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METHOD FOR DETERMINING SEABED PENETRATION DEPTH IN MARINE SEISMIC EXPLORATION

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Abstract

The paper introduces a straightforward method aimed at determining the depth of penetration into the seabed during marine seismic exploration through bottom sounding. This technique was developed to support the establishment of technical specifications for the components of an underwater robotic complex intended for seismic surveys beneath ice formations. These components include a suite of autonomous underwater vehicles (AUVs) outfitted with either geophones or short streamers equipped with hydrophone sensors, alongside high-precision positioning systems. The complex comprises an underwater docking station responsible for deploying AUVs to the designated work area, managing their operations, and towing low-frequency sound emitters. Moreover, it encompasses coastal infrastructure dedicated to the maintenance of AUVs and the support of the docking station. The developed method considers various factors including the pressure exerted by the sound emitter and the energy dissipation of the probing signal due to wave front expansion, signal transmission into and back from the ground, spatial damping during signal propagation in water and soil, and reflection from oil or gas-containing lenses. Illustrative examples demonstrate the computation of ground penetration depth in shallow and deep waters, contingent upon the pressure exerted by the sound emitter towed at a depth of 100 meters. It also assesses the method’s reliability by comparing the computed outcomes against existing experimental data.

Keywords: marine seismic exploration, bottom sounding, sound emitter

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МЕТОДИКА РАСЧЁТА ГЛУБИНЫ ПРОНИКНОВЕНИЯ В ГРУНТ ПРИ МОРСКОЙ СЕЙСМОРАЗВЕДКЕ

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Аннотация

Приведена упрощённая методика расчёта глубины проникновения в грунт при морской сейсморазведке, разработанная в интересах обоснования технических характеристик элементов подводного робототехнического комплекса, предназначенного для проведения сейсморазведки подо льдом и включающего: комплект автономных необитаемых подводных аппаратов (АНПА), оснащенных геофонами либо короткими сейсмокосами (стримерами) с датчиками-гидрофонами, а также средствами высокоточного позиционирования; подводную док-станцию, обеспечивающую доставку АНПА в район проведения работ, управление ими, а также буксировку низкочастотных гидроакустических излучателей; береговую инфраструктуру для обслуживания АНПА и док-станции.

Ссылка для цитирования: *Машошин А.И.*, *Цветков А.В.* Методика расчета глубины проникновения в грунт при морской сейсморазведке // Фундаментальная и прикладная гидрофизика. 2024. Т. 17, № 1. С. 95–103. doi:10.59887/2073-6673.2024.17(1)-8

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Разработанная методика учитывает давление, создаваемое гидроакустическим излучателем, а также потери энергии зондирующего сигнала вследствие расширения фронта волны, прохождения сигнала в грунт и обратно, пространственного затухания при распространении сигнала в воде и в грунте, отражения от линзы, содержащей нефть либо газ. Приведены примеры расчёта глубины проникновения в грунт для условий мелкого и глубокого морей в зависимости от давления, создаваемого излучателем, буксируемым на глубине 100 м, при использовании приёмной антенны из гидрофонов, сформированной на глубине 100 м, а также приёмной антенны из геофонов, лежащей на дне. Качественно оценена адекватность разработанной методики путём сравнения результатов расчёта с имеющимися экспериментальными данными.

Ключевые слова: морская сейсморазведка, донное зондирование, гидроакустический излучатель

1. Introduction

Apparently, a significant volume of hydrocarbon deposits within the Russian Federation lies within the Arctic region. The exploration and subsequent extraction of these resources are deemed a national strategic priority [1–3]. The primary method for addressing this challenge is through seismic exploration. This method involves emitting powerful low-frequency acoustic signals into the water, which penetrate the seabed and reflect off various subsurface heterogeneities, including cavities containing hydrocarbon deposits. The reflected signals are recorded by arrays of bottom stations equipped with geophones or extended linear multi-element antennas (seismic streamers) towed behind vessels, or by seabed-mounted seismic streamers. Captured signals undergo processing using specialized programs on powerful computers in coastal facilities, enabling the interpretation of the recorded data.

Currently, for conducting seismic exploration, specially equipped hydrophysical vessels are utilized, which are capable of towing an array of acoustic emitters and a seismic streamer, as well as deploying and subsequently retrieving bottom stations on board [1–6].

A downside of using hydrophysical vessels for seismic exploration is their heavy reliance on sea surface conditions. Naturally, such a method is unsuitable in ice-covered regions. Proposals to utilize icebreakers for seismic exploration are economically impractical [7]. Moreover, seismic exploration faces difficulties during stormy weather. In the seas of the Russian Arctic, favorable weather conditions for seismic exploration occur for only 3–4 months per year, making vessel-based seismic exploration economically ineffective.

The solution to the situation is the creation of underwater robotic complexes (URCs) for hydrocarbon exploration on the continental shelf. The idea of creating such URCs is not new [8]. However, due to the exceptional complexity of their development, efforts in this direction worldwide are in the stage of exploratory research and preparatory procedures.

The most well-known foreign research project is the Widely Scalable Mobile Underwater Sonar Technology (WiMUST) project [9, 10]. It is dedicated to the development of technology for creating underwater URCs based on the joint operation of a large number of autonomous unmanned underwater vehicles (AUVs), serving as receivers of reflected seismic signals. The project was carried out from 2015 to 2018 under the auspices of the European Union and was considered a continuation of a series of projects completed over the past 10 years. To implement the project, a consortium consisting of four research organizations and five industrial partners with practical experience in marine seismic exploration was established. The goal of the WiMUST project was the development of methodology, technology, and procedures for creating a robotic system based on autonomous unmanned underwater vehicles (AUVs) for conducting seismic exploration on the continental shelf, aiming to:

– enhance the efficiency of seismic exploration by increasing the informativeness of the obtained data through the formation of an optimal (in terms of the task at hand) adaptive receiving dynamic spatial 3D antenna array, where the sensors are short-aperture seismic streamers towed by AUVs;

– simplify and reduce the cost of the seismic exploration process.

The task of ensuring seismic exploration under ice was not set or addressed in the project.

To achieve the stated goal in the WiMUST project, the following technologies were developed:

– calculation of the optimal spatial 3D antenna array formed by the group of AUVs for receiving signals reflected from subsurface heterogeneities;

– dynamic formation and stabilization of this array;

– cooperative control of the group of AUVs;

– mutual positioning and navigation of the group of AUVs;

– creation of a streamer towed by AUVs, including vector-scalar receivers;
– underwater acoustic communication between AUVs and the control vessel.

The project concluded with demonstration tests of the developed URC and was deemed successful in terms of developing the listed technologies. Decisions were made by relevant European Union bodies to continue the project as industrial development.

Similar research in Russia is conducted by JSC "Central Design Bureau for Marine Engineering "Rubin" [11].

According to the concept, the underwater robotic complex for seismic exploration should include:
– a set of AUVs (estimated to be several hundred to several thousand), equipped with geophones or short seismic streamers (seismic streamers) with hydrophone sensors, as well as high-precision positioning tools;
– an underwater docking station (i. e., a specialized submarine), providing the delivery of AUVs to the work area, their management, and towing of low-frequency hydroacoustic emitters;
– coastal infrastructure for servicing the AUVs and the docking station.

The creation of such a robotic complex is associated with solving a set of complex technical problems and should begin with substantiating the technical characteristics of each element of the robotic complex. At the core of this substantiation lies the determination of the maximum penetration depth into the seabed required by geophysicists in each specific sea area during seismic exploration, which can reach up to 10 kilometers or more.

Advantages of the underwater robotic complex compared to traditional seismic exploration methods include:
– the ability to tow the hydroacoustic emitter away from the sea surface, increasing the energy efficiency of the probing signal emission;
– improved reception quality of echo signals on geophones when using AUVs capable of burying geophones into the seabed, which is challenging with bottom stations [1];
– operational efficiency of seabed seismic exploration, based on the AUVs' capability to rapidly change their position.

However, the application of the underwater robotic complex has its limitations, the main one of which (besides the difficulty of managing a large number of AUVs) is the inability to use airguns, which are the primary type of hydroacoustic emitter in traditional seismic exploration. When using other types of emitters that can be towed behind the underwater carrier (in particular, electrodynamic ones), it will be necessary to settle for a significantly lower (less than 1 MPa) pressure of the emitted probing signal.

The aim of the proposed study was to develop a methodology intended for substantiating the technical characteristics of elements of the robotic complex. The methodology enables the linking of physicochemical parameters of water and sediment, technical characteristics of elements of the robotic complex with the depth of penetration into the sediment during marine seismic exploration.

2. Justification of the Methodology

The geometry of seabed probing concerning the underwater robotic complex is illustrated in Fig. 1.

The probing signal (PS), emitted by the hydroacoustic transmitter (HT) located within the water column at a distance H_{emit} from the seabed, traverses the water layer, penetrates the sediment, reflects off the upper boundary of the lens within the sediment, filled with oil or gas, and returns to the receiver along the same path. The receiver considered is a multi-element antenna, comprising hydrophones, positioned within the water column at a distance H_{rec} from the seabed, or an antenna consisting of geophones, in contact with the sediment.

Since it was not possible to find an example of a quantitative description of the seabed structure in the available literature sufficient for modeling, based on the existing data [4, 6, 12, 14–16], it is assumed that the seabed has a thin-layered structure with layer thickness uniformly distributed in the range of 20–50 m, layer density uniformly distributed in the range of 1240–2210 kg/m^3, sound velocity in each layer uniformly distributed in the range of 1650–1800 m/s, and spatial attenuation coefficient at a frequency of 50 Hz uniformly distributed in the range of 5–10 dB/km. As a result, during propagation in the sediment, the PS loses energy in each layer first due to crossing the layer boundary, and then due to sound attenuation in the layer.

In the calculations, the following factors will not be taken into account:
– the vertical distribution of sound velocity in the water column, as it does not significantly affect the signal intensity during vertical sounding;
– the influence of the sea surface on the PS, as it is assumed that PS emission will occur away from the sea surface in the case of the underwater robotic complex.

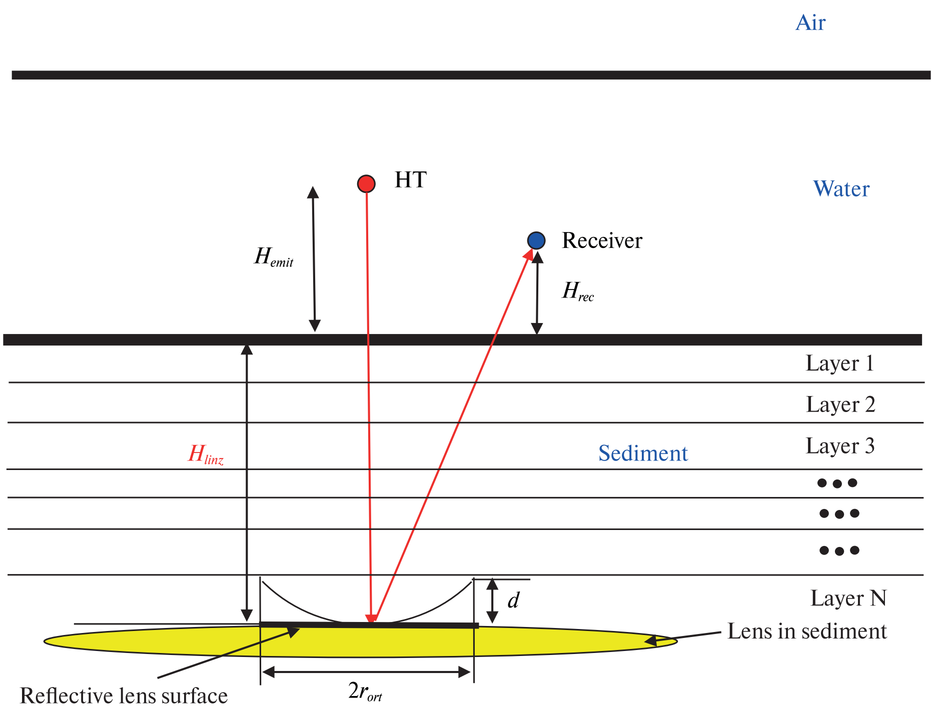

Fig. 1. Geometry of seismic exploration

The depth of penetration into the sediment will be considered as the distance from the seabed to the upper boundary of the lens filled with oil or gas H_{linz}, at which the ratio of echo signal (ES) power to sea noise power at the input of a single antenna receiver equals the specified threshold value Q_{tr}:

$$\frac{P_{es}^2}{P_n^2} = Q_{tr}, \tag{1}$$

where P_{es}^2 is the square of the pressure of the ES at the receiver input in the frequency band Δf; P_n^2 is the square of the pressure of sea noise at the receiver input in the PS band Δf, computed using the equation [12]:

$$P_n^2 = P_{shm}^2 \cdot \Delta f . \tag{2}$$

P_{shm} is the sea noise level at the receiver input in the 1 Hz band at the average PS frequency f_{zs}.

The square of the pressure of the ES in the frequency band Δf at the receiver input is computed using the equation:

$$P_{es}^2 = P_{zs}^2 \cdot L_{sum}, \tag{3}$$

where P_{zs}^2 is the square of the PS pressure in the frequency band Δf, normalized to a distance of 1 m from the HT; L_{sum} is the relative magnitude of the total energy losses of the PS during propagation along the route “HT – lens – receiver”, calculated using the equation:

$$L_{sum} = L_{sph/emit\_linz} \cdot L_{pvo} \cdot L_{z/emit\_bot} \cdot K_{pr/w-g} \cdot L_{z/bot\_linz} \cdot K_{refl/linz} \times \\ \times L_{z/linz\_bot} \cdot L_{sph/linz\_rec} \cdot K_{pr/g-w} \cdot L_{z/bot\_rec}, \tag{4}$$

where:

$L_{sph/emit\_linz}$ is the relative magnitude of the energy losses of the probing signal (PS) due to spherical wavefront expansion during propagation from the HT to the lens filled with oil or gas:

$$L_{sph/emit\_linz} = \left(\frac{1}{H_{emit} + H_{linz}} \right)^2 . \tag{5}$$

L_{pvo} is the relative magnitude of the energy losses of the PS due to refraction of acoustic rays according to Snell’s law at the water-soil interface. Since the sound velocity in the soil c_g is greater than the sound velocity in water c_w, only the energy within the critical angle $\Delta\psi$ passes from water into the soil, calculated by the equation:

$$\Delta\psi = 2 \cdot \arcsin \frac{c_w}{c_g}. \quad (6)$$

The relative magnitude of energy losses due to the refraction of acoustic rays amounts to:

$$L_{pvo} = \left(\frac{\Delta\psi}{\pi} \right)^2. \quad (7)$$

$L_{z/emit\_bot}$ is the magnitude of energy losses of the PS due to spatial signal attenuation during propagation in water from the HT to the seafloor:

$$L_{z/emit\_bot} = 10^{-0,1 \cdot \beta_w \cdot H_{emit}}, \quad (8)$$

where β_w is the spatial attenuation coefficient in water at the mean frequency of the PS;
$K_{pr/w-g}$, $K_{pr/g-w}$ is the relative magnitude of energy losses of the PS when the signal passes from water into the soil and from the soil into the water, respectively, calculated by the equation: [13]:

$$K_{pr/w-g} = K_{pr/g-w} = \frac{4 \cdot Z_w \cdot Z_g}{\left(Z_w + Z_g \right)^2}, \quad (9)$$

where $Z_w = \rho_w \cdot c_w$ is water's acoustic impedance; $Z_g = \rho_g \cdot c_g$ is the acoustic impedance of the upper layer of soil; ρ_w, ρ_g are the density of water and the upper layer of soil, respectively. c_w, c_g are the speed of sound in water and in the upper layer of soil, respectively;
L_{z/bot_linz}, $L_{z/linz\_bot}$ are relative energy loss values of the seismic signal due to signal attenuation during propagation in the soil from the seabed to the lens and back. Taking into account the adopted model of thin-layered soil with random values of layer thickness, their acoustic stiffness, and attenuation coefficient:

$$L_{z/bot\_linz} = L_{z/linz\_bot} = \prod_{i=1}^{N} K_{pr_i} \cdot 10^{-0,1 \cdot \beta_{g_i} \cdot \Delta H_i}, \quad (10)$$

where N is a random number of soil layers from the seabed to the lens, corresponding to a given distribution of layer thickness probabilities; K_{pr_i} is the relative energy loss value of the seismic signal when passing from the $i - 1$ to the i-th soil layer at the mean frequency of the seismic signal:

$$K_{pr_i} = \frac{4 \cdot Z_{i-1} \cdot Z_i}{\left(Z_{i-1} + Z_i \right)^2}, \quad (11)$$

$Z_i = \rho_i \cdot c_i$ is the random acoustic stiffness of the i-th soil layer, distributed within specified limits; β_{g_i} is the random spatial attenuation coefficient of sound in the i-th soil layer at the mean frequency of the seismic signal, distributed within specified limits; ΔH_i is the random thickness of the i-th soil layer, distributed within specified limits;
$K_{relf/linz}$ is the relative energy loss when the seismic signal is reflected from the upper boundary of the lens filled with oil, with area S_{refl}, calculated by the formula:

$$K_{refl/linz} = k_{refl} \cdot S_{refl}, \quad (12)$$

where k_{refl} is the coefficient of signal reflection from a unit area of the interface between the soil and the lens calculated by the formula:

$$k_{refl} = \left(\frac{Z_{linz} - Z_N}{Z_{linz} + Z_N} \right)^2. \quad (13)$$

$Z_{linz} = \rho_{linz} \cdot c_{linz}$, $Z_N = \rho_N \cdot c_N$ are the acoustic stiffness of the lens filled with oil, and the bottom layer of the soil, respectively: S_{refl} is the area of the upper boundary of the lens, from which the signal is reflected over the duration interval of the seismic signal τ (Fig. 1), calculated by the formula:

$$S_{refl} = \pi \cdot \left(\left(H_{emit} + H_{linz} \right) \cdot tg \left[\arccos \frac{H_{emit} + H_{linz}}{H_{emit} + H_{linz} + \frac{c_g \cdot \tau}{2}} \right] \right)^2. \quad (14)$$

$L_{sph/linz\_rec}$ is the relative loss of energy magnitude of the seismic signal due to the spherical expansion of the wavefront during propagation in the ground from the lens to the receiving antenna:

$$L_{sph/linz\_rec} = \left(\frac{1}{H_{linz} + H_{rec}} \right)^2, \qquad (15)$$

L_{z/bot_rec} is the relative magnitude of energy loss of the seismic signal due to signal attenuation during propagation from the seabed to the receiving antenna.

$$L_{z/bot\_rec} = 10^{-0,1 \cdot \beta_g \cdot H_{rec}}. \qquad (16)$$

When receiving the echo signal on geophones in equation (4), the last two factors are absent, and the penultimate one takes the form:

$$L_{sph/linz\_bot} = \left(\frac{1}{H_{linz}} \right)^2. \qquad (17)$$

As a result, the methodology involves solving equation (1) for the depth of the lens H_{linz}, substituting formulas (2) to (17) into it.

3. Examples of Calculation

Let's calculate the penetration depth into the ground for conditions of shallow (depth of 300 m) and deep (depth of 4000 m) seas.

The HT in both cases is towed by a docking station at a depth of 100 m. The reception of the echo signal is carried out by an antenna formed from autonomous unmanned underwater vehicles (AUVs), using hydrophones or geophones as receivers. In the first case, the antenna is formed from AUVs positioned 20 m above the seafloor, while in the second case, the AUVs forming the antenna are located on the seafloor with geophones embedded in the ground.

Calculation will be performed using the following initial data:

– frequency band of the acoustic signal from 10 to 90 Hz with a mean frequency of 50 Hz;

– duration of the probing signal is 12.5 ms;

– the pressure of the probing signal ranges from 0.2 to 2.5 MPa×m;

– the signal-to-noise ratio at the input of one receiver is 6 dB;

– the spatial attenuation coefficient at a frequency of 50 Hz in water is 4×10^{-4} dB/km [12, 14, 15];

– the level of sea noise at the input of the receiver at a frequency of 50 Hz in a 1 Hz band under moderate navigation conditions is 6.3 mPa (50 dB). [12];

– the density of water is 1030 kg/m^3, while that of oil is 835 kg/m^3 [4];

– the speed of sound in water is 1490 m/s, and in the oil-filled lens, it is 1290 m/s. [14].

The estimation of sound propagation in the ground is carried out by modeling random thin layers with the probability distributions of their characteristics mentioned above.

The results of solving equation (1) regarding the depth of the lens H_{linz} by substituting formulas (2)...(17) for shallow (depth 300 m) and deep (depth 4000 m) conditions are presented in Fig. 2.

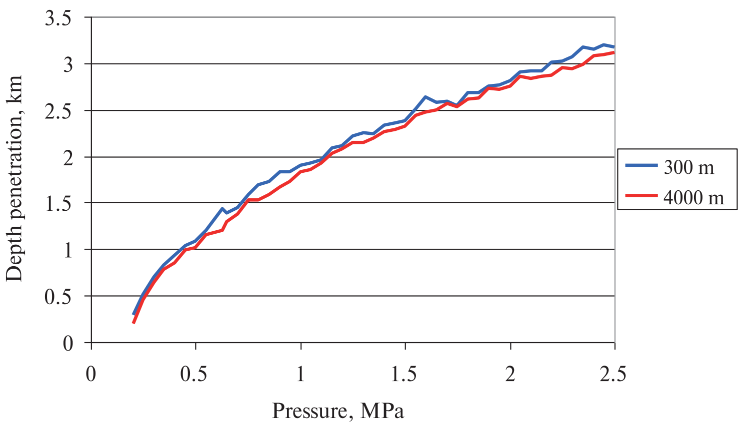

Fig. 2. Dependences for shallow (depth 300 m) and deep (depth 4000 m) seas of penetration depth into the ground as a function of the pressure generated by the hydroacoustic transmitter located at a depth of 100 m when receiving echo signals on a single geophone

From Fig. 2, it can be inferred that:

– at pressures generated by the probing signal ranging from 0.2 to 2.5 MPa×m, the penetration depth into the ground varies from 0.25 to 3.2 km;

– the penetration depths of the probing signal into the ground in shallow and deep seas differ insignificantly for two reasons: firstly, the magnitude of spatial attenuation of low-frequency probing signals in water is negligible, and secondly, energy losses due to the larger wavefront expansion in deep seas are compensated by the expansion of the lens area from which the probing signal is reflected within its duration interval;

– for the same reasons, the penetration depths into the ground are practically indistinguishable when using hydrophones and geophones.

The dependence of the number of layers in the upper soil layer when modeling a thin-layered soil structure with layer thicknesses uniformly distributed in the range of 50–100 m is shown in Fig. 3.

Figure 4 depicts the dependencies of penetration depth into the soil as a function of the probing signal pressure, calculated for different intervals of soil layer thickness distribution.

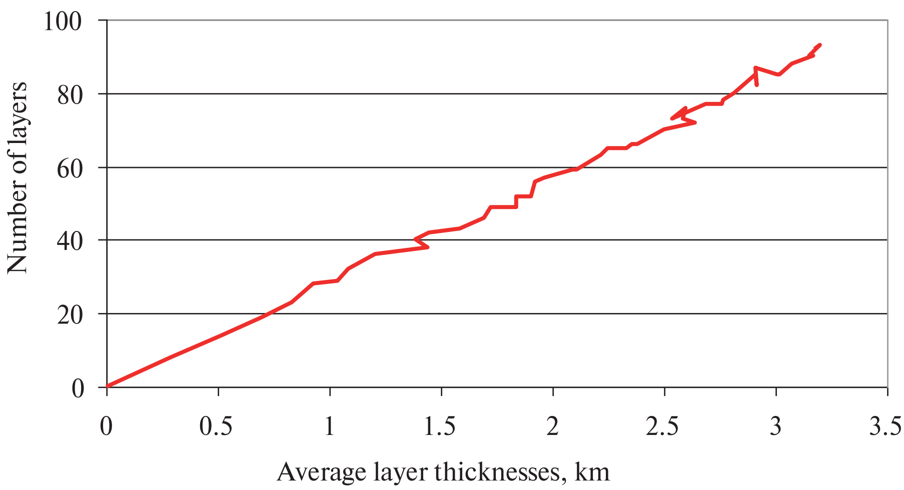

Fig. 3. Dependence of the number of layers in the upper layer of the soil when modeling the thin-layered structure of the soil

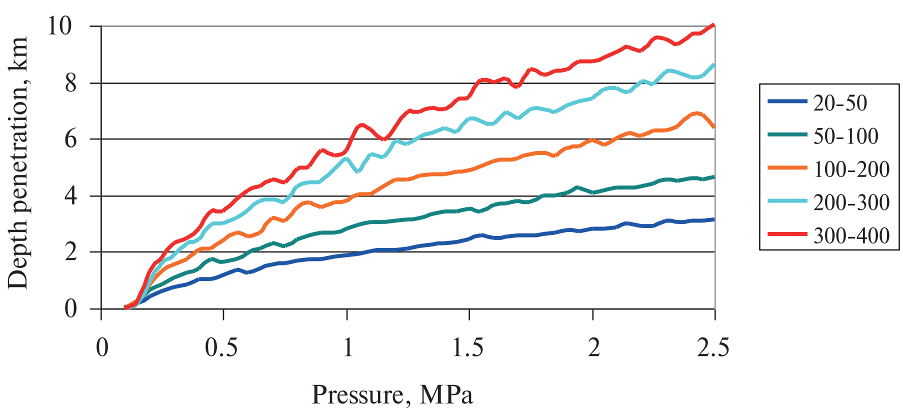

Fig. 4. The dependence of the depth of penetration into the ground as a function of the pressure of the probing signal. The colored lines represent intervals of random thickness for the soil layers

From the analysis of Fig. 4, it can be inferred that as the thickness of the soil layers increases and, consequently, the number of layers decreases, the depth of penetration into the soil increases. This is explained by the fact that with a decrease in the number of soil layers, the energy losses of the probing signal decrease, which occur when crossing the boundaries of each layer.

Obtaining sufficient experimental data from specialized organizations to evaluate the adequacy of the developed methodology proved to be unattainable. In one of such organizations, it was informally reported that using a set of pneumatic guns generating a total pressure of about 2.5 MPa, the depth of penetration into the soil is approximately 3 km. These data align with the calculation results shown in Fig. 2, as well as in Fig. 4 for soil layer thicknesses in the range of 20–50 m. Hence, it can be inferred that the thicknesses of soil layers with different physical and chemical parameters lie precisely within this interval.

4. Conclusions

The development of an underwater URC for seismic exploration beneath the ice is a promising direction in the search for hydrocarbon deposits in the Arctic seas.

Since the creation of such a RC is associated with solving a complex set of technical problems and should begin with justifying the technical characteristics of each RC element, based on the required depth of penetration into the soil in the working area. To assist in conducting such justification, a methodology has been developed in the study that allows linking the physico-chemical parameters of seawater and soil in a specific sea area and the technical characteristics of URC elements with the depth of penetration into the soil during marine seismic exploration.

It is worth noting that, as the methodology hasn't undergone testing through comparison with reliable experimental data, the results obtained using it are indicative.

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