Proceedings of the 26th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 14-18, 2021, Moscow, Russia

Increasing the efficiency of seabed topography hydrographic survey for the Northern Sea Route

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ABSTRACT

A new scheme for the seabed relief survey in the water area of the Northern Sea Route (NSR) is proposed in the paper. It is shown that the need to develop such scheme is due to the vessel movement trajectories deviations from the recommended routes, especially during the winter navigation period in the central and eastern sectors of the Arctic. It is noted that the task of developing a new scheme for surveying the bottom topography arose due to the need for the fastest possible coverage of all promising navigable areas of the NSR with hydrographic surveys. It is shown that the survey of the seabed relief in the promising navigable areas of the NSR, which is implemented in accordance with the traditional schemes, makes it practically impossible to cover these areas in the foreseeable future. The main navigational features of the central and eastern parts of the NSR are presented. The main factors that determine the navigation conditions in the central and eastern parts of the water area of the NSR are highlighted. The areas of shallow water sites in the central and eastern parts of the NSR are estimated. It is emphasized that within these water areas there are sites of significant area that have insufficient hydrographic knowledge. Hydrographic conditions for safe navigation of ships with a given draft are formulated. The time required to survey the bottom topography of the NSR waters, which today has insufficient hydrographic knowledge, is estimated. It is concluded that it is necessary to develop such scheme for performing the survey of the bottom relief, which would significantly increase its productivity. The basic principles on which the proposed scheme is based are given. It is emphasized that in order to ensure safe navigation of a vessel with a given draft, the seabed topography model should provide a given level of surface uncertainty at a given depth, and not to the bottom. It is proposed to survey the bottom relief using multibeam echo sounders along parallel strips that do not have intersections. A comparison of the proposed scheme with the traditional schemes for surveying the bottom relief is given: a single-beam echo sounder and a multi-beam echo sounder with overlapping adjacent survey bands. The conclusion about the advantage of the proposed scheme in terms of increasing labor productivity when taking a survey of the bottom relief and increasing its efficiency is made.

KEY WORDS: Northern Sea Route; seabed topography; hydrographic conditions of safe navigation; hydrographic reserve; uncertainty of the bottom relief model; hydrographic uncertainty.

INTRODUCTION

Navigation routes of vessels in the water area of the Northern Sea Route (NSR) in conditions of year-round navigation will change significantly in recent years. Vessels will be forced to deviate from the recommended routes, especially in winter to overcome ice fields. The actual routes of ships during the winter navigation in the Kara Sea deviate from the recommended routes by tens of miles (Olkhovik, 2019). These deviations are caused by the presence of heavy ice and are manifested throughout the entire Kara Sea. The similar scenarios should also be expected in the central and eastern sectors of the Arctic in winter. At the same time, in contrast to the Kara Sea, the seas of the central and eastern sectors of the Arctic have more complex hydrographic navigation conditions (Afonin, 2020). The main factors that determine the navigation conditions in the central and eastern sectors of the Arctic are shallow depths of vast area (Afonin, 2017) and the presence of areas with insufficient hydrographic knowledge (Reshetnyak, 2006), ice fields (Pastusiak, 2020). In some areas, there are sites where no hydrographic survey has been carried out at all (Afonin, 2018). In absolute terms, the area of shallow water with depths of less than 30 meters in the NSR is estimated at about 1,500 thousand square kilometers. The shallow waters of the Arctic seas do not affect the safety of navigation of ships with a draft of up to 6 meters. However, recently, ships with a draft of up to 15 meters have begun to operate in the NSR (Andreeva, 2018). For such vessels, the shallow water factor significantly limits the area of maneuvering when avoiding ice fields. In absolute total terms, the area of sites with insufficient hydrographic knowledge in the water area of the NSR is estimated at about 970 thousand square kilometers. Historically, the navigation of ships in the water area of the NSR was carried out along the recommended routes. Navigation along the recommended routes is used in areas with insufficient hydrographic knowledge. The schema of recommended routes is shown as lines in Figure 1. The hydrographic knowledge of the recommended routes ensures the safe navigation of vessels with a draft of up to 6-7 meters in the absence of ice in the conditions of summer - autumn navigation (thin lines in Figure 1) and vessels with a draft of 12-14 meters year-round (green lines in Figure 1). The hydrographic knowledge of the areas adjacent to the recommended routes is much lower. Therefore, it is undesirable for vessels to deviate from the recommended routes. This condition is easily met in summer.

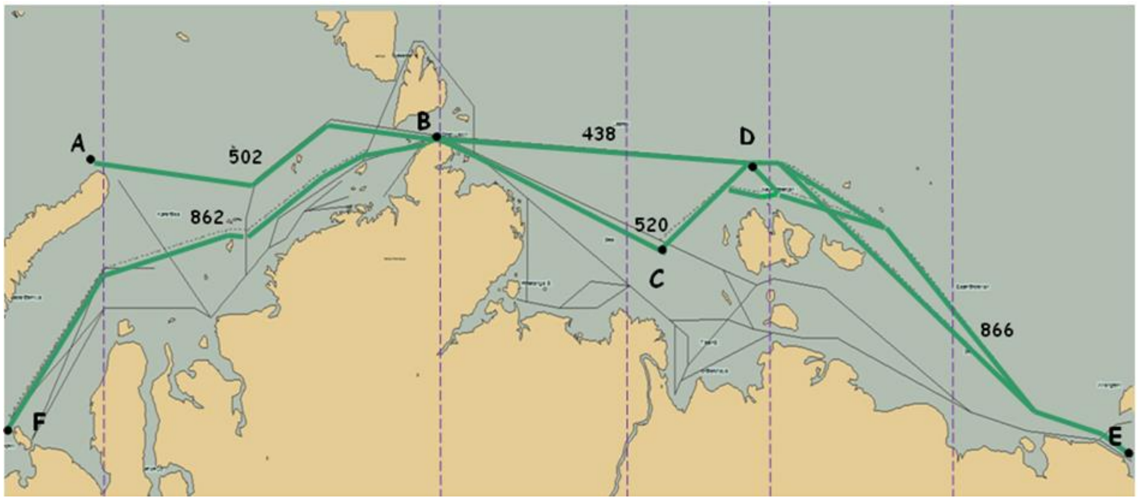

Figure 1. The schema of network routes, recommended in the water area of the NSR

In Figure 1, the letters indicate the entry-exit points and the crossing of the boundaries of the Arctic seas, the numbers indicate the length of the route sections. Insufficient hydrographic knowledge of certain areas of the water area of the NSR also reduces the areas of maneuvering of large-tonnage vessels. Moreover, some poorly explored areas are adjacent to the recommended routes. These circumstances require an early hydrographic survey of both shallow water areas and areas that are poorly studied hydrographically. The sections adjacent to the existing routes for the movement of vessels in the water area of the NSR should be classified as important navigation areas. At the same time, the factor of shallow depths in these areas, compared with the draft of large-tonnage vessels, turns them into areas in which the water supply under the keel is of critical importance. In such areas, in accordance with the existing regulations (Rules PGS-4, 1984), it is necessary to perform a detailed survey of the bottom relief with 100% and even 200% acoustic coverage. According to Afonin (2020) paper the performance of an areal survey of the bottom relief of the water area of 970 thousand square kilometers with an overlap of adjacent survey strips by one vessel will take about 270 years, and with a double overlap - 540 years. This time can be shortened by improving the performance of surveying using multi-beam acoustic systems. For the first time, the task of increasing productivity was posed in Reshetnyak (2011) paper. As its solution, it is proposed to perform areal survey not with overlapping adjacent survey strips, but along non-intersecting strips parallel to each other. The distance between the stripes is selected based on the general understanding of the geomorphological features of the bottom topography. In this case, the bottom topography is presented as a composition of the background component and local bottom uplift. The background component of the relief is determined from the results of depths measurements within the survey strip. The sizes of the local bottom uplift, which may be in the interval between the stripes, are estimated based on general ideas about the bottom topography in the water area of the NSR. Taking a survey of the bottom relief using the proposed method reduces the time for surveying an area of 970 thousand square kilometers up to 190 years, then the morphological and morphometric characteristics of the bottom topography are used to determine the distance between the survey bands. These characteristics are determined from the results of depths measurements obtained within the survey bands. Based on these characteristics, it is proposed to calculate the distance between survey bands. This distance corresponds to a way of estimating the depth between survey strips, which gives the minimum value of the uncertainty in the estimated depth. However, in the general case, we are interested in the maximum possible distance between survey bands, which allows us to determine the guaranteed depth with a given level of security. The purpose of this paper is to develop a method for planning a hydrographic survey by strips, which will ensure the survey is performed with maximum discreteness while maintaining a given level of guaranteed depths in the intervals between survey strips.

METHOD AND MATERIALS

The method of planning hydrographic survey in the water area of the NSR is based on the formalization of the problem using set theory, probability theory, geometric probability theory, mathematical statistics and the theory of random functions. The task of planning a hydrographic survey by strips is to choose the maximum distance between survey strips, at which the obtained values of the guaranteed depths between the strips ensure the safe navigation of vessels with a given draft. This can be written as the following expression:

$$Z_G = Z_O - \Delta_Z \geq d + \Delta_n, \qquad (1)$$

where: Z_G – the value of the guaranteed depth at the point between the strips, Z_O – the depth estimate at the same point between the survey strips, Δ_Z – the uncertainty of the depth estimate Z_0, d – the vessel draft, Δ_n – the navigational water reserve under the keel.

Depending on the method of estimating the depth between the stripes at a point E, a set of values of depth estimates is formed as $\{Z_O\}$, wherein:

$$\{Z_O\} = \{Z_i\ (I_i; L; \{Z, Z^{'}\}\ )\ \}, \qquad (2)$$

where: Z_i – the i value of the depth estimate at a point E, obtained using the i estimation method, $i = [1 \div n]$;

n – the total number of assessment methods;

I_i – depth estimation method;

L - distance between gaps, $L = const$;

$\{Z, Z'\}$ – a set of depths and their derivatives, obtained within the survey bands.

Each value of the depth estimate Z_i is characterized by the uncertainty Δ_i, and the set of values of the depth estimates $\{Z_O\}$ forms a set of their uncertainties, as:

$$\{\Delta_Z\} = \{\Delta_i\,(I_i; p; L; M_i)\}, \quad (3)$$

where Δ_i is the uncertainty due to the use of the i method for assessing the depth, $i = [1 \div n]$;

n is the total number of assessment methods;

I_i - depth estimation method;

p is the confidence level of uncertainty Δ_i, $p = const$;

L - distance between gaps, $L = const$;

M_i- a subset of statistical, probabilistic, morphological and morphometric characteristics of the bottom topography, which are used to estimate depths by the i method. Sets (2) and (3), in accordance with expression (1), form sets of values of guaranteed depths at a given point in the interval between survey strips. The elements of this set are the differences $(Z_i - \Delta_i)$, corresponding to the i method for estimating the depth at a given point and the i value of its uncertainty:

$$\{Z_G\} = \{(Z_i - \Delta_i)_i\}, \quad (4)$$

The measured depths, their derivatives, statistical, probabilistic, morphological and morphometric characteristics of the bottom topography within the surveyed strips are the initial data for assessing the depth values in the interval between survey strips at a given point Z_i. The same data and the chosen method for assessing the depths determine the values of the uncertainties in the obtained depth estimates Δ_i.

RESULTS

As a result, it is proposed to determine the value of the inter-haul distance as a solution of the following equation for L:

$$max\{Z_G\} = \{(Z_i - \Delta_i)_i\}=\left\{Z_i\left(I_i; L; \{Z, Z'\}\right) - \Delta_i\,(I_i; p; L; M_i)\right\} = d + \Delta_n, \quad (5)$$

where $max\{Z_G\}$ is the maximum element of the set (4);

d is the draft of the vessel;

$\Delta_н$ is the minimum water reserve under the ships keel.

The maximum element of the set (4) determines the optimal way of assessing the depth value and its uncertainty based on the combination of the criteria for the maximum value of Z_i and the minimum value of Δ_i.
The proposed scheme for carrying out hydrographic work in conditions of insufficient information about the seabed topography is shown in Figure 2.

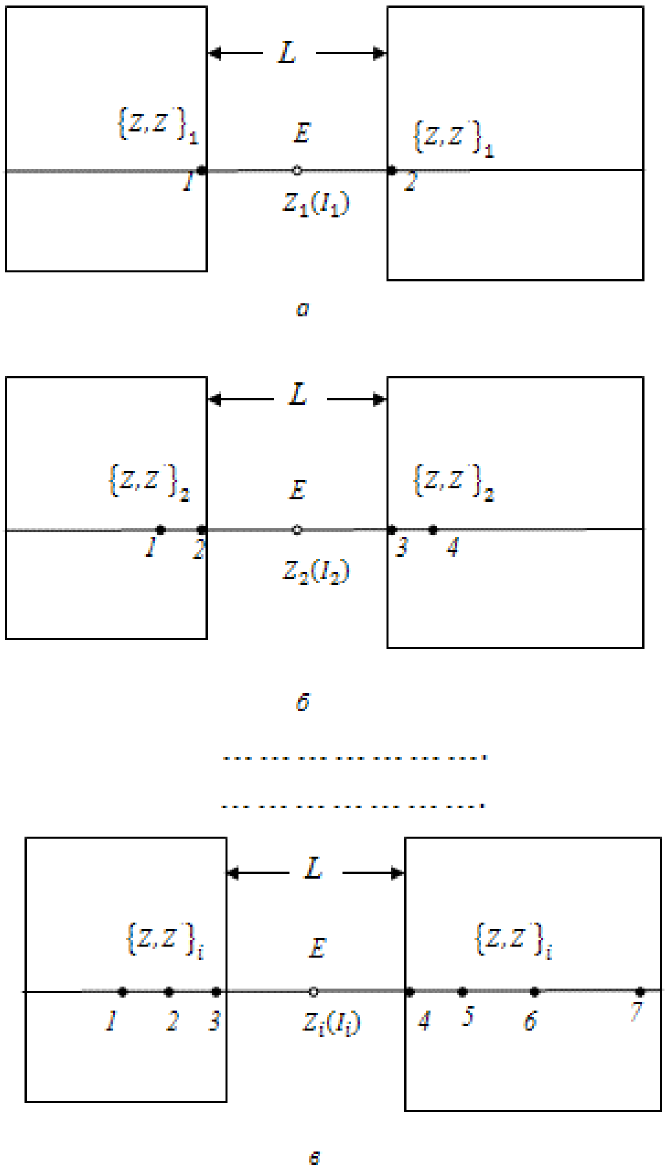

Figure 2. Developed scheme for calculating multiple depth estimates $\{Z_O\}$ at assessment point E

Depth estimation is performed at point E. Figure 2a shows two adjacent survey swaths. The distance between them is indicated by the letter L. The estimation of the depth between the stripes at point E is made using the estimation method I_1. The initial data for determining the depth estimate was the set $\{Z,Z'\}_1$. In this case, this set includes the values of the depths measured at points 1 and 2. The value of the depth estimate at point E turned out to be equal to $Z_1(I_1)$. The resulting estimate of the depth $Z_1(I_1)$ at point E became the first element of the set of estimates $\{Z_O\}$ (2). Figure 2b shows the same survey bands. The estimation of the depth between the bands at the same point E is made using the estimation method I_2. The initial data for determining the depth estimate was the set $\{Z,Z'\}_2$. In this case, this set includes the values of the depths measured at points 1,2,3,4. The value of the depth estimate at point E turned out to be equal to $Z_2(I_2)$. The obtained estimate of the depth $Z_2(I_2)$ at point E became the second element of the set of estimates $\{Z_O\}$ (2). Figure 2в shows an intermediate option for assessing i. The estimation of the depth between the bands at point E is done using the estimation method I_i. The initial data for determining the depth estimate was the set $\{Z, Z'\}_i$. In this case, this set includes the values of the depths measured at points 1,2,3,4,5,6,7. The value of the depth estimate at point E turned out to be equal to $Z_i(I_i)$. The resulting estimate of the depth $Z_i(I_i)$ at the point E became the i - th element of the set of estimates $\{Z_O\}$ (2). Thus, at point E, a set of depth estimates $\{Z_O\}$ is formed (2).

DISCUSSION

The proposed method for performing hydrographic survey of the Arctic seas and determining its maximum discreteness is based on the transfer of estimates of the relief static characteristics obtained within the surveyed bands beyond their limits. The application of this method will require a large amount of computer calculations to obtain in real time the statistical and probabilistic characteristics of the bottom topography within the surveyed strips, which will necessitate the development of special software, which is being developed at the Arctic Faculty of the Admiral Makarov State University of Maritime and Inland Shipping. A further direction of research is to develop the specific methods for determining the details of the survey, providing a given level of uncertainty of the bottom topography model at a given depth and to justify the choice of the direction of the main coverage area and control tacks. Florinsky and Filippov (2019, 2021) present the results of the development of a digital model of the seabed with a resolution of 5 and 10 kilometers based on data extracted from the International Bathymetric Map of the Arctic Ocean, which was smoothed taking into account morphology and other factors affecting the topography of the seabed. This approach is undoubtedly useful for imaging and large-scale research, but in the area of shallow depths it is insufficient to ensure the safety of navigation. Morlighem et al. (2017) in their work have already presented a 150-meters horizontal topographic (bathymetric) map of the seabed relief for Greenland with a horizontal resolution, which is built taking into account smooth transitions at the interface between ice and sea, which provides additional information for the navigation safety of ships on the NSR, taking into account ice massifs.

CONCLUSIONS

The proposed method for performing hydrographic surveying of the bottom topography makes it possible to significantly increase the productivity of hydrographic work in the water area of the Northern Sea Route and to reduce the time required to cover little-surveyed areas of the NSR to 30 - 40 years by one hydrographic vessel. Ten vessels will cope with this task in 3÷4 navigation. The proposed scheme can be used as the main one for the survey of shallow water areas of the NSR, which are large in area and have insufficient hydrographic knowledge. Determination of the distance between steps according to the formula (5) will allow formalizing the process of controlling the quality of the survey, both at the planning stage and at the stage of its implementation with using a multibeam echo sounder. The input data that provide the quality management process are the depth and maximum draft of the vessel, which is supposed to navigate in a given area, and the statistical and probabilistic characteristics of the relief. The output data are the operatively calculated values of the inter-haul distances. At the planning stage, the estimate of the inter-haul distance is carried out on the basis of the available materials of the hydrographic knowledge of the area. At the stage of the survey, the distance between gaps can be promptly corrected depending on the results of the measurements performed. Thus, the foundations for creating dynamic measuring networks, which, on the one hand, have the maximum permissible measurement discreteness, and on the other hand, provide safe navigation of ships with a given probability are being formed. In addition, the calculated data allow us to estimate the possible minimum draft of vessels in order to ensuring the safety of their free passage and navigation and identifying the most optimal routes, which is an urgent practical task when developing new routes on the Northern Sea Route.

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