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Ice freezing for hydrotechnical structures

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Abstract. In the domain of hydrotechnical structures, novel methods are emerging to increase ice thickness, notably in the context of ice islands. The layer-by-layer freezing process serves as a cornerstone, where freezing time determines efficacy. The article explores diverse freezing techniques, their stages, and implications. Layer-by-layer freezing entails water pouring, followed by freezing after each layer. Augmentations involve introducing ice rubble and inclined plane freezing. Sprinkling accelerates freezing through water droplet adhesion. The block method uses extracted ice blocks, creating vertical surfaces without formwork. Volumetric freezing involves pipelines and refrigerants. One method blends ice rubble with additives for versatility. Combined methods expedite construction, especially for substantial projects. These techniques cater not only to ice island creation but also to temporally reviving deteriorating structures such as moorage contractions.

1 Introduction

The development of innovative methods for enhancing ice thickness holds paramount significance in the realm of hydrotechnical structures, particularly in the context of ice islands. These methodologies are pivotal for creating robust ice foundations that offer structural stability and reinforce the integrity of various projects, such as ice islands [1-2]. The process of layer-by-layer freezing is central to these techniques, with the freezing time of each water layer being a critical determinant of success. The interaction between water layers and the environment dictates the overall efficiency of the process. This article delves into the intricacies of different freezing methods, their stages, applications, and implications.

The layer-by-layer freezing technique encompasses several discernible stages, each contributing to the eventual formation of thick ice layers on hydrotechnical structures. First, the water is cooled to the crystallization temperature. Subsequently, primary crystals form, giving rise to a thin ice layer on the surface. This layer experiences continuous growth until it merges with the ice base. The meticulous layer-by-layer approach involves pouring water, typically 3-5 cm thick, onto the surface and allowing it to freeze completely before the next layer is added. The freezing process is contingent on various factors, including air temperature and water salinity, and thus, careful attention to these parameters is essential for effective results.

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To expedite freezing and enhance the ice's structural quality, augmentations to the layer-by-layer method have been explored. The introduction of an initial layer of ice rubble, about 10 cm thick, followed by subsequent layer-by-layer water pouring of up to 3 cm thickness, can intensify the freezing process. Furthermore, freezing on an inclined plane is advocated to mitigate the initial salinity of ice derived from seawater. In this technique, water is supplied to an inclined plane, allowing it to wash away salt from previously frozen layers and subsequently freezing a thin layer of ice.

The method of sprinkling, or spraying, offers an alternative approach to ice construction. Water is sprayed onto a base, and depending on hydrometeorological conditions and the duration water droplets remain airborne, frozen or supercooled water drops adhere to the base. This technique yields higher freezing rates compared to traditional layer-by-layer methods, reaching up to 50-80 cm/day. While this method expedites the process, the resultant ice's strength and density tend to be lower. To address this limitation, the compacted ice is often further treated by flooding it with water, increasing its robustness.

An alternative method, termed the block method, involves extracting ice blocks from fast ice using ice-breaking equipment and placing them within a structure. This technique leverages the inherent strength of natural ice and enables the creation of vertical surfaces without the need for formwork. The placement of ice blocks involves meticulous attention to seam alignment, and the gaps are subsequently filled with water layers and frozen to ensure structural integrity.

Volumetric freezing presents yet another innovation in ice construction, entailing the use of a network of pipelines within the water area, through which a refrigerant is circulated via a compressor unit. This method's uniqueness lies in its ability to create an ice mass, with the upper portion frozen using complementary techniques such as layer-by-layer or sprinkling methods.

An intriguing advancement in ice construction is prepared ice rubble mixed with additives like pulp or acrylic fiber and sand. This mixture is placed in layers and frozen, offering a unique blend of strength and versatility. However, this approach demands sophisticated equipment and meticulous temperature control, making it suitable for specific applications where its benefits outweigh its higher costs.

2 Analysis

Different methods can be used to create extra thick ice for hydrotechnical structures, e.g. ice islands (fig. 1) [3-5]. The rate of layer-by-layer freezing depends on the freezing time of an elementary layer of water, which is determined mainly by the intensity of its heat exchange with the environment. In the process of ice formation during layer-by-layer freezing, following stages are distinguished [6]:

- Cooling of water to the crystallization temperature;
- Primary crystals formation and growth of the thin ice layer on the surface;
- Growth of the ice crust until it merges with the ice base.

Fig. 1. Mars Ice Island
(https://www.researchgate.net/publication/44051168_Sliding_of_Grounded_Spray_Ice_Structures)

The method of layer-by-layer freezing consists in the repeated layer-by-layer pouring of water with a thickness of 0.5 to 10 cm, followed by its freezing. In construction practice, the layer of poured water is usually 3-5 cm. With a greater thickness of the water layer, the freezing rate decreases due to the formation of a surface crust of ice. The next layer of water is poured after the previous one completely freezes and reaches a temperature of minus 5-7 ° C. At air temperatures above minus 10 °C, the method is ineffective, since the freezing of a layer of water, especially sea water, takes a long time. To increase the intensity of freezing, it is recommended to lay a layer of ice rubble up to 10 cm thick, followed by layer-by-layer pouring of water in layers up to 3 cm. To reduce the initial salinity of artificial ice from sea water, a method of freezing on an inclined plane has been developed, which consists in the portioned supply of water to an inclined plane. The flow of water washes salt from the previous layer of frozen water and freezes a thin layer of ice. The method was tested under semi-natural conditions. In case of real freezing on the underlying surface, the freezing time also includes the time of flooding, spreading over the ice surface, the time of water cooling to the crystallization temperature, the time of solidification and the time of cooling of newly frozen ice or its cold accumulation [7-10].

A number of formulas have been developed to determine the freezing time of a layer of water on ice. For practical purposes, the dependence developed by V.A. Gosman [11] based on the field studies:

$$\tau = 6300\frac{h}{t_в}\left[\frac{1}{0,85+0,5\left(\dfrac{v^{0,86}}{b^{0,14}}\right)}+h\left(\frac{1+0,5t_в}{1+0,1t_в}\right)\right] \quad (1)$$

where τ is the freezing time of the water layer;
h - is the thickness of the frost layer;
t_b - average air temperature during the freezing period;
v — average wind speed;
b - characteristic geometric size of the freezing surface.

The dependence is derived for freezing of fresh water, but it also gives good convergence with field studies of sea water freezing.

The theoretical dependence of the freezing time of a water layer on the thickness of the layer and hydrometeorological factors was also taken out [11].

$$\tau = \frac{73400h + R_{\Sigma} + R}{\alpha\left[2{,}6\left(p_1 + \varphi p\right) - t_{в}\right]} \quad (2)$$

where R_{Σ} — total solar radiation absorbed by the freezing layer;
R — effective radiation;
α — heat transfer coefficient between the freezing layer and the surrounding air;
p_1 — elasticity of saturated water vapor on the surface of the freezing layer;
φ — relative humidity;
P — elasticity of saturated water vapor in air.

The method of sprinkling (spraying) consists in a drip spray of water on the base (fig. 2). Depending on the hydrometeorological conditions and the time the dispersed water stays in the air, the main volume of water freezes and frozen or supercooled drops of water fall on the base. Due to this, the rate of freezing of artificial ice obtained by sprinkling is much higher than the rate of layer-by-layer freezing and reaches 50-80 cm/day. The physical processes of interaction of dispersed water with atmospheric air are well studied [11]. The strength and density of ice obtained by sprinkling is significantly low compared to frozen ice in layers. Therefore, such ice is often compacted, followed by flooding with water. The ice obtained by the method of raining is used in the creation of ice crossings, airfields. During the construction of ice structures, it is necessary to choose such modes of dispersed water supply, when no more than 20–30% of the water volume freezes in the air. In this case, due to the freezing of supercooled water, on the basis of the density and strength, they will approach the characteristics of layer-by-layer freezing ice and the freezing rate will be 20-25 cm / day.

Fig. 2. Spraying method

The block method consists in the extraction of ice blocks from fast ice using ice-breaking equipment and their placement in a structure. The dimensions of the blocks are determined based on the carrying capacity of the fast ice and lifting equipment. Before laying the blocks, it is recommended to carry out their cold charging on storage sites. To prevent blocks from freezing during cold charging, polyethylene film gaskets are installed with the base and between each other. It is possible to specially freeze ice blocks of the required sizes and configurations or harvest them in nearby freshwater reservoirs. Before laying ice blocks, it is necessary to clean the base from snow, in addition, it is recommended to pour water over the base or the previously laid course of ice blocks. To increase the reliability of the ice structure under the influence of a horizontal load, it is recommended to make ice blocks of a figured shape and increase the roughness of the surfaces of the structure by corrugation for their better freezing. It is necessary to provide for the laying of ice blocks with dressing of the seams along the length and height of the structure. After laying the blocks, the seams between them are filled with water in layers and frozen. The advantages of the methods are the high strength characteristics of natural ice, the possibility of creating vertical surfaces without formwork, and rather high construction rates.

During volumetric freezing, a system of pipelines is placed in the water of the water area, through which a refrigerant is pumped using a compressor unit, which makes it possible to create an ice massif. The distance between the pipelines should be no more than 2 meters. Part of the structure above the water level is frozen by one of the methods described above. The method has passed full-scale tests [11] and can be used in the construction of permanent ice structures, which will have a sufficiently high reliability. However, the cost of construction and operation of such structures will be much higher than the cost of structures built by other methods.

A technology has been developed for the construction of ice "icecreat", which is obtained from artificial prepared ice rubble with the addition of pulp or acrylic fiber and sand. Ice is produced from fresh water in ice generators, then it is crushed and, at a temperature of minus 20 °C, it is placed in the structure in layers of 7–10 cm. To ensure strength, water or pulp is added to the laid layer. A formwork with a refrigeration system is recommended to maintain a constant operating temperature of minus 10 °C. The upper structure is made of concrete. A pilot facility with an area of 20 × 53.5 m and a volume of about 6000 m^3 was built in the Oslo region. The cost of “icecreat” is quite high and requires special equipment, but it is believed that this method will be economically justified for large volumes.

The combined method consists in combining the described technologies for the creation of ice structures at one facility. As a rule, this is connected with a reduction in construction time and with a more productive use of equipment and mechanisms when creating structures with a large volume of artificial ice.

3 Conclusion

The construction of ice islands is less expensive and does not require sophisticated equipment. Construction material is available at the place (sea water). The work considered the main provisions and features of strengthening by additional freezing; types of ice freezing are presented: layer-by-layer, flare, volumetric and masonry from ice blocks. Based on the literature overview, it can be concluded that: ice frozen layer-by-layer is more durable than ice frozen by the spray method, since it has a denser structure; ice structures must be left for the period of cold accumulation and only then covered with heat-insulating material.

Ice construction technology has been successfully applied to wooden structures, e.g. for the restoration of the bearing capacity of the moorage structures (piers). To determine the strengthen effect of frozen ice, it is possible to carry out a calculation of the structure, both with and without additional ice.

In the Arctic region there are many wooden piers that have lost their bearing capacity. Ice freezing methods could be a temporary solution for them.

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