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by

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Field Study on the Load Bearing Capacity of Ice Covers

L. W. GOLD
Division of Building Research
National Research Council

Introduction

Frozen lakes and rivers are widely used in Canada for transportation purposes. It is therefore of importance to determine the dependence of the bearing capacity of an ice cover on the physical properties of the ice. Because the knowledge of how ice behaves when under load is still very incomplete, it is impossible at this time to calculate with confidence the bearing capacity of an ice cover from the information now available on the elastic and plastic behaviour of ice. As is often the case in such circumstances, recourse is made to the empirical approach. Those who use ice covers continuously for transportation purposes, develop through experience a knowledge of the load which can be transported safely over ice of given thickness and quality. Unfortunately, this experience gained in the field is rarely recorded and therefore not generally available.

The pulp and paper industry makes continuous use of frozen lakes and rivers in their logging operations. With the assistance of the Woodlands Section of the Canadian Pulp and Paper Association, the National Research Council undertook a project to record some of the experience of this industry in their use of ice covers. A form was prepared upon which companies could record relevant details whenever a vehicle or horse broke through the ice. A second form was prepared which asked for the maximum load that was successfully placed on the ice, and the associated ice thickness and quality. Copies of these forms were distributed to the pulp and paper companies through the Canadian Pulp and Paper Association. This report contains a summary of the information obtained from the forms which were returned to the National Research Council during the winter of 1958—59 and part of the winter of 1959—60. The observations are compared with some of the formulae available in the literature for predicting the bearing capacity of an ice cover and implications arising from the comparison are discussed.

Paper presented at the Annual Meeting of the Woodlands Section, Canadian Pulp and Paper Association, held in Montreal, Que., March 22, 23, 24, 1960.

Observations

The information obtained from the reports is summarized in Tables I and II. In each case, the loads given are those contained in the report. No attempt was made to take into account wheel or track spacing when calculating the load on the ice. It was thought that this refinement was not warranted at this time.

In calculating the effective ice thickness, it was assumed that two inches of white ice was equivalent to one inch of good "blue ice". For example, if the measured ice thickness was 30 inches, of which 10 inches was white ice, the effective ice thickness was recorded as 25 inches.

In Fig. 1, the logarithm of the observed load is plotted against the logarithm of the effective ice thickness. Some information on the ice thickness required by various companies before given loads are allowed on the cover was available and this is plotted in Fig. 2 as "experience data".* Also shown in Fig. 2 are the observations on the maximum load successfully placed on the ice cover.

Discussion

There is now available in the literature, a number of formulae for the prediction of the safe load-bearing capacity of an ice cover. Many of

*The author is indebted to C. R. Silversides for making this information available to him.

TABLE I

PULP AND PAPER SURVEY OF BEARING STRENGTH OF ICE: RESULTS FROM BREAKTHROUGH AND MAXIMUM LOAD REPORTS

Vehicle	Weight (tons)			Ice Thickness (in.)			Speed (mph)	Snow Depth (in.)	Temp. (°F.)	Symbol (Fig. 3)	Remarks
	Vehicle	Load	Total	Measured	White	Effective					
Tr	3	—	3	3	—	3	5	10		●	
T	5.5	9.6	15.1	15	6	12	3	2	10	▲	20′ from shore, lake shallow, bottom "hot".
T	3	6.5	9.5	8	4	6	parked	3	0	▲	Parked 1 min, backed off slushed area, rear wheels went through.
H	—	—	0.83	4	2	3		7	15		Ice broke in front — horse went in head first.
B	2.3	1.5	3.8	8	4	6	5	2	20	▲	On narrow river near bank, ice underlain by air space.
T	4	4.5	8.5	12	9	7.5	10	2	6	▲	
Tr	8	—	8	12.3	1.3	11.5	1	0	−10	●	Creek landing, scraping ice.
B	1.5	1.6	3.1	—	—	5.5	3	4	− 5	▲	Travelling on creek, ice thickness varied between 1 and 10 inches.
T	8	—	8	13	1	12.5	1	2	−10	●	Creek landing — scraping road, water depth 4′ max.
H	—	—	0.7	6	4	4		0	−10		Scraping ice, water level changing.
H	—	—	0.85	6	4	4		0	−10		
T	10	13.5	23.5	27	11	21.5	12	0	− 1	▲	Lake shallow, "hot" bottom, depth 20′, week of +35°F followed by −2°F. 2′ snow off road, note speed.
B	1.4	—	1.4	3	2	2	8	6	5	▲	3″ ice ran from sink hole to shore. 20′ ahead and behind vehicle 9″ ice.
B	1.4	—	1.4	7	4	5	5	4	−20	●	
T	5	8.7	14.7	18	—	18	35	5	15	▲	1 rear dual through first, 50′ further second, truck stopped with rear sunk to platform level.
H	0.75	3.2	3.95	5	3	3.5		2	30		Double layer of ice with 2″ between.
Tr	1.65	0.35	2.0	8	—	8	7	3	−30	▲	Pulling empty tank, tank did not go through
B	1.7		1.7	14	9	8.5	parked	5	−10	▲	Double layer of ice with 3″ water between, parked 1 min.
T	5.5	11.25	16.75	19	0	19	10	0	−35	■	Both rear wheels went through.
T	3.8	9.0	12.8	19	0	19	20	0	−35	■	One rear wheel went through.
T	4.15	9.0	13.15	22	0.	22	parked	0	−35	■	One rear wheel went through, parked for 2 minutes.
T	4.15	10.25	14.4	20	0	20	parked	0	−25	■	One rear wheel went through, parked for 2 minutes.
T	5.65	9.0	14.65	22	12	16	5	0	0	■	One rear wheel went through.
T	5,6	10.25	15.65	19	0	19	5	0	−35	■	One rear wheel went through.
H	1.6	2.3	3.9	4	2	3	—	8	−20	●	
H	0.75	1.0	1.75	4	0	4	—	6	10	●	
H	0.9	1.35	2.25	6	4	4	—	2	8	●	
T	6.5	11.0	17.5	21	12	25	parked	4	−10	●	Parked 2 minutes.
T	6	11.0	17.0	6	3	4.5	1	2	−10	●	
T	5	8.25	13.25	4	0	4	1	4	−5	●	
T	4.2	1.5	5.7	17	8	13	1	3	−12	●	
T	5	10	15	22	12	16	15	2	−10	▲	
T	5	13.5	18.5	21	4	19	parked	4	20	▲	Side of truck closest to shore went through, Water level changing.
T	4.5	0	4.5	6	2	5	5	2	−10	▲	Accident on river. 100 feet from truck 18″ ice.
T	4.5	12.5	17.0	18	4	16	parked	3	10	▲	Ice in 2 layers with 2″ water between, rear end went through.
T	4.0	13.5	17.5	18	6	15	5	2	10	▲	Ice in 2 layers with 2″ water between, rear end broke through.
Tr	2.75	—	2.75	8	4	6	2	8	15	▲	Went through "warm hole". Ice 14″ thick around place where tractor sank.
T	5.4	13.5	18.9	19	8	15	8	1.5	−22	▲	Heaviest of 30 loads already passed over. Ice surrounding about 22″ thick.
T	6	16	22	17	13	10.5	5	2	−30	▲	Ice in 2 layers with 2″ water between.
T	4	9	13	14	6	11	5	3	8	●	
T	15	27	42	29	5	26.5	2	1	−29	■	
T	6.2	26.8	33	14		14	1	1	−16	■	Rear wheels went through 14″ ice near shore, cab on 27″ ice.
Tr	3.5	12.5	16	19	6	13	3	3	15	▲	4 layers ice with water between thickness water plus ice 24″
T	9	21	30	18	4	16	15	1	8	▲	

T = Truck
H = Horse
Tr = Tractor
B = Bombardier

these formulae are too complicated for general application. In practice, it is often assumed that the allowable load is proportional to the square of the ice thickness or

$$P = A h^2$$

where P is the allowable load in tons
h is the effective thickness of the ice in inches
A is a constant which depends on the quality of the ice, the geometry of the load and the factor of safety appropriate for the situation.

Some published curves giving for a single vehicle the safe load for ice of given thickness are presented in Fig. 2. In Fig. 3 are plotted some of the calculated safe ice thicknesses which have appeared in the literature for given individual loads.

In Fig. 1 is shown the line $P = 0.025 h^2$, below which all except one of the observed breakthroughs occurred. This line is drawn in Figs. 2 and 3 so that the maximum load observations, experience criteria and information obtained from the literature could be compared with the breakthrough observations. Also shown in the figures is the line $P = 0.125 h^2$,

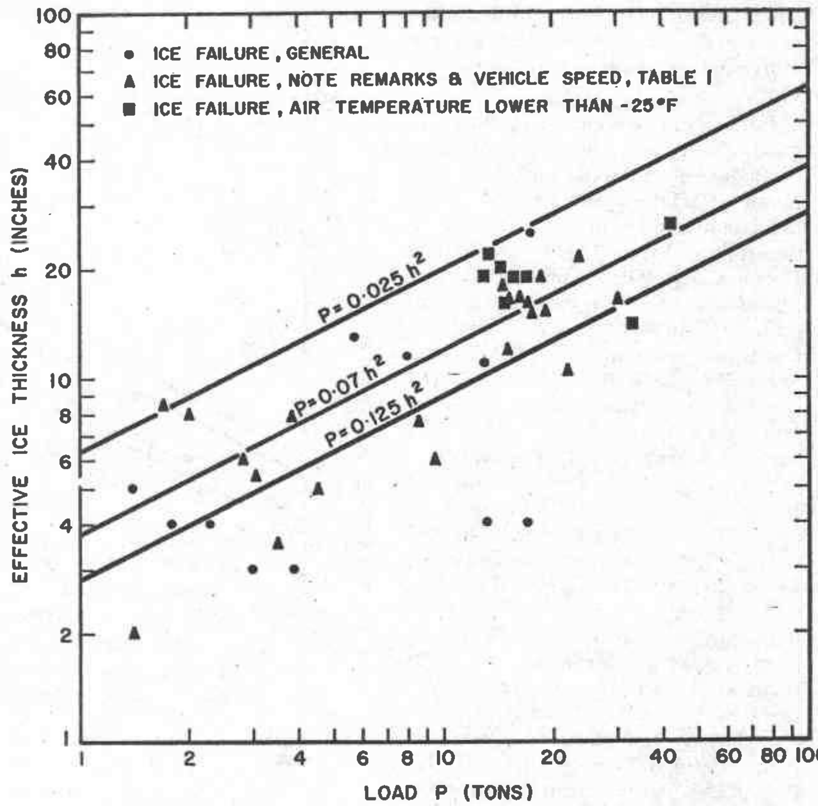

Fig. 1. Failure load and the associated effective ice thickness.

TABLE II

MAXIMUM LOAD REPORTS

Vehicle	Weight (tons)			Ice Thickness (in.)			Snow in.	Remarks
	Vehicle	Load	Total	Measured	White	Effective		
T	10	25	35	42	11	36.5	11	
Tr	17.2		17.2	28	0	28	12	
T			23	30	20	20		
T	8.85	18.9	27.75	30	24	18	0	
T	16.25	30	46.25	24	4	22	6	
T	14.0	38	52	28	0	28		
T	12	32.1	44.1	30	8	26		
T	10.25	18.55	28.80	36	6	33	3	
T	11	9	20	23-29	5	20.5-26.5	36	
T	18	13	31	31-33	6	28-30	36	
T	11	7	18	26	6	23	30	
T	8.5	15.8	24.3	23	4	21	2	Mild weather followed by severe cold checks ice — extreme caution necessary.
T	15.05	26.65	42.70	24-42	5	21.5-39.5	2	
T	8.5	15.8	24.3	24-44	2	23.43	2	
T	11	15.5	26.5	30	18	21	4	
T	5	26	31	30	18	21	30	
T	28	37.4	65.4	38	26	25	0	
T	7	15.0	22.0	30	15	22.5	4	
T	3.5	15.5	19	17	4	15	10	
T	4	9	13	16	8	12	4	Consider 16" minimum for safe landing
T	14	38	52	34	6	31	0	
T	10.5	18.9	29.4	30	12	24	0	
T	9.3	21.0	30.3	28	0	28	0	
T	15.5	37.8	53.3	38	17	29.5	1	

T = Truck
Tr = Tractor

which defines the lower limit to the calculated safe ice thickness for the individual wheeled loads shown in Fig. 3.

For single vehicles travelling on good quality ice, the value of A is normally between 0.03 and 0.07. The factor of safety to be associated with the recommendation $P = 0.07\ h^2$ is uncertain. From field experience Korunov (1956) considered this formula to give "a considerable reserve of strength". The calculated ice thickness for given loads lying between $P = 0.07\ h^2$ and $P = 0.125\ h^2$ in Fig. 3 are for military vehicles primarily or emergency situations where a degree of risk is accepted.

Accepting the recommendations $P = 0.125\ h^2$, $P = 0.07\ h^2$ and $P = 0.025\ h^2$ as defining regions of decreasing degree of risk, it is seen from Fig. 1 that out of 40 observed ice failures, 12 occurred with loads greater than that defined by $P = 0.125\ h^2$, in the region of maximum risk. Eight failures occurred in the region defined by $P = 0.07\ h^2$ and $P = 0.125\ h^2$. Twenty failures occurred in the region defined by $P = 0.07\ h^2$ and $P = .025\ h^2$ where, from the information available in the literature, the ice would normally have been considered safe. These observations indicate that either the expressions available for predicting the bearing capacity of an ice cover are not valid or that the assumptions made for the mathematical calculations were violated under the field conditions. The assumptions normally made for the mathematical prediction are:

1) The ice responds elastically, which means in practice that the load must be travelling at a speed greater than about 1 mile/hr.
2) The speed of the load is sufficiently slower than the speed of the hydro-dynamic disturbance set up in the water so that no resonant wave is formed in the ice cover. In practice this limits the upper speed of a vehicle to between 5 and 10 miles/hr. depending on the depth of the water and the thickness of the ice.
3) The ice is of good quality.
4) The thickness of the white ice can be taken into account when calculating the effective ice thickness. In most mathematical approaches, two inches of white ice is assumed to be as effective as one inch of good "blue" ice.
5) There are no cracks which pass right through the ice cover.

For the cases plotted as solid triangles or squares in Fig. 1, there was some evidence that one or more of

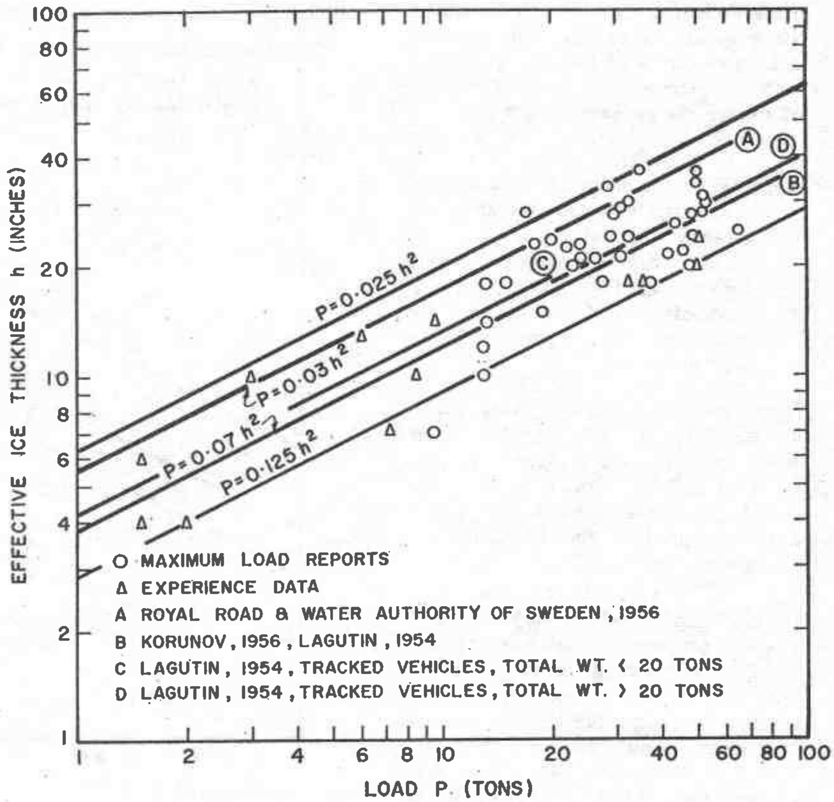

Fig. 2. Maximum load observations and experience data from pulp and paper companies and recommended ice thicknesses from other sources.

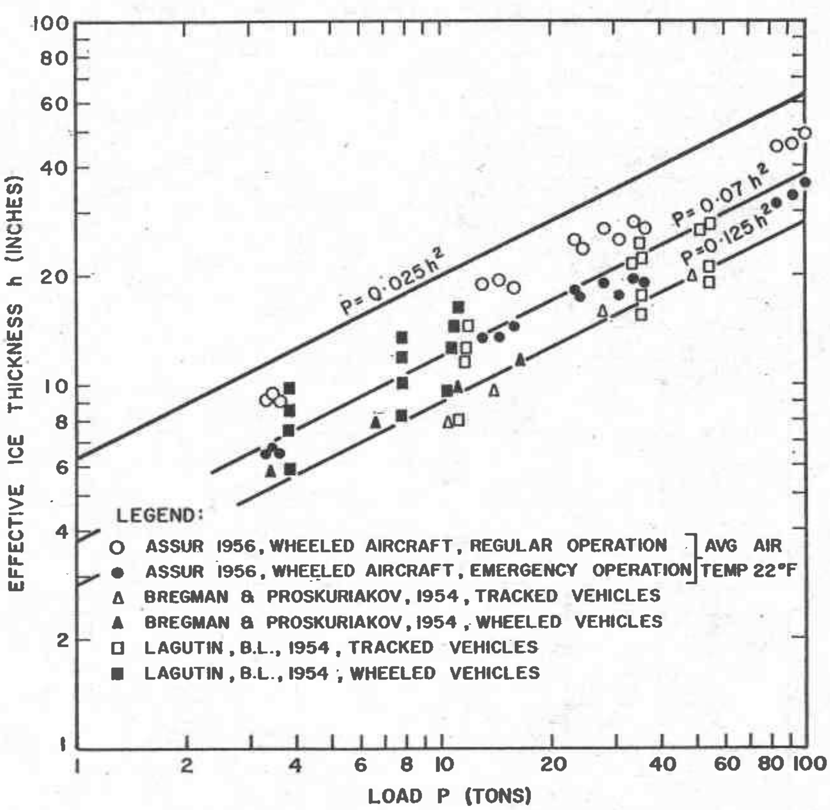

Fig. 3. Calculated effective ice thickness for given loads obtained from various sources.

the preceding assumptions had been violated. The cases plotted as squares are particularly interesting as they point out a possible situation which has not been dealt with in the literature to any extent as yet. The nature of the breakthrough and the low temperature which prevailed at the time of the accident would suggest that the ice may have developed cracks due to thermal stressing. The cracks could decrease the effective thickness of the ice to the point where the ice failed by "punching". Many operators are aware of the danger associated with going onto an ice cover after or during a period of rapid fall in air temperature. In one maximum load report, the observer stated that in their operations extreme caution is used when mild weather is followed by extreme cold.

From the records it would appear that many of the breakthroughs occurred during the period when the log dumps were being constructed, perhaps before there had been an opportunity to properly assess the condition of the ice cover with the facilities available in the area of operation. When the ice is thin, the bearing capacity of the cover would be more sensitive to the stresses and cracks caused by air temperature changes and other factors than later in the season when the ice had developed its maximum thickness.

In the series of papers edited by Lagutin (1954) the Russian authors give information on how the expression

$$P = A h^2$$

should be modified by various coefficients to take into account such factors as white ice and open cracks. In particular, if a vehicle is travelling across an open crack, the safe load is about ½ of that calculated for an uncracked cover. If the load travels parallel and along the edge of an open crack, the safe load is about ¼ of that calculated for the uncracked cover. In all the literature which has been cited, the continual checking of the ice cover and in particular the locating and marking of open or potentially dangerous cracks was emphasized. It is possible that some of the recorded failures are due to vehicles travelling on ice whose bearing capacity had been reduced by the presence of cracks.

Although the observations received to date do suggest possible reasons for the discrepancy between the field observations and the mathematical predictions for loads smaller than those defined by $P = 0.07 h^2$, the information recorded was not sufficient to determine with reasonable confidence the actual cause of this discrepancy except in a very few cases. If it were possible to keep a continual check on the presence of potentially dangerous cracks at a log dump, then this information, along with the information on the quality of the ice and marked changes in air temperature, would assist greatly in determining if failures which occur with loads smaller than those defined by $P = 0.07 h^2$ are due to a predictable lowering of the safe bearing capacity of the ice cover.

Conclusions

The number of observations which have been made are not sufficient to be used as a basis for empirical rules giving the dependence of the bearing capacity of an ice cover on its thickness, quality and other properties; nor are the observations sufficient or complete enough to show that the expressions given in the literature for predicting the safe bearing capacity of the ice are valid. The observations do show that if thickness only is taken as a measure of the bearing capacity of an ice cover and factors such as presence of cracks, thermal stresses and natural variation in effective thickness are neglected, then ice failures can be expected to occur with single vehicles of total load less than that defined by $P = 0.07 h^2$.

Recommendations

It is recommended that the recording of pertinent information for each failure of an ice cover under load should be continued. Every effort should be made to make the information as accurate and as complete as possible. The report should contain additional information such as a description, including size, of any cracks near the location of the breakthrough and whether there was a marked decrease in the air temperature during the six hour period prior to the accident.

It is recommended also that experience criteria concerning the loads which companies allow on the ice cover during the making of a log storage area and during its use should be recorded along with the associated ice thickness. This record should include a description of the steps taken in the construction of the storage area as well as a description of the safety precautions practised both during its construction and later use.

Acknowledgements

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