi_b}{\ell}}} \]  

where \( \lambda \) - hydraulic resistance coefficient; \( \xi_b \) - local resistance coefficient of a ball joint; \( D \) – the inner diameter of the pipeline; \( \ell \) - link length the composite pipeline of positive buoyancy; \( L_1 = \sigma H_1 \left( \frac{R}{H_1} \right)^2 \) - the length of the bottom the pipeline, where the safety factor \( \sigma \) into account fluctuations of the wave surface, and varies widely depending on the place of production [21].

The critical flow rate is determined by a formula that takes into account volumetric concentrations [22]:

\[
v_{cr} = 4.9 \sqrt[4]{\frac{gD}{C}} \cdot S_v^{0.36} = K_4 \cdot S_v^{0.36}
\]  

where \( C \) – front resistance coefficient of the nodules [23], \( K_4 = 4.9 \sqrt[4]{\frac{gD}{C}} \) - dimensional coefficient. The volume concentration and the slurry density determined by the formulas:
\[ S_v = \frac{\rho_d - \rho_w}{\rho_s - \rho_w} = K_1 K_2 \sqrt{\frac{2g}{\lambda + \xi b}} + \rho_s K_1 \]  

\[ \rho_d = \frac{q \rho_w + \rho_s (1-m)}{q + (1-m)} = \frac{K_3}{K_1 K_2 \sqrt{H + K_3}} \]  

At the same time the solid volume flow is a function of performance dredge device, and hence the marine mining complex \( Q_s = \frac{G_m}{\rho_s} \). \( K_1 = \sqrt{\frac{2g}{\lambda + \xi b}} \cdot \sigma \left[ 1 + \left( \frac{R}{H_1} \right) \right] \), \( K_2 = \frac{F}{G_w} \), \( K_3 = 1-m \) - dimensional (\( K_1 \) and \( K_2 \)) and dimensionless (\( K_3 \)) coefficients.

Substituting coefficients \( K_1...K_4 \) in formula (2-5) condition (1) with a safety factor \( \alpha = 1,1 \), replacement \( \sqrt{H} = Z \), and the grouping of these constants in the form: \( a = \frac{K_3}{K_1 K_2} \); \( b = \alpha K_3 \), takes the following form:

\[ Z^4 + \alpha Z^3 - b = 0 \]  

A solution of equation (6) are four roots, but the decision of the task - the definition of a rational immersion depth of the capsule is a non-negative real root, which after replacement feedback \( Z^2 = H \) takes the form:

\[ \overline{H} = \frac{a}{4} - \frac{\sqrt{16a^2 \cdot N + 9a^4 - 256 \left[ \frac{b}{3M} + \frac{a^2}{16} - M \right]^2}}{16a^2 - \frac{128b}{3M} + 128M} + \frac{4a^2 - \frac{32b}{3M} + 32M}{32N} \]  

where: \( M = \left( \frac{a^2 b^2}{256} + \frac{b^3}{27} - \frac{a^2 b}{16} \right)^{0.33} \), \( N = \left( \frac{a^2}{4} - \frac{2b}{3M} + 2M \right) \).

The result is a solution of a numerical value, which is a rational immersion depth of the capsule on the condition of sustainable hydroascent the nodules and other SMR specified size.

4. Practical application of the proposed mathematical model.

Been calculated rational depth of immersion of the capsule for the following initial data (depth of mining operations is chosen from the condition that the average depth of the nodules in the offshore areas of the Russian Federation):

\( H = 120 \) m, \( R = 100 \) m, \( D = 0.25 \) m, \( \ell = 5 \) m, \( \lambda = 0.02 \), \( \xi = 1.76 \), \( \rho_s = 2.1 \ t/m^3 \), \( \rho_w = 1.03 \ t/m^3 \), \( m = 0.25 \), \( G_p = 320 t/h = 0.089 t/s \), \( C = 0.45 \), \( d = 50 \ldots 100 \) mm.
The coefficients of the form "K" have the following meanings: K_1=7.62 m/s; K_2=1.16 m/s; K_3=0.75; K_4=9.37 m/s, their combination of form are the dimensionless coefficients of the equation: a=0.0848; b=0.2096. For these initial data, the solution of equation (7) will \( \overline{H} = 0.428 \).

Fig. 2. Example of determining the estimated mode mining complex

In Fig.2 illustrates the behavior of the slurry flow rate curves (2) and the critical speed (3) by changing the relative deepening of the capsule \( \overline{H} = H / H_1 \) in the range from 0 to 1. Condition (1) is performed at point A (the intersection of the curves and flow rate of the critical speed), where \( \overline{H} = 0.428 \), and absolute immersion \( H = 51.4 \) m. In the area to the left of the design mode (1) is not satisfied; in the right area - the condition is met with a greater safety factor \( \alpha > 1.1 \).

The calculation results obtained using the mathematical model can be represented as plots of basic parameters hydrotransport complex systems: a) the dependence of the volumetric concentration \( S_v \), pulp density \( \rho_s \) and the specific volume \( q \) of the relative capsule immersion; b) the dependence of the performance of the complex from the relative capsule dive; c) Feedback relative to the value of immersion capsule diameter slurry pipeline; d) dependence of the radius of the front of mining operations from relative depth of immersion capsule.

5. Conclusions

Among the many industrial stocks SMR greatest interest are the FMN, CMC and DPS mainly occurring at the bottom of the Pacific Ocean.

Mining complexes, which include the intermediate capsule with atmospheric pressure, are promising because they are energy efficient, provided the correct determination of the required depth of the capsule location.

The proposed mathematical model to determine the depth of a rational capsule dive, taking into account the parameters of minerals (\( \rho_s, d \)), parameters of the pulp flow (\( \rho_{ps}, \rho_v, q, S_v \)), slurry pipeline construction (\( D, L, \ell \)) and its characteristics (\( \lambda, \xi \)), geological (\( H_1 \)) and operational (\( R \)) data, as well as with information about the performance of the dredge device (\( G_p \)).

References
