FORCE MEASUREMENTS AND ANALYSIS OF RIVER ICE BREAKUP

by

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Abstract

Measurements were made near Oil City, Pennsylvania, during February 1981 to evaluate the performance of a floating ice control structure during an ice run on a shallow and steep stream, Oil Creek. The primary objective of the structure was to assist in forming an early, stable ice cover upstream of Oil City that would prevent prolonged frazil ice generation. The control structure was a double timber ice boom. This paper focuses on the forces exerted on the structure during ice breakup.

The forces transmitted to the ice control structure prior to breakup and during the ice run were monitored through a strain-gaged tension link, which had been incorporated into the design of the structure, and this ice force was recorded with respect to time. Analyzing the measured forces by use of the momentum equation has shown that the maximum ice forces that develop during an ice run can be estimated. The breakup force due to momentum in a shallow and steep stream should be used as the design criterion, as well as the widely accepted static method of applying a shear stress to the underside of the ice over some finite length.

The design of the structure was based on the expected force predicted by a static ice analysis. This estimated force in the downstream direction was 174 kN. The maximum measured dynamic force was 343 kN, and the observed ice velocity was about 5 m s^{-1}.

Introduction

The business district of Oil City is situated on a floodplain at the confluence of the Allegheny River and Oil Creek. This site is subject to annual freezeup ice jams consisting of frazil ice. These events, while causing severe flow restrictions, produce no overbank flooding. However, the site does experience breakup ice jams nearly biennially, (Fig. 1) which cause overbank flooding and heavy economic loss to the city. A detailed field study was conducted during the winter of 1980, and the results were reported by Deck and Gooch (1981).

It was proposed to Oil City officials that the ice jam flooding could be alleviated by controlling the ice in both the Allegheny River and Oil Creek. A field demonstration of an ice boom on Oil Creek was planned during the 1980-81 winter season.

The ice control structure was initially conceived to serve several purposes. Its primary objective was to form an early, stable ice cover upstream of Oil City. An early ice cover would prevent the prolonged frazil generation, which in past years led to a massive freezeup jam at the confluence of the Allegheny River and continuing upstream. An early, stable ice cover would also reduce the total volume of ice in the creek, resulting in a lower probability of breakup ice jam flooding. It was anticipated that the tributary, Oil Creek, would form an ice cover before the Allegheny River did. If so, we could observe the river freezeup without any significant ice being introduced by the creek, and we could develop a better understanding of ice formation in the two streams separately.

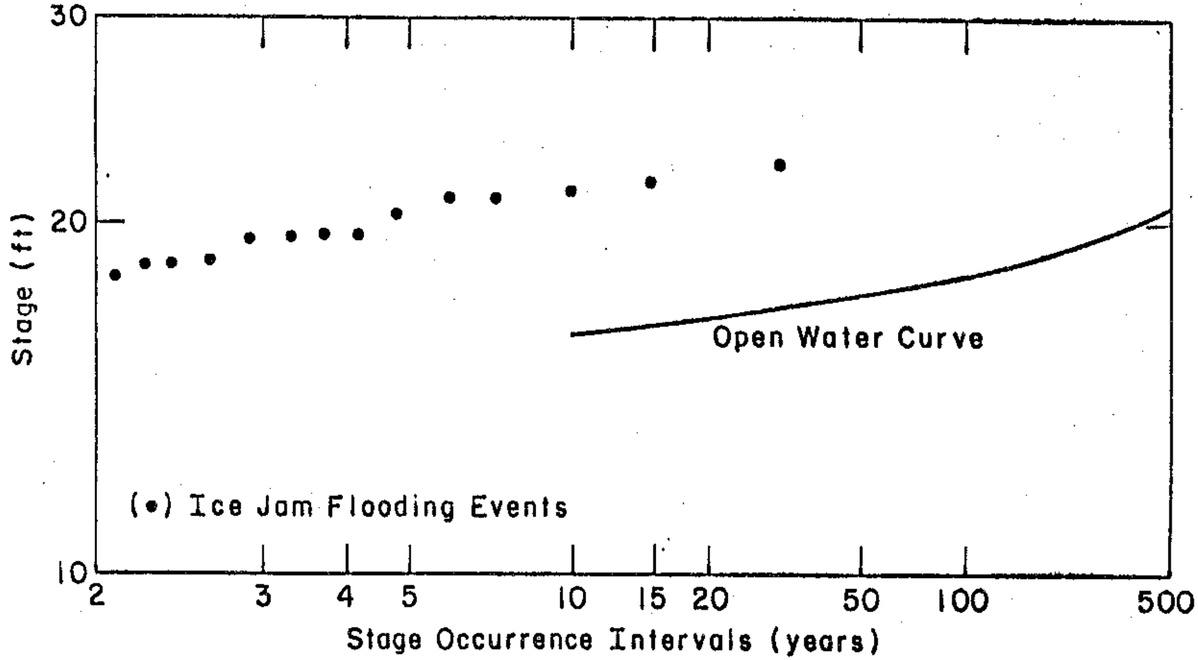

FIG. 1. OIL CREEK OVERBANK FLOODING
REPRESENTED BY A RIVER STAGE
OF 18 FEET.

In this paper, we report the measured forces on the structure during the breakup period and compare these with those obtained from the momentum equation.

Site Conditions

The site chosen for the structure is located about 5.5 km upstream of the confluence of the Allegheny River, where there is a relatively large pool. Flow conditions at the site appeared favorable for the successful deployment of an ice boom.

This reach of the creek had been the site of a bridge crossing. Although the bridge had been abandoned and removed many years ago, a stone pier in the stream remains, approximately 38 m from the right shoreline. At the average winter flow of about 14 $m^3\ s^{-1}$, the width of the stream in this location is about 58 m, the mean depth is 0.6 m, and the mean velocity is 0.5 $m\ s^{-1}$. The left side of the creek at this site consists of a high and rather steep bank. The right side is a designated flood plain.

Ice Boom Design

The original intention was for the structure to span the full width of the creek. However, permission was not obtained from the owner of the left shore property for a right of way to install an anchor. The abandoned stone bridge pier was then used as an anchor point. The structure spanned approximately two thirds of the stream width.

The preliminary design of the floating ice control structure was provided through consultation with Roscoe Perham of CRREL. He suggested the use of a double timber ice boom to provide increased stability in this unique applicaton. A plan view of the design is shown in Figure 2.

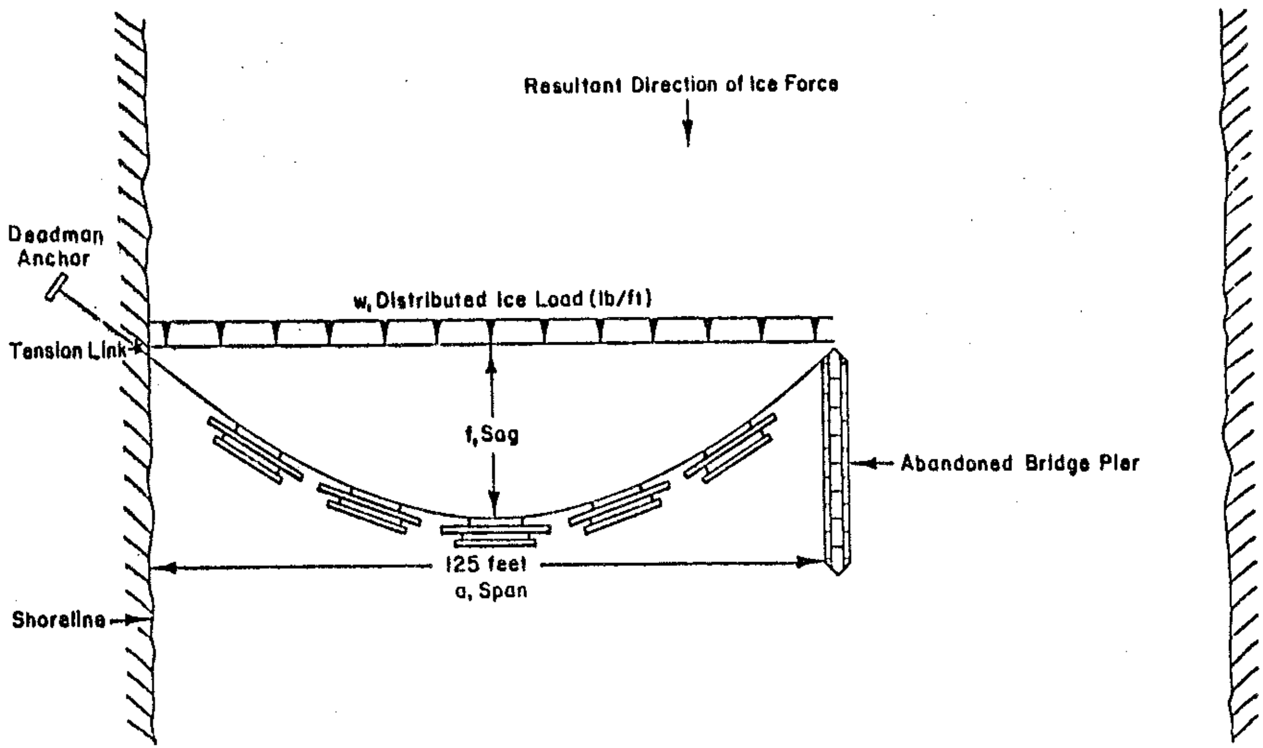

FIG. 2. ICE CONTROL STRUCTURE ON OIL CREEK, PA.

The design load of the structure was estimated from the shear stress due to water flow under the frazil ice accumulation. Perham (personal communication) conducted a flume study to determine a value for the drag coefficient associated with frazil ice. He reported a mean value of 0.16. The shear stress τ applied to the ice can be found by the equation

$$\tau = 0.5 \; C_f \; \rho \; V^2 \qquad (1)$$

where C_f = drag coefficient

ρ = mass density of water

V = mean stream velocity

For $V = 0.5 \text{ m s}^{-1}$, $\tau = 20 \text{ N m}^{-2}$

Assuming that the effective ice cover length is equal to 6 boom widths, as suggested by Daly and Stewart (1981), the distributed load w applied to the ice boom would be

$$w = \tau \times 6 \times 38.1 \text{ m}$$

$$= 4572 \text{ N m}^{-1}$$

and the total static load would be w x 38.1 = 174 kN. Pariset et al. (1966) introduced a method of predicting the loading on an ice boom during the ice formation stage by using a shear stress equation that includes the Chezy coefficient. The above expected loading is in agreement with their analysis.

The load potential in an ice boom on a small stream such as Oil Creek could not be verified as there was no known precedent for comparing the predicted load. A 22-mm 6 x 25 IWRC wire rope was used, which increased the design load of the structure to $11{,}100 \text{ N m}^{-1}$ to be on the safe side. A strain-gauged tension link developed by Perham (1974) was included in the design to measure the force exerted on the boom during operation.

Construction and Installation

The ice boom was constructed by Oil City employees under the direction of the Ice Engineering Research Branch of CRREL. Delays in obtaining a right of way to allow access to the site caused postponement of the installation of the structure until the week of 19 January 1981. A freezeup jam on the creek had occurred at the end of December. Our primary goal of initiating an early, stable cover was obviously lost for that winter, but there was still time to observe the effects and behavior of the boom and, in particular, to measure the forces on the ice boom during breakup.

The structure was installed on the solid ice cover and was attached to the pier and shore anchor. When it was completed a backhoe was rented to break up the ice and allow the boom to float in the water. Cold weather the following week refroze the ice surrounding the structure. The conditions remained unchanged until breakup.

Ice Breakup

The ice breakup on Oil Creek occurred on 17 February 1981. This breakup was the result of about 16 mm of rain over a period of two days during which the air temperature also rose up to 8°C. The leading edge of the ice cover was about 12 km upstream of the structure. The mean measured thickness of this ice cover was approximately 0.4 m prior to the warm weather and rain. Thickness measurements made after breakup revealed that significant melting had occurred during the two days before the breakup. The mean ice thickness had been reduced to less than 0.3 m.

Two separate ice runs occurred during the creek's breakup. The initial run began at 2045 hours and lasted until 2055 hours. This small run, which was initiated by the breakup of a tributary to the creek, consisted of only about 1.5 km of ice immediately upstream of the structure. Open water conditions continued at the structure until the remaining ice upstream from the boom let loose and ran from about 2145 hours to about 2215 hours. Forces exerted on the ice boom were recorded throughout the breakup period.

Ice Force Measurements

Forces exerted on the structure were monitored by the strain gauged tension link shown in Figure 2. The calibration range of the link was 27-267 kN. To correlate the measured tension in the structure to a distributed ice load, it was assumed that the load was uniformly distributed and thus the wire rope had a parabolic shape. Under these conditions, the equation of maximum tension T_{max} in a parabolic structure is

$$T_{max} = \frac{1}{2} \; wa \left(1 + \frac{a^2}{16f^2}\right)^{0.5} \qquad (2)$$

where

w = load per unit width ($N\ m^{-1}$)

a = span (m)

f = sag (m)

The span and sag of the structure were measured to be 38.1 m and 8.8 m, respectfully, and equation 2 reduced to

$$T_{max} = 28.1\ w$$

In Table 1, the time and range of the measured ice boom forces and downstream forces are listed during the ice breakup. Figure 3 shows the corresponding downstream ice force intensity versus time during the ice breakup. This data has been used to estimate the streamwise force range that develops during ice breakup in steep, shallow streams such as Oil Creek.

The force exerted on floating ice retention structures has usually been predicted by estimating the shear stress exerted by the flowing water on the underside of a static ice cover. This approach does not account for the potential maximum impact loading that can develop from the momentum of the ice during a run. The lack of field data makes it difficult to predict the expected ice momentum at a specific location, mainly due to the ice velocity.

At Oil Creek we were able to estimate the ice velocity by timing the ice floes. The estimated velocity was about 5 m s^{-1}. Similar values have been observed in other streams similar to Oil Creek, including sites in Pennsylvania and Vermont visited by the author and a local river in Vermont reported by Calkins (1981).

The ice boom behaved as expected during the majority of the ice run. The ice floes generally rode over the structure without much difficulty except during the time interval from 2205 to 2211 hours, when a jam occurred behind the boom. This appeared to have been caused by floes trying to go over and under the timbers simultaneously. The shallow depth of flow prevented this and the ice jammed, although the ice floes continued to pass freely on the left side of the pier. It is assumed that the force measured on the boom at this time was indicative of the total ice

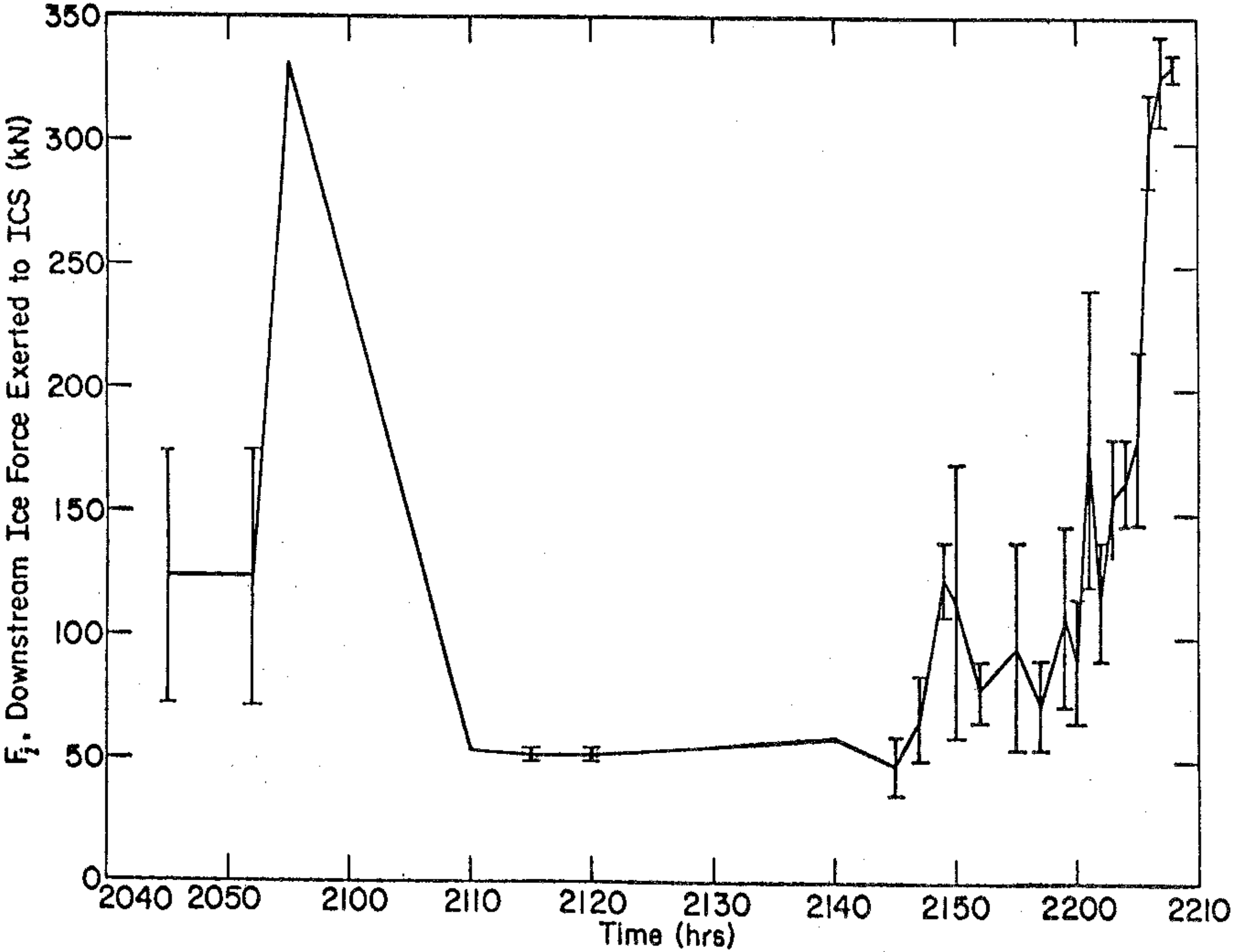

FIG. 3. OIL CREEK BREAKUP ICE FORCE
RECORD, FEBRUARY 1981.

Table 1. Ice force Record - Oil Creek ICS, February 1981

Real Time (hr)	Measured Force on ICS (kN)	Corresponding Downstream Force (kN)
2045	53-129	72-174
52	53-129	72-174
55	245	331
2100	44	59
10	40	54
15	36-40	49-54
20	36-40	49-54
40	44	59
45	27-44	36-59
47	36-62	49-84
49	80-102	108-138
50	44-125	59-169
52	49-67	66-91
55	40-102	54-138
57	40-67	54-91
59	53-107	72-145
2200	49-85	66-115
01	89-178	120-241
02	67-102	91-138
03	98-133	132-180
04	107-133	145-180
05	107-160	145-216
06	209-236	282-319
07	227-254	307-343
08	240-249	324-336

force that could be transmitted to it. The average measured force on the boom was about 210 kN. The estimated ice velocity can be checked by determining the momentum flux as the ice floes went from their initial velocity to zero velocity. The average measured force corresponds to an average total force F_i developed by the ice of about 284 kN, and we can write

$$F_i = \rho_i Q_i V_i \qquad (3)$$

where

ρ_i = mass density of ice (N s^2 m^{-4})

Q_i = ice discharge (m^3 s^{-1})

V_i = mean ice velocity (m s^{-1}).

F_i the force necessary to continuously arrest a supply of ice at a rate of Q_i.

Equation 3 can be rewritten as

$$F_i = \rho_i t_i \, w_i \, V_i^2 \qquad (4)$$

where

t_i = ice thickness (m)

w_i = ice boom width (m)

Using t_i = 0.3 m, w_i = 38.1 m, ρ_i = 916 N s^2 m^{-4}, and V_i = 5 m s^{-1} we obtain an estimate of F_i, from equation 4 of 261.7 kN which is close to the average measured value of the downstream force which ranged from 145 to 343 kN (Table 1). The estimation of ice forces on an ice boom should be based on both the dynamic loading (eq 4) and the static loading (eq 1).

Discussion

It has been shown here that the forces developed due to momentum during an ice run provide the ultimate design criteria for a floating structure. To predict these forces accurately we must first quantify the mechanics of the transport wave of the ice during a run. These forces could be estimated quite well if only the ice velocity could be pre-determined.

It must be clearly noted what conditions are present when the momentum force of the ice is analyzed. These conditions are not to be confused with the force obtained by the impact of one large piece of ice being decelerated. The case analyzed here is when the entire mass of fragmented river ice is running. The force exerted from the momentum flux is due to the aggregate of small forces developed by each of the many ice floes being arrested. When the flow of ice in Oil Creek was stopped, it did so over a period of about two minutes. As some ice flows began to slow down and others began to stop temporarily, the riverbanks began to take more of the load. At this time the ice arriving from upstream began to layer, which eventually distributed some of the force to the shallow river bed. The force transmitted to the river barrier in this case of many ice floes is the force found by applying eq 4.

Frazil ice control structures in steep and shallow rivers are in the developmental stage. Experiments are being conducted to assess the effectiveness of such structures. It is believed that if the production of frazil ice can be reduced, the result will be the alleviation of ice jam flooding.

Observations made at many shallow Pennsylvania and Vermont rivers similar in size to Oil Creek indicate that their ice runs are very similar. The major runs in these streams are usually bankfull when the ice is flowing freely, and the depth of flow in these streams at this time are approximately equal. Experience indicates that the depth of flow during a major ice run in these rivers is about three times the original depth of flow under the static ice sheet. The average bed slopes of the shallow rivers are of the same order of magnitude as Oil Creek (0.002), which suggests that the ice velocities should also be about the same.

The data collected on Oil Creek, combined with observations made at other similar rivers, indicate that ice velocities of 6 $m\ s^{-1}$ are not unreasonable to assume. It is felt that by using this value in eq 4, an upper limit of the ice force distributed to any barrier across a steep and shallow stream can be found.

Summary

The largest ice force potential in rivers occurs during breakup due to the momentum of the ice. Presently, design loads for floating ice control structures are predicted by analyzing the shear stress exerted on a static ice cover. The effective length of the ice used is typically six river widths or less.

Moving ice, not a static ice sheet, should determine the design criteria for an ice control structure, especially in shallow, steep rivers. However, our lack of understanding of the mechanics of ice breakup prevents us from predicting the dynamic event. The high ice velocities obtained during breakup result from the release of stored water behind minor ice jams prior to the complete breakup of a river. Quantifying the velocity is difficult. The need to supplement theoretical work with extensive field investigations of river ice breakup is evident.

Acknowledgment

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DISCUSSION

D. Andres, Alberta Research Council

During the time interval 2205 to 2211 hours a jam formed behind the boom and in Figure 3 it appears that the forces on the boom were fairly steady. Do you have any idea what the length of the cover was upstream of the boom during this period? Also, in your presentation you indicated the boom broke. Again, what was the force on the boom at the time of failure and what was the length of the accumulation upstream of the boom?

Reply by D. Deck

Unfortunately, I was unable to obtain the ice cover length at that time for several reasons. The entire ice run was observed and the measurements made from on top of an old bridge abutment at the water's edge. The darkness limited the upstream field of view to about 100 m. Also, the stage rise resulting from the jam encircled the abutment with water and ice which prevented me from descending to inspect the ice cover length.

The time of failure was 2211 hours while the force record shown on Figure 3 ends at 2208 hours. The downstream force level during these three minutes remained very stable until the failure of the boom and ranged from 320 to 340 kN. Again, the length of the ice accumulation behind the structure was unknown.