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Publisher's version / Version de l'éditeur:

Proceedings of a Conference on Ice Pressures Against Structures Held at Laval University, Quebec City, November 1966., pp. 135-141, 1968-11-01

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REPRINTED FROM
PROCEEDINGS OF A CONFERENCE ON
ICE PRESSURES AGAINST STRUCTURES
HELD AT LAVAL UNIVERSITY, QUEBEC CITY, NOVEMBER 1966
P. 135 - 141

RESEARCH PAPER NO. 383
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA

PRICE 10 CENTS

NOVEMBER 1968

NRC 10481

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OBSERVATIONS ON THE MOVEMENT OF ICE AT A BRIDGE PIER

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ABSTRACT

Photogrammetric observations on the movement of an ice cover about a bridge pier are presented. Most of the movement was across river rather than up or downstream, and appeared to be related to the crack pattern that developed about the pier due to changes in water level. It is suggested that when cracks form on the under side of the cover they fill with water which subsequently freezes. Because of the resulting increase in area, a thrust is developed in the cover when the water returns to its original level. Flooding of the cover about the pier had a major influence on the characteristics of the ice adjacent to the pier. Observations on the vertical deflection of the cover and the location of cracks gave for $E/(1-\sigma^2)$ a value of about 3.5×10^5 psi where E and σ are the effective Young's modulus and Poisson's ratio. It is suggested that observations on the deflection of ice covers adjacent to long straight walls can give useful information on the vertical forces that ice can exert on structures.

RÉSUMÉ

L'auteur présente les résultats d'observations photogrammétriques du déplacement d'une nappe de glace aux alentours d'une pile de pont. Les déplacements se sont plutôt produits perpendiculairement au fil de l'eau plutôt que vers l'amont ou l'aval, et ont semblé dépendre des fissurations se produisant aux alentours de la pile à cause des variations du niveau de l'eau. L'auteur suppose que lorsque les fissures se forment à la face intérieure de la nappe, elles se remplissent d'eau qui gèle. En conséquence la superficie de la nappe de glace se trouve accrue, et des poussées s'y manifestent quand l'eau revient à son niveau habituel. La submersion de la nappe de glace alentour d'une pile a une forte influence sur les caractéristiques de la glace enserrant cette dernière. Les observations sur la déformation verticale de la nappe de glace et sur l'emplacement des fissures ont attribué à $E/(1-\sigma^2)$ une valeur d'environ $3,5 \times 10^6$ liv./po.², E représentant le module d'élasticité longitudinale et σ le coefficient de Poisson. L'auteur indique que les observations sur les déformations verticales des nappes de glace abutant de longs murs droits peuvent donner des renseignements utiles sur les forces verticales exercées par les nappes de glace enserrant les ouvrages.

Forces due to ice must be taken into consideration in the design, construction, and operation of many structures. These forces may be caused by moving ice floes, or by horizontal or vertical movements of a solid cover. In order to predict the forces that might occur, it is necessary to have information not only on the properties of ice and of the cover, but also on the probable motion of the cover when subject to the constraints imposed by the shore and the structure. Because knowledge of the motion of ice covers and its dependence on factors such as weather, type of structure and nature of shoreline is not generally available, it is not possible for engineers to estimate with the accuracy desired for design purposes, the forces that ice can exert under given site conditions. This paper presents the results of observations that give some information on the movement of ice about bridge piers.

In 1963, work was begun on the MacDonald-Cartier Bridge between the cities of Ottawa, Ontario, and Hull, Quebec. By the Fall of 1964, the piers and erection of steel was completed but work on the road deck was not to be initiated until the Spring of 1965. This provided an opportunity to observe ice movements about the bridge piers not only from the ice cover, but also from the open deck above the piers. A programme of observations was undertaken therefore, with the following three objectives:

1) to observe the nature of the movement of an ice cover about a pier
2) to experiment with a photogrammetric method of measuring movement of ice covers under field conditions, and to determine the accuracy that can be achieved with it
3) to measure the vertical movement of the ice cover that occurred due to fluctuations in water level, and to obtain, from the observations, information on the vertical forces that ice can exert against structures.

FIELD ARRANGEMENT

Pier No. 3 from the Quebec side was chosen as the site for the observations. The water at this location is about 50 ft deep and the top of the open deck about 65 ft above the water surface. A photograph of the pier is shown in Figure 1. Information concerning the dimensions of the pier is given in Figure 2.

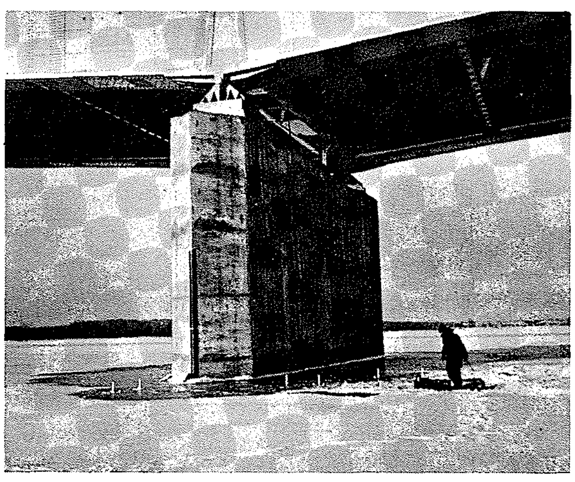

Fig. 1. View of Pier and Target Area from the Ice Cover. Note Flooded Area.

A platform was built on the beams of the bridge deck. Two camera stations about 16 ft apart were constructed in the platform along a line perpendicular to the side of the pier. A single theodolite plate camera with a 168-mm focal

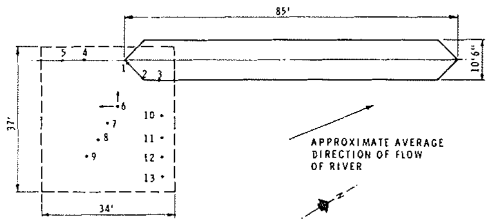

Fig. 2. Location of Targets and Target Area at Pier No. 3.

length and 9 by 14 cm^2 image size was used consecutively at both stations. The area of overlap of the stereo-pairs taken from the two stations was a rectangle about 34 ft by 37 ft at the southwest corner of the pier. This area is shown in Figure 2.

Ten targets, consisting of a black cross on a 2 by 2-in. white background, were placed in a regular pattern on the surface of the ice in the area of overlap. The targets were mounted on 1½ by 1½-in. pickets 1 ft high to keep them above the snow and water that might be present on top of the cover. Targets were also placed directly on the 1 by 1-ft base of the picket. The base was pinned to the cover with two 3-in. lag bolts. The base and pickets were painted white to minimize heating by solar radiation.

Details concerning the stereophotogrammetric measurements and establishment of the control points are given in the paper by Van Wijk (1966).

OBSERVATIONS AT ICE LEVEL

Targets were first placed on the ice on 21 December 1964. A subsequent warm period melted most of the ice between piers 2 and 3 and some of the targets were carried away. It was not possible to replace the targets until 4 January 1965 when the general ice thickness was about 6 in.

It was noted at times during the first part of the winter that the ice did not freeze solidly to the pier and water could be seen flowing in an open space 1 to 2 in. wide. At times there was a thin layer of ice over this section. Later in the winter the ice appeared to adhere more firmly to the pier. At piers 1 and 2 the ice cover froze firmly to the piers throughout the winter. It is considered that warm water discharged by a paper mill upstream from the bridge flows between piers 2 and 3 and through the region occupied by pier 3, and that turbulence induced in the water by the pier brings this warmer water to the surface causing the condition of poor ice adhesion that was observed.

The ice cover was usually attached to the pier sufficiently firmly to cause its surface to be depressed below water level when the water level rose. This resulted in flooding about the pier. It was found that the targets, particularly those close to the pier, gradually became submerged in the ice due to this flooding. This occurred to such an extent that the closer targets finally disappeared below the surface and new targets had to be placed on the cover. The targets placed directly onto the base of the picket could not be used for measuring movement because they became covered with ice shortly after being put in place.

During the first part of the season the thermal conditions were such that as flooding and subsequent freezing occurred at the top of the ice cover, melting occurred at the bottom. Later, however, melting did not occur, or was not so great, and the ice near the pier became greater in thickness than that further away. Profiles observed at piers 2 and 3 on 4 February are shown in Figure 3. The vertical displacement of the ice cover and targets had an influence on the photogrammetric observations that will be discussed later.

Cracks appeared in the surface of the cover in a well-defined pattern about the pier. These cracks were associated with the periodic change in water level. If the ice cover is frozen solidly to the pier and the water level rises, the bending moment induced in the cover is a maximum at the pier and the maximum tensile stress occurs at the under side of the cover. It would be expected that the first cracks to form in the cover due to an increase in water level would be at this location. It is considered that the very marked decrease in ice thickness near the pier, shown in the profiles of Figure 3, may be due to

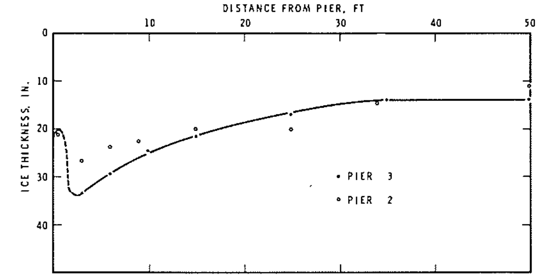

Fig. 3. Ice Thickness Perpendicular to the Long Axis of Piers 2 and 3, Feb. 4, 1965.

the formation of such cracks and subsequent erosion of the ice in the immediate vicinity of the crack by flowing water. With further rise in water level, cracks can be expected to form at the surface away from the pier at the location of the second maximum in the bending moment, as was observed.

PHOTOGRAMMETRIC OBSERVATIONS

Photographs were taken at seven times during the period 5 January 1965 to 4 March 1965. An example, taken on 24 February, is shown in Figure 4. Apparent horizontal movements determined photogrammetrically are given in Table I.

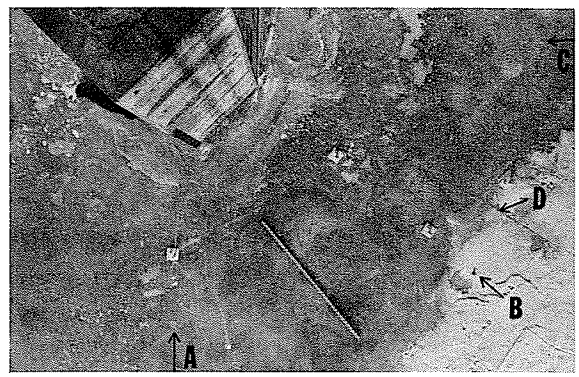

Fig. 4. The Ice Cover and Targets Seen from the Camera Stations on the Bridge Deck. A—Targets 4 and 5; B—Targets 6, 7, 8 and 9; C—Targets 10, 11, 12 and 13; D—Crack Radiating from Nose of Pier. Note New Targets Placed on Ice Because of Submergence of Old Targets by Flooding.

The position of the targets is shown in Figure 2. Targets 4 and 5 were placed along the long axis of the pier; Nos. 6, 7, 8, and 9 along a radial line from the nose and about 60° to the long axis of the pier; and targets 10, 11, 12, and 13 along a line perpendicular to the long axis of the pier and about 4 ft 6 in. back from the beginning of the triangular nose. Δx in Table I refers to movement perpendicular to the long axis of the pier and Δy to movement parallel to the long axis. Movement upstream, or from the Ontario side toward the Quebec side, is given as positive.

When the ice cover was displaced vertically and the ice remained attached to the pier, the cover in the target area became tilted. This caused the targets to tilt as well. Since the targets were located up to 12 in. above the ice surface, tilting of the cover contributed to the observed movements. An estimate of this contribution at

TABLE I

Summary of Movement of Targets

Apparent Movement Determined from Stereophotographs, in.

Date	January					February							March	
	5—18		18—25		25—8		9—17		17-24 (a.m.)		24 (a.m.)-24 (p.m.)		24 (p.m.) 4	
Target	x	y	x	y	x	y	x	y	x	y	x	y	x	y
4	4.0	0.9	0	0.3	0.3	−0.1	0.4	0	0.4	0.2	−0.2	−0.2	0.4	−0.1
5	4.0	1.1	0	0.3	0.3	−0.1	0.4	0	0.3	0.2	−0.2	−0.3	0.4	−0.1
6	3.8	0.7	0.8	0.2	0.6	0.1	0.1	0.1	0.1	0.3	−0.1	−0.1	0.5	0
7	3.8	0.8	0.6	0.3	0.4	0	0.1	0.1	0.1	0.2	−0.1	−0.1	0.4	−0.1
8	3.7	0.9	0.4	0.3	0.4	−0.1	0	0.1	0.1	0.2	−0.1	−0.1	0.5	−0.1
9	3.6	1.0	0.5	0.1	0	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.4	−0.1
10	4.6	0.9	1.2	0.3										
11	3.9	1.0	0.7	0.4	0.6	0	−0.3	−0.4	−0.4	−0.2	0	−0.1	0.4	−0.1
12	3.8	1.3	0.6	0.5	0.4	0	−0.2	−0.4	−0.4	−0.7	0.1	0.4	0.5	−0.1
13	3.5	1.1	0.7	0.5	0	−0.1	−0.2	−0.4	−0.3	−0.2	0	−0.2	0.4	0.1
Δx, target 11 due to tilt of ice	0.4		0.1		−0.3		−0.1		−0.1		0.1		0.1	

targets 11 and 12 is given at the bottom of Table I for the Δx component for each period between observations. The amounts given are considered to be maximum for the Δx direction. For targets 10 to 13 there should be no, or insignificant, contribution to Δy due to tilting, for targets 6 to 9 a possible small amount, and for targets 4 and 5 a contribution about equal to Δx for targets 11 and 12. The movements given in the Table are not corrected for tilting.

MOVEMENT OF ICE COVER

5 January to 18 January—On 5 January, open water existed on the Quebec side of pier 3. By 18 January, this area had frozen and the ice cover well away from the pier in all directions was about 6 in. thick. Measurement of the stereophotographs showed a fairly uniform displacement of the ice cover of about 4 in. perpendicular to the long axis of the pier and in the direction of the Quebec shore; and about 1 in. parallel to the long axis in the upstream direction. The net displacement was about perpendicular to the shoreline. Flooding of the cover occurred about the pier. In the photograph of 18 January small pieces of ice could be seen frozen into the flooded area. The transverse movement of the cover caused two small pieces of ice to be thrust upward at the nose of the pier. Evidence of these two pieces could be seen at the nose for the remainder of the winter.

Observations made at the downstream end of the pier on 14 January showed very marked and extensive buckling of the cover off the east corner. The ridges formed were about 12 in. high and the ice from 4 to 6 in. thick. There was also evidence of flooding. It appeared that when the cover shifted transverse to the pier, the ice constrained by the downstream portion of the pier conformed to this movement by folding. Melting of the ice immediately adjacent to the side of the pier probably allowed the ice in the target area to move without similar folding.

18 January to 25 January—The thickness of the cover about 150 ft from the pier was about 10½ in. Snow had fallen since 18 January. Cracks in the upper surface near the pier and flooding about the pier indicated that the water level had fallen and subsequently risen.

The horizontal movements were quite interesting. There appeared to be a general movement upstream of a little over 0.25 in. The measured movement across river was zero for targets 4 and 5, and 0.5 in. to 1 in. for the remaining targets, with the maximum movement occurring at the targets closest to the pier. Targets 4 and 5 showed a significant net downward movement whereas the remaining targets showed an upward movement that increased with distance from the pier. These observations suggest that the cover was forced towards the pier from both sides and that it buckled along the axis of the pier.

The association of crack formation with change in water level suggests that a possible explanation of the observed movement is the filling of these cracks with water which subsequently freezes. When the direction of the change in water level is reversed, a thrust is established between the shore and the piers or between adjacent piers resulting in a movement of ice about the pier.

25 January to 8 February—The measurements showed that there was no significant movement parallel to the long axis of the pier, whereas at targets 4 and 5, about 0.30 in. of transverse movement was observed. The movement at the other targets was almost nil for the two outer ones (9 and 13), and increased to about 0.6 in. for the near targets (6 and 11). Target No. 10 became submerged in the cover and was not replaced. Calculations indicate that because of tilting of the cover, the measured Δx component at targets 11 to 13 was about 0.3 in. less than actual. These movements could be explained by formation and subsequent filling of cracks that formed in the cover adjacent to the pier when the water level changed.

The thickness of the ice between piers Nos. 3 and 4 was about 14 in. on 4 February, and between piers Nos. 2 and 3, about 12 in.

8 February to 17 February—The interesting feature of this period was that targets 6 to 9 remained almost stationary whereas targets 4 and 5 moved across river toward the Quebec side about 0.40 in. and targets 11 to 13 moved toward the Ottawa side about 0.25 in. and downstream about 0.4 in. Target No. 12 showed a larger downstream component. A crack radiating from the nose of the pier between the line of targets 6 to 9 and 11 to 13 was clearly visible in the photograph of 17 February. Evidence of this crack can be seen in Figure 4 taken 24 February. The opening of this crack is in agreement with the observed movements, indicating again that the movements are associated with changes in water level and formation of cracks.

17 February to 24 February (9:00 a.m.) The general behaviour observed from 8 February to 17 February was continued during this period.

24 February (9:00 a.m.) to 24 February (2:00 p.m.) These observations were undertaken to see if significant movements occurred during one day. Movements of about 0.25 in. were observed at targets 4 and 5 cross river toward the Ontario side and downstream. No explanation can be given for the apparent erratic behaviour of target 12.

24 February to 4 March—The measurements for this period show a general cross-river movement of about 0.45 in. toward the Quebec side. By 4 March deterioration of the ice cover had begun. The photographs taken on that day showed evidence of this deterioration and opening of cracks in agreement with the observed movement. There was evidence of melting immediately adjacent to the pier and this melting may have allowed the movement that was observed. By 11 March deterioration had advanced to the point where thin spots had formed in the cover.

The ice thickness on 3 March was about 20 in. between piers Nos. 3 and 4 and about 18 in. between piers Nos. 1 and 2. Between piers Nos. 2 and 3 it was about 14 in. The ice thickness observations indicate that during the winter the cover between piers Nos. 2 and 3 was always thinner than on the shore side of these piers. This may be due to the release of warm water by the paper mill mentioned earlier.

VERTICAL MOVEMENTS

If, during a change in water level, a crack forms in the ice cover adjacent to a long straight wall in such a way as to reduce to zero the bending moment at the wall, and it is assumed that the deformation of the ice is dissolved, by simple elastic plate theory, then the deflection of the ice cover is given by

$$y = He^{-bx} \cos bx \qquad (1)$$

where
y is the vertical deflection at a distance x from the wall
H is the change in water level
b is a constant determined by the characteristics of the cover.
The constant b is given by

$$b = \sqrt[4]{\frac{k}{4D}} \qquad (2)$$

$$D = \frac{Eh^3}{12\,(1-\sigma 2)} \qquad (3)$$

where
k is the density of water
h is the thickness of the ice
E is Young's modulus
σ is Poisson's ratio.

From the deflected shape of the cover due to a change in water level, H, it should be possible to determine the value of b.

It was assumed that the side of the pier acted as a long straight wall. Vertical movement of the targets between observation periods was determined from the stereophotographs. It was observed that the vertical deflections of targets 10 to 13 did fit an equation of the above form. The time allowed to elapse between photographs was too long, however, which, when combined with the lack of an accurate record of the change in water level and the complicating effect due to the nose of the pier and flooding adjacent to the pier, greatly reduced the confidence that could be placed in values of b calculated from Eq. (1). Observations on the deflection did indicate, however, that the effective value of $E/1-\sigma^2$ (Eq. (3)) was greater than 3.0×10^5 psi. This value may be high because the increase in thickness in the ice adjacent to the pier was neglected. The general dependence of the thickness of the ice on distance from piers Nos. 2 and 3 had a form that was in agreement with Eq. (1).

If it is assumed that the surface crack parallel to the long direction of the piers formed where the bending moment is maximum according to Eq. (1), then $b = \frac{\pi}{4X_c}$ where X_c is the distance from the crack to the pier. Using this equation for b and observed values for X_c and associated ice thickness at the location of the crack, Eqs. (2) and (3) give $E/(1-\sigma^2)$ equal to about 3.6×10^5 psi.

The value of $E/(1-\sigma^2)$ that would be obtained using reported values for E and σ for no plastic deformation is about 1.2×10^6. Plastic deformation of the ice cover would cause the effective value of $E/(1-\sigma^2)$ to be reduced. For a given change in water level, however, plastic flow will result in a reduction in the vertical load, and so the value of the vertical force obtained assuming that the ice deforms elastically would be an upper limit.

CONCLUSIONS

The photogrammetric observations showed that the ice cover moved a significant amount relative to the pier during the winter. The largest movements occurred before the ice was 10 in. thick. Most of the movement was cross river, that is, transverse to the long direction of the pier, rather than upstream or downstream. Toward the end of the winter, when the cover had attained its maximum thickness, the movement of the cover appeared to be related to the crack pattern that developed about the pier. It is considered that cracks formed by a change in water level, then filling with water and subsequently freezing, were responsible for most of the movement. Flooding of the cover about the pier due to changes in water level had a major influence on the characteristics of the ice adjacent to the pier.

It is known that lateral pressures on piers can be significant, although such pressures are not usually taken into consideration in design. McClure and Herman (1965) report a case of a pier being badly cracked by such pressures, which in that particular case was estimated to be between 175,000 and 380,000 lbs. Whether the movements observed in the present study would cause a thrust to develop, and if so, the size of that thrust, would depend not only on the characteristics of the cover, but on the restraints imposed by the cover on the opposite side of the pier.

This study showed that stereophotogrammetry is a practical technique for observing in detail movement of ice adjacent to structures such as piers. Greater control than was used in the present work, however, is required to establish corrections to measurements if changes in water level occur, particularly if the changes are accompanied by flooding. It must be appreciated also that, although photogrammetry can reduce the amount of time spent in the field, considerable time must be expended in obtaining information from the photographs, particularly if it is required to determine movements in detail. With conditions similar to those for the present observations, it is considered that an accuracy of better than 0.1 in. can be achieved without difficulty.

The study indicated that useful information on the properties of ice and the deformation and failure characteristics of ice covers could be obtained from observations on the deflections and cracks that occur adjacent to a simple structure when the water level is changed. Such observations could probably be made most easily using conventional surveying techniques. The observations on vertical movements in the present study were not complete enough to allow characteristics of the cover to be determined with the reliability desired. Observations on the shape of the deflected surface and the location of cracks parallel to the long direction of the pier gave a value for $E/(1-\sigma^2)$ in Eq. (3) of about 3.5×10^5 psi. Observations on Young's modulus and Poisson's ratio show that it should be less than about 1.2×10^6 psi.

ACKNOWLEDGEMENTS

The author is indebted to the Federal Department of Public Works for permission to conduct the observations about the pier of the MacDonald-Cartier Bridge, and to use the deck as a platform from which to photograph the movement of the ice. The author wishes also to express his appreciation to Mr. Ramsay Murray, Field Engineer at the Bridge Site, for his co-operation and assistance throughout the project, and to W. Ubbink, R. Armour and K. Timmins for their assistance in making the observations. He is especially indebted to Mr. T. Blachut, Head of the Photogrammetric Research Section of the Division of Applied Physics, National Research Council, for the contribution his Section made in measuring the movement of the ice by stereophotogrammetry.

This paper is a contribution from the Division of Building Research of the National Research Council, and is published with the approval of the Director of the Division.

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