Experimental Research Into Ice-Loading of Supports of Hydraulic Structures

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Abstract. The paper states the problem and presents the results of experiments designed to find the ice loads of supports of hydraulic structures. Experimental studies were carried out in an ice tank. The experiments were designed to analyze how ice loads would affect a single-row set of piles, how using multiple rows would affect pile icing, and what kind of loads first- and second-row piles would have to sustain. Experimental data were recalculated in kind with adjustment to the scale of modeling; they were also calculated for the natural conditions as set forth in standards and regulations.

1. Introduction
In recent years, the development and extraction of fossil fuels in the north of Russia and on the Arctic coast has become an urgent problem. Handling it requires constructing new ports and upgrading the existing ones. When constructing or designing a hydraulic structure in the North, calculating the ice loads is crucial. Hydraulic structures are a critical class. Standards and regulations require that when designing such a structure, calibrations must use mathematical and physical modeling.

Overview of the papers [1–16] that present experimental and theoretical research into how ice interacts with the supports of such structures shows that ice loads on the supports depend on numerous parameters, including the pile-to-pile distance in a row, row-to-row distance, the relative positioning of piles in rows, the angle at which ice formations approach the piles, the ice thickness and strength.

Calculation of ice loads on supports is set forth in standards and regulations [1, 2, 15, 16]. Papers [3–14] present data on support loads. Thus, paper [3] presents the ratios of back-pile loads to front-pile loads. Depending on the experimental parameters, the ratios are in range of 0.1 to 0.4.

Notably, most of such data was collected on a 1:30 scale, which is too small for experimental quantification of loads, as such quantification requires sensors to be placed on supports.

2. Statement of Problem
This paper describes experimental research of how supports of hydraulic structures interact with smooth ice fields on a 1:7 scale; it also presents the results of the experiments.

Supports are either single- or double-row pile structures. Experiments were run in a 5 meters deep ice tank sized 7×14 m in plane.

The ice in the tank appeared due to the natural freezing of nearly fresh water of the Vyborg Gulf, the Baltic Sea. Ice fields could in strength and thickness depending on the time of freezing as well as on the degree-days. Field size depended on the model geometry and scale.
The physical and mechanical properties of ice were found by compressive tests carried out under the same conditions as the ice-support interaction experiments.

The experiments were run as follows. Structure mockups were placed in the tank, which was further filled with water to the necessary level. Low temperatures caused the water to freeze and form an ice cover of required thickness. The resulting ice field approached the mockups at a certain speed.

The field was moved forcibly by a special loading system that comprised distribution beams, hydraulic cylinders, and a pumping station.

To collect readings on the ice loads the support mockups had to sustain, the mockups were equipped with:
- sensors to measure force applied to the supports;
- sensors to measure the kinematics of the field movement;
- sensors to measure the force applied to the ice field (mounted on the distribution beams).

An individual instrumentation system was designed and mounted for each particular experiment. Figure 1 shows the general experiment design.

![Figure 1. Ice tank with deployed instrumentation](image)

2.1. Ice and Piles in Single Row

Figures 1 and 2 show the experimental setup involving a single-row pile system. Figure 2 shows an overview of the ice tank and describes the design of the experiments carried out to analyze how ice fields would interact with a single pile and a single-row, five-pile system.

Piles were made from metal pipes: diameter $d=203$ mm, metal wall thickness $\Delta=12$ mm, length $l=1.7$ m, with 0.5 m of each pile being submerged in reinforced concrete for firmer placement.

Modeling was done on a linear scale of 1:7. Inter-pile distance in the row was 3d; row to single pile distance was 6 d.

The experiments were run to find the force applied to the piles, $F_{P_i}(t)$, and the pressure each pile had to sustain, $N_{P_i}(t)$, as functions of time at different values of ice thickness (h). Typical $N_{P_i}=f(t)$ oscillograms are shown in Figure 3.
The experiments revealed that:
– force applied to a pile peaks not simultaneously for all the piles in a row;
– comparing the force applied to the piles experimentally, $F_m^\text{э}$, against the values calculated per [1], $F_m^\text{р}$, revealed that experimental values were lower than the calculated values as shown in the following ratio: $F_m^\text{э}=(0.5÷0.7) F_m^\text{р}$.

In [5], the coefficient of uneven ice destruction is assumed to equal $k_j=0.9$ in the absence of experimental data.

It could be assumed the resulting matrix of forces $F_m^\text{э}$ and $F_m^\text{р}$ was valued the way it was due to the fact that the analysis in [1] assumed that force would peak for all the piles in a row simultaneously.

### 2.2. Ice and Piles in Double Row

Figures 4 and 5 show the experimental setup involving a double-row pile system.

The tank contained two double-row pile systems. In one of them, piles were placed in pairs opposite to each other; in the other row, piles were placed with a 1.5d displacement against each other, see Figure 4.

The systems were separated by a single pile standing in the second row (counting in the ice movement direction), see Figure 4.

The experiments were designed to evaluate:
– how having multiple rows could affect the pile icing;
– the loads on piles in the first row vs the second row.

Experiment analysis produced the following findings:
– for the first row, loads peaked at 12 kN to 65 kN in case of thin ice (h=12.5 cm, h/d=0.61), 45 kN to 110 kN for thick ice (h=22.0 cm, h/d=1.1). Uniaxial compression strength was $R_c=1.2$÷1.6 MPa for $h=12.5$ cm and $h=22$ cm, respectively;
– the scatter of peak loads on first-row piles was ~6x when encountering thin ice, which suggests the piles worked independently;
– scatter was only ~2x in the thick-ice encounter, suggesting a more uniform pile loading;
– mean second-row load to first-row load ratio was $K_1$≈0.02 for thin ice ($h/d \leq 0.6$) and $K_1$≈0.1 for thick ice ($h/d \geq 1.0$);
– second-row load to first-row load ratio was nearly identical for both fields, i.e. the arrangement of piles did not affect the load ratios.
2.3. Parameters of Bustling and Icing of Double-Row Piles
Since icing is a hazard for hydraulic structures, additional experiments were run to estimate pile field icing.

After discharging water from the tank, the experimenters measured the bustles around the piles. Figure 6 shows the bustle sizes for the first and the second row; Figure 7 shows the icing on the first-row piles.
The following was noted:
- bustles were wider in the second row than in the first one: ~400 mm or ~2d;
- first-row icing was rather uniform at ~140 mm (0.7d) in thickness but varied from 170 to 195 mm (0.84-0.96d) in the second row;
- icing parameters differed for the two ice fields. In the one where the rows were offset by 1.5d (Field 1), the ice thickness was 195 mm (0.96d); for Field 2, 180 mm (0.88d).

3. Conclusions
Experimental data were recalculated in kind with adjustment to the 1:7 scale of modeling; they were also calculated for the natural conditions as set forth in standards and regulations. Loads thus estimated were different. The difference between calculated and experimental values was most prominent for single piles and for thin ice. For a double-row field exposed to thick ice, the ratio of calculated and experimental loads was ~1.57, indicating a good match of calculated and experimental values; it also proves that 1:7 experimentation is adequate for describing the ice-pile interaction and for quantifying the ice loads on supports.

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