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Compactibility of the stamukha sail as a granular medium

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ABSTRACT

A stamukha is a special case of granular medium with a wide range of fractions. It represents a chaotic piling-up of ice blocks occurring in the sail under the action of gravity; and in the keel, the Archimedes force. An important characteristic of the internal structure of stamukhas is their porosity. The purpose of the present work was to reveal new porosity distribution regularities in the stamukha sail with depth. The stamukha porosity is identified by means of processing the thermodrilling records. In this paper, porosity is interpreted as a step function equal to zero if there is an ice at the spatial point, and one if there is no ice. The Skachkov's model of compaction of the granular medium under the influence of gravity is applied. Zero depth corresponds to the upper surface of the sail, so each individual porosity distribution of the sail at the drilling point must be shifted up until the maximum sail height is reached in the region under consideration. After alignment, the step curves are averaged. The first-year stamukhas were considered and divided into groups according to the geographical regions. In each group, an averaged distribution of sail porosity with depth was obtained. According to the distributions, average porosity decreases exponentially. Each distribution was approximated according to the model, taking into account the average ice density in the region. One more parameter characterizing the sail porosity distribution is a compactibility. For each distribution, the values of compactibility and porosity at zero depth, i.e. at the upper edge of the sail, were obtained; the second one makes mathematical sense only. The steepness of the exponent approximating the average porosity curve depends on the compactibility. The obtained numerical estimates of compactibility are analyzed.

KEY WORDS: Compactibility; Stamukha; Ice ridge; Sail; Porosity.

INTRODUCTION

Comprehensive studies of large hummocked sea ice features, such as pressure ridges and stamukhas, including analysis of their internal structure and approaches for evaluation of patterns in morphometric characteristics, are becoming increasingly topical in the context of economic activities in the Arctic. Being impressively large ice features and constantly afloat, ridges pose a navigational threat to offshore engineering infrastructure and marine operations. Let alone the time of the season when stamukhas, having a larger mass, are moved off the ground surface and set afloat and become none the less hazardous. When determining admissible loading on the offshore structures to design appropriate protection, one requires knowledge of geometry of such ice formations, porosity (relative content of voids in ice ridges), thickness of the consolidated layer (CL), etc. They are generally inferred from a comprehensive analysis of different factors using tools, methodologies and techniques that are frequently based on different physical principles. Numerous studies of physical, mechanical, and other properties of ice have been conducted over the past three decades both in Russia and abroad (Astafyev, et al., 1997; Surkov, et al., 2002; Zubakin, 2006; Gorbunov, et al., 2010; Bukharitsin, 2019). The Arctic shelf development requires basic scientific knowledge about the ice cover structure in the region, thus accentuating the relevance of such research.

Stamukha is a hummocked ice feature formed from accumulation of broken ice blocks while the ridge keel was in contact with sea bed and is partially frozen together, which is run aground and is distinguished by a low keel/sail ratio, steep sail slopes and complex exterior and underwater configuration. Porosity of stamukhas is one of the important parameters of their structure. Two levels of porosity can be identified: macroporosity and total porosity (Høyland, 2002). The macroporosity is the ratio of the volume of any non-sea ice material in the selected area of the stamukha to the total volume of this area. The voids can be filled with snow, water, shuga or air. Total porosity can be defined by including the porosity of the level ice from which the stamukha is formed. In other words, micropores in ice blocks are also taken into account. The thermodrilling data processing gives such characteristics as the above-water and under-water parts of the ice cover, the boundaries of the CL of the stamukha, the boundaries of the voids and the boundaries of ice layers of various porosities. In this paper, porosity Θ is interpreted as a step function:

$\Theta(x, y, z) = 0$, if there is an ice at the point (x, y, z), and

$\Theta(x, y, z) = 1$, if there is no ice at the point (x, y, z). (1)

Linear porosity is derived by averaging of Θ vertically at a given depth range, and bulk porosity is derived by averaging at a given volume. Depth-wise distribution of porosity at each drilling point (x_i, y_i) is realised as the staircase curve $\Theta(x_i, y_i, z)$, where zero corresponds to ice, and one corresponds to voids. Bubbles with air and cells with brine are not taken into account.

Determination of volumetric porosity of the stamukha is impossible due to its complex internal structure. It can only be estimated using the obtained distributions of linear porosity at different points. The volumetric porosity is equal to the mean value of an infinite number of linear (in this case, vertical) porosities. Ice explorers commonly regard the averaged values of linear porosity as volumetric porosity of the ice formation (Høyland, 2002).

It was noted in (Grishchenko, 1988) that for fresh (i.e. at the stage before the CL formation) Arctic ice ridges, the ice fraction (opposite value of porosity) in the sea level area was by 0.1-0.2 higher than in the ridge top and keel parts. The author gave a graph of the ice fraction depending on the shape of the elements of the granular medium. He connected this peculiarity of ice fraction distribution by vertical with the action of gravity and surfacing forces, contributing to concentration and subsequent compacting of small ice fragments in the sea level area. Surkov (2001a) noted that the keel porosity in first-year ice ridges below the CL increases with depth. The length of ice areas along the borehole in the unconsolidated part of the keel does not change, and the length of cavities increases with depth (Surkov, 2001b). Norwegian scientists investigated ice ridge structure in the Barents Sea in 2002 (Bonnemaire, et al., 2003). According to the authors' data, porosity in the ridge changed with depth, below the CL increasing from 0.2 to 0.5, and the largest cavities in vertical dimension were concentrated at the bottom of the keel. The authors note that the closer to the sea level, the more compact the blocks in the ice ridge are, and it is presumed that this is also associated with positive buoyancy of ice.

Andreev (2013), summarizing the results of studying ice ridge formations in 2003-2007 in the Barents Sea, notes that in fresh ice ridges, in which the CL was either absent, or had just started to form, porosity in the upper part of the ice ridge keel is less than that in the lower part. The author also associates this phenomenon with the action of Archimedes forces and even suggests a quadratic dependence approximating the porosity distribution in the ice ridge keel with depth. According to this dependence, porosity varied from 0.1 at zero depth to 0.4 at the maximum keel, however, unfortunately, the author did not present any physical justification for the quadratic approximation proposed by him.

Ice blocks are in the sail under the action of gravity. When calculating ice loads on hydraulic structures, ice features are often considered as a special case of a granular medium with a wide range of fractions, for example (Alekseev, et al., 2001; Bolgov, et al., 2007). The paper by Skachkov (2011) considers the granular medium compaction under the action of gravity, and the proposed models are compared with experimental data on rocks and snow. According to the reasoning given in the paper, the porosity of the granular medium decreases with depth due to increasing pressure.

The purpose of this work is to reveal the porosity distribution pattern in the sail of stamukhas. To achieve this goal, it was necessary to accomplish the following tasks:

- to obtain the averaged depth-wise distributions of porosity in the sails of stamukhas for different regions;
- to assess the characteristic parameters of the porosity curves of the unconsolidated sail as a granular medium;
- to identify the association of these parameters with other attributes of the structure of stamukhas.

The present work is a logical continuation of the research started in (Kharitonov, 2021).

METHOD

The data selected as the basis of this research were obtained in 2007-2017 in the Baydaratskaya Bay, Caspian Sea and Laptev Sea. Investigation of the structure of stamukhas was carried out by means of thermal drilling unit of AARI comprising thermal drill and equipment for penetration rate recording on a computer. The drilling rate depends on the power supply, ice porosity and ice temperature. The location of voids, hard and porous ice along the drilling hole is identified by the thermodrill penetration rate. The obligatory condition for this identification to be valid is drilling at constant thermal capacity or recording the changes of capacity during drilling. Within the segments of porous ice and, especially, the voids filled by snow, sea water, shuga or air, the penetration rate of thermodrill sharply increases. In addition, the distance from snow (ice) surface to the sea level is measured. The thermodrilling data processing gives such characteristics as the above-water and under-water parts of the ice cover, the boundaries of the CL of the stamukha, the boundaries of the voids and the boundaries of ice layers of various porosities.

MODEL

Skachkov (2011) offers a formula for the porosity Θ of the granular medium:

$$\Theta = \frac{1}{1 + \left(\frac{1}{\Theta_0} - 1\right) e^{k\rho_i g z}}, \qquad (2)$$

where Θ is porosity, Θ_0 is porosity at zero depth, i.e., in our case, at the higher edge of the sail; κ, coefficient characterizing the compactibility of the granular medium; ρ_s, matrix density, i.e., ice density; g, gravitational constant; z, depth. Zheltov (1998) suggests such a dependence of porosity on stress σ:

$$\Theta = \Theta_0 e^{-\beta_c(\sigma - \sigma_0)},$$

where β_c is compressibility, σ_0, initial average normal stress. Importantly, both authors suggest an exponential relationship.

Let us apply Skachkov's model to the stamukha as a granular medium and confine ourselves to the consideration of the sail. In this case, the area in which there are no compressive stresses and which is characterized by initial porosity will be the area adjoining the upper surface of the sail. With increasing depth, the porosity will decrease under the pressure of the accumulated ice blocks. The penetration rate record at every point of drilling can be realised as the staircase curve, where zero corresponds to ice, and one corresponds to voids.

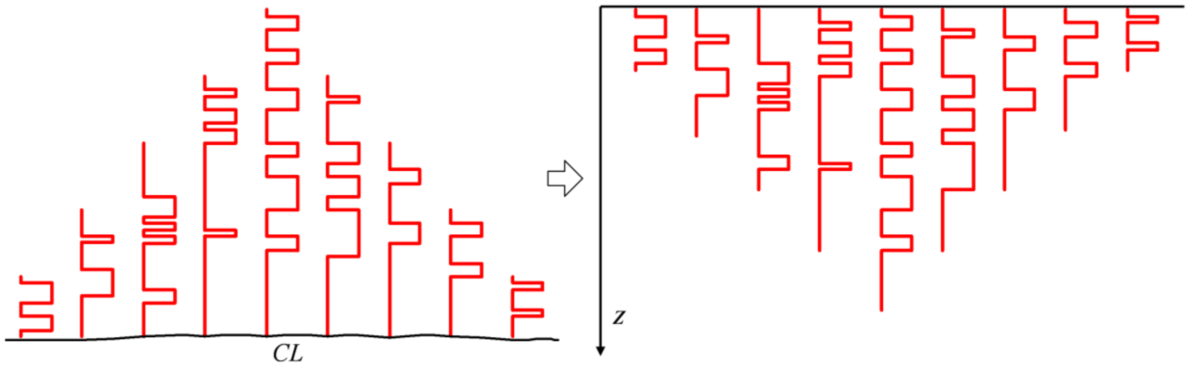

Figure 1. Schematic image of the stamukha sail (left) and scheme for shifting individual porosity distributions of the unconsolidated part of the sail to the maximum sail height (right). CL – consolidated layer. The red color indicates the porosity distributions of the unconsolidated part of the sail in individual boreholes.

For establishing the distribution parameters of porosity as a granular medium based on Skachkov's model, let us average the individual distributions of the sail porosity at all drilling points for each region. The averaging procedure will be as follows. Since in expression (2) the zero depth corresponds to the upper surface of the sail, and each individual distribution of porosity occurs in its depth interval, for averaging they should be shifted upwards until the maximum sail elevation is reached. This procedure is schematically shown in Fig. 1. The red color indicates the porosity distributions of the unconsolidated part of the sail in individual boreholes. Height of the staircase curve corresponds to borehole length in the sail. After adjusting all individual distributions by the height of the maximum sail elevation, all heights from the maximum sail height to the sea level are considered successively, and the steplike curves are averaged for the boreholes that are elevated above the considered depth. The depth is counted downwards starting from the height of the maximum sail. Only the boreholes in which the sail exceeds 1 m are included into averaging.

RESULTS

As a result of this procedure, depth-wise porosity distributions in the unconsolidated part of the stamukha sail as a granular medium were obtained for the study areas.

Change in porosity of the granular medium (the sail) with depth is well illustrated by the example in Fig. 2 showing the results of averaging over all drilling points on stamukhas with a discreteness of 1 cm, as well as the number of the averaged porosity values at each depth. The data were obtained while studying stamukhas in the Caspian Sea in 2002-2008. There are no compressive stresses on the upper surface of the sail, and as the depth increases and approaches the sea level, the sail porosity will decrease. Scatter of the mean porosity values with depth grows due to a decreasing amount of the averaged data, which is shown by the curve of the number of values.

Since the stepped distribution of porosity at each drilling point in the upper boundary part of the sail always starts with a zero corresponding to ice, the average porosity here will be zero. With depth, more and more often voids will occur in individual boreholes, and the average porosity will increase. The nature of the change in the mean porosity in this area will be determined by the distribution of the vertical size of ice blocks on the upper boundary of the sail. An increasing scatter of the mean porosity values with depth is due to a decreasing amount of the averaged data.

Trends in porosity changes with depth are inherent to distributions in all the study areas. Fig. 2 also shows an approximation of the porosity distribution by Skachkov's formula (2). According to Skachkov (2011), compactibility κ does not depend on stresses. Then, the compactibility of ice blocks in the keel of the drifting ice ridges will also be determined by the compression of the block heaps. In this case, pressure will be created by the upward Archimedes force. Instead of gravity acceleration g, the following value should be used

$$g_A = g\,\frac{\rho_w - \rho_i}{\rho_i} \approx 1.2 - 1.4\,, \qquad (3)$$

where ρ_w and ρ_i are densities of sea water and ice. Considering ice density in the sail of stamukhas and in the keel of the drifting ice ridges as being approximately the same, the exponential factor for the keel will be g/g_A times less, i.e., the exponent for the keel will be more flattened. This is shown schematically in Fig. 3. The porosity at zero depth is chosen to be the same, because from the viewpoint of the granular medium, there are no grounds for other assumptions. The more so, Θ_0 makes mathematical sense only.

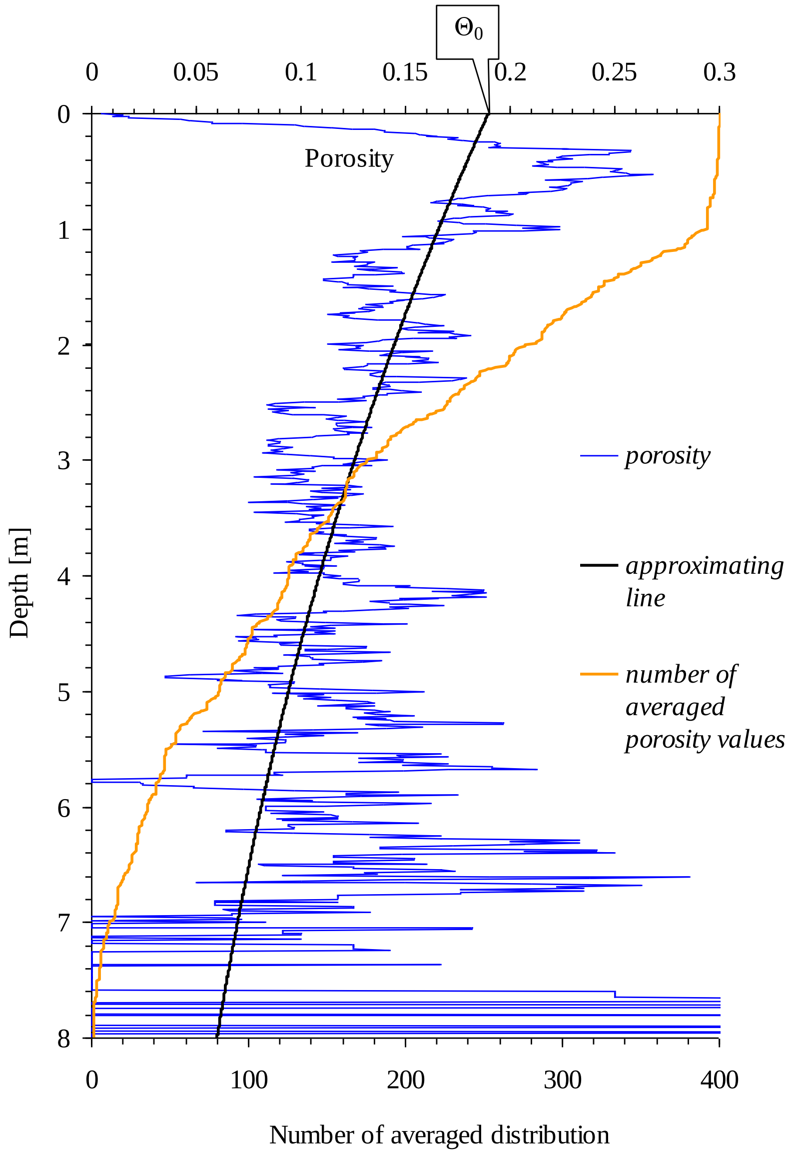

Figure 2. Depth-wise distribution of the averaged porosity of stamukha sail investigated in 2002–2006 in the Caspian Sea. 1 – porosity, 2 – approximating line by formula (2), 3 —the number of averaged porosity values on each depth. Θ_0 – porosity at zero.

However, the chosen hypothesis is not supported by experimental data. Fig. 4 shows the porosity curves of the sail of stamukhas and of the keel of drifting ice ridges as a granular medium as well as their approximation by formula (2). Averaging of the steplike curves in the keel of the drifting ice ridges was also carried out following the above-described methodology with the curves shifted, but downwards to the depth of the maximum keel draft. More detailed information is contained in the paper by Kharitonov (2021). For a better perception, it was decided to smooth the porosity distribution pattern by a moving average with a two-metre smoothing width. The data were obtained during ice engineering survey in the Baydaratskaya Bay in 2007–2010.

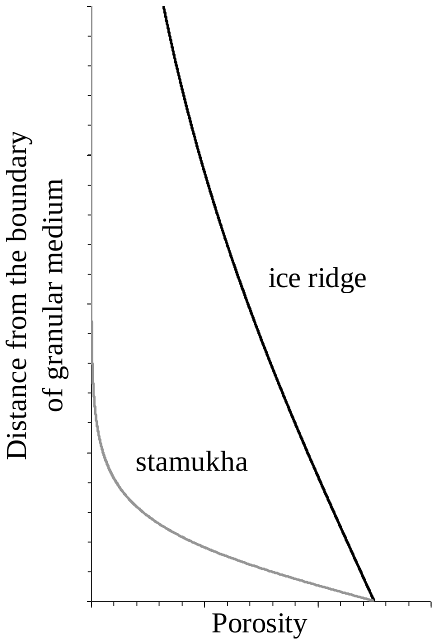

Figure 3. The change in porosity of the stamukha sail and the ice ridge keel is consistent with the Skachkov’s model.

The amount of data on porosity of the keel of ice ridges is several times larger than for stamukhas; therefore, the keel porosity curve is smoother. Approximation of the porosity curve of the stamukha sail is performed in the depth range of 0.5...4.6 m. The coefficients in formula (2) which determine the type of the approximating curves are given in Table 1. Also added are the multiplier values before the depth variable, which determines the slope of the exponent. Θ_0, i.e. porosity at zero depth differs twofold for the stamukha sails and ice ridge keels. The compactibility values differ by about one order. However, the multiplier values are of the same order and even display a minor scatter (mean value is 0.243; standard deviation, 0.066). It means, for example, that by $\Theta_0 = 0.5$ the rubble porosity will be about 0.04…0.15 at the depth of 10 m.

Table 1. Values of parameters of approximating curves

	Stamukha sail			Ice ridge keel		
	Θ_0	κ	$\kappa\rho_i g$	Θ_0	κ	$\kappa\rho_i g_A$
Laptev Sea	0.22	0.00003	0.269	0.42	0.00033	0.353
Caspian Sea	0.19	0.000019	0.162	0.38	0.00023	0.252
Baidaratskaya Bay	0.19	0.000025	0.214	0.37	0.0002	0.205

Thus, the nature of changes in the granular medium porosity under the action of gravity and the Archimedes forces will not differ by the steepness of the exponent, as it was assumed pursuant to the chosen hypothesis, but by the shift of the entire porosity curve towards lower values. The exponent in the first approximation remains unchanged.

ANALYSIS AND DISCUSSION

Maximum sail height of the studied stamukhas is greater than 14 m (Mironov, et al., 2019). Mean sail porosity of the studied stamukhas is similar for all three regions and amounts to 0.106...0.118. The monographs (Astafyev et al., 1997; Alekseev et al., 2001) summarize the results of studying stamukhas in the Sea of Okhotsk and provide data on the mean porosity of stamukhas. It is 0.10...0.23 for different sea areas averaging at 0.13. The mean porosity of stamukhas in the Laptev Sea is 0.11 (Mironov, et al., 2019); in the Caspian Sea, 0.10 (Mironov & Porubaev, 2011). Porosity of the unconsolidated part of stamukhas in the Caspian Sea according to Croasdale, et al. (2013), is 0.20...0.25. Mean typical vertical size of voids in stamukhas is 0.2 m.

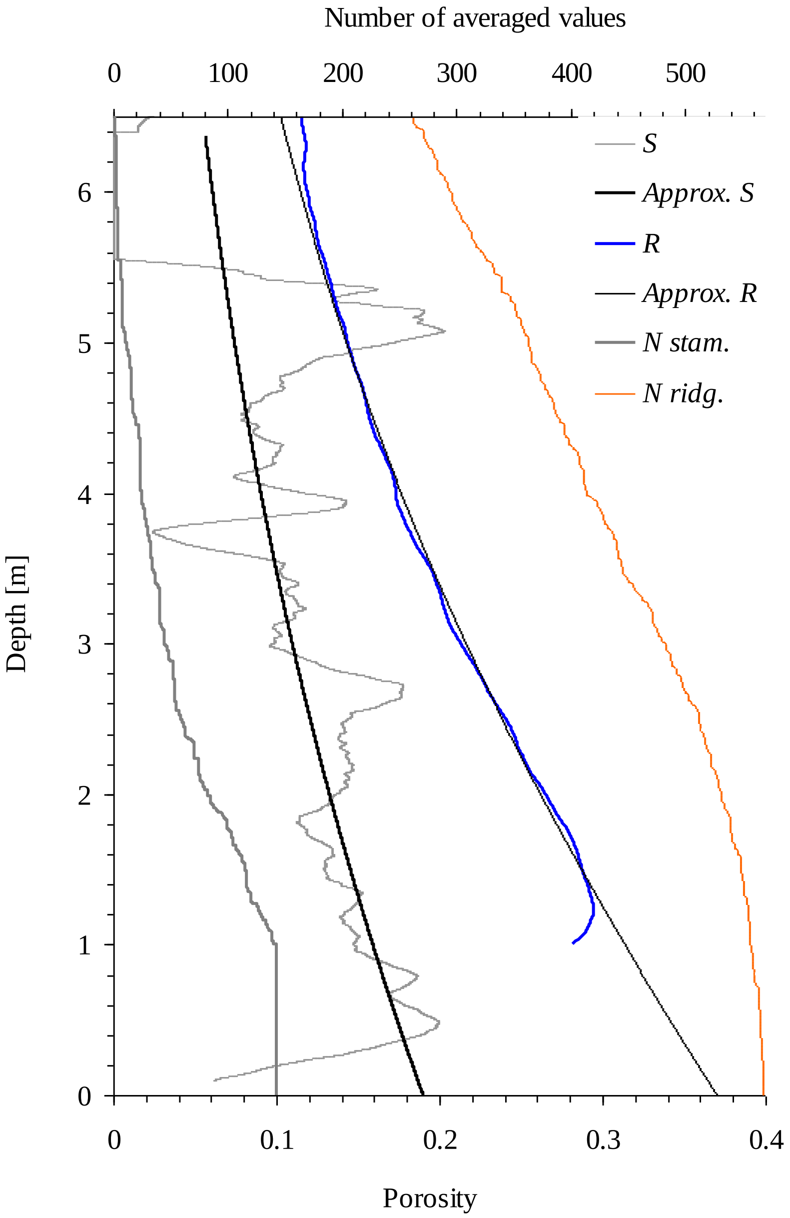

Figure 4. Smoothed depth-wise distributions of the averaged porosity of stamukha sail (S) and ice ridge keel (R) investigated in 2007–2010 in the Baidaratskaya Bay as a granular medium. Approx. S and Approx. R are their approximations by formula (2).
N – number of averaged values.

In (Skachkov, 2011), the formula for the porosity was derived based on two hypotheses. As a result, the concept of compactibility of the granular medium was introduced, which does not depend on either stresses, or coordinates. Not considering himself an expert in this field, the author will allow an assumption about the falseness of one of the hypotheses. The results obtained indicate that the exponential factor, i.e., the rate of the medium compactibility with depth, does not depend on stresses. The nature of compactibility is determined by the initial porosity, i.e., porosity at the edge of the sail or keel. An increasing load during transition from the Archimedes force to the gravity force leads to a drop in marginal porosity by about a factor of two.

It should be borne in mind that the compactibility of the stamukha sails is considered on the assumption of the uniformity of the fractional composition of ice blocks, i.e., the quantitative composition of fractions is approximately the same at all depths. However, this is not entirely true due to the specific features of the formation of stamukhas. As such, the scenario for stamukhas forming in shallow waters of the Caspian Sea is described by Bukharitsin (2019). During the initial period, inceptive internal layers of stamukha form from thin and small fragments. As the freezing degree-days accumulate in concert with the thermally-induced process of ice growth, another layer is formed during the subsequent motion of ice masses, which exceeds the previous one both in height and extent, as well as in size of ice fragments acting as building blocks. In old stamukhas, there may be several layers thus formed over the winter season. Due to the fact that in such a multi-layered hummocked formation, fragments of ice floes become stuffed until they fill the water column height completely, from surface to bottom, while during further ice mass motion, the ice field may not necessarily be broken into small pieces, slowly piling up instead and gradually heaving over the water surface, and thereby forming an ice dome. As the ice field continues to creep onto the inner layers of the stamukha, the ice dome becomes increasingly steeper and finally bursts out, thereby forcing huge ice blocks to stand up almost vertically, which sometimes become upturned, thus producing the exterior, most prominent layer of the stamukha. It is to be hoped that a regular grid of boreholes will neutralize such heterogeneity.

CONCLUSIONS

A total of 37 stamukhas were examined according to their sail porosity as a granular medium. Some conclusions of this study are:

- Porosity of the unconsolidated stamukha sail as a granular medium tends to decrease exponentially with depth.
- The exponential factor remains approximately the same under compaction by the gravity and Archimedes forces, but the porosity at zero depth in the equation of the approximating curve is different. In the gravity field, zero porosity is approximately two times less.
- Unconsolidated parts of ice ridges and stamukhas are compacted under the action of gravity in the sail of ice ridges and stamukhas and the Archimedes force in the keel of ice ridges. That is, the compaction of the same medium occurs at stresses that differ by about one order. The uniqueness of this situation allows considering the results obtained as a reference sample for testing the hypotheses of the granular media compaction.

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