

ICE MODEL STUDIES FOR THE  
NORTHUMBERLAND STRAIT CROSSING\*

by J. E. Cowley\*\*

ABSTRACT

A novel form of structural-hydraulic model was used as one approach to the determination of the forces which moving fields of sea ice might impose on bridge piers in the Northumberland Strait. A synthetic "ice" material with mechanical properties to the scale of the hydraulic forces was employed. Both the modes of ice failure and the loads derived from the model results agree well with predictions made by other means. These results suggest that other problems involving a close coupling between hydraulic loads and structural response might be profitably studied with hybrid models of this type.

1 - BACKGROUND

The Northumberland Strait is located about 500 miles northeast from Boston. It separates Canada's smallest province, Prince Edward Island, from the mainland provinces of New Brunswick and Nova Scotia. (Refer to Figure 1.)

The Strait which is approximately 200 miles long varies in width from 8 to about 40 miles. It is subject to a

---

\* The work which is described in this paper was carried out by Northumberland Consultants Limited for the Department of Public Works of Canada.

\*\* Hydraulic Engineer, H. G. Acres & Company Limited, Niagara Falls, Canada.

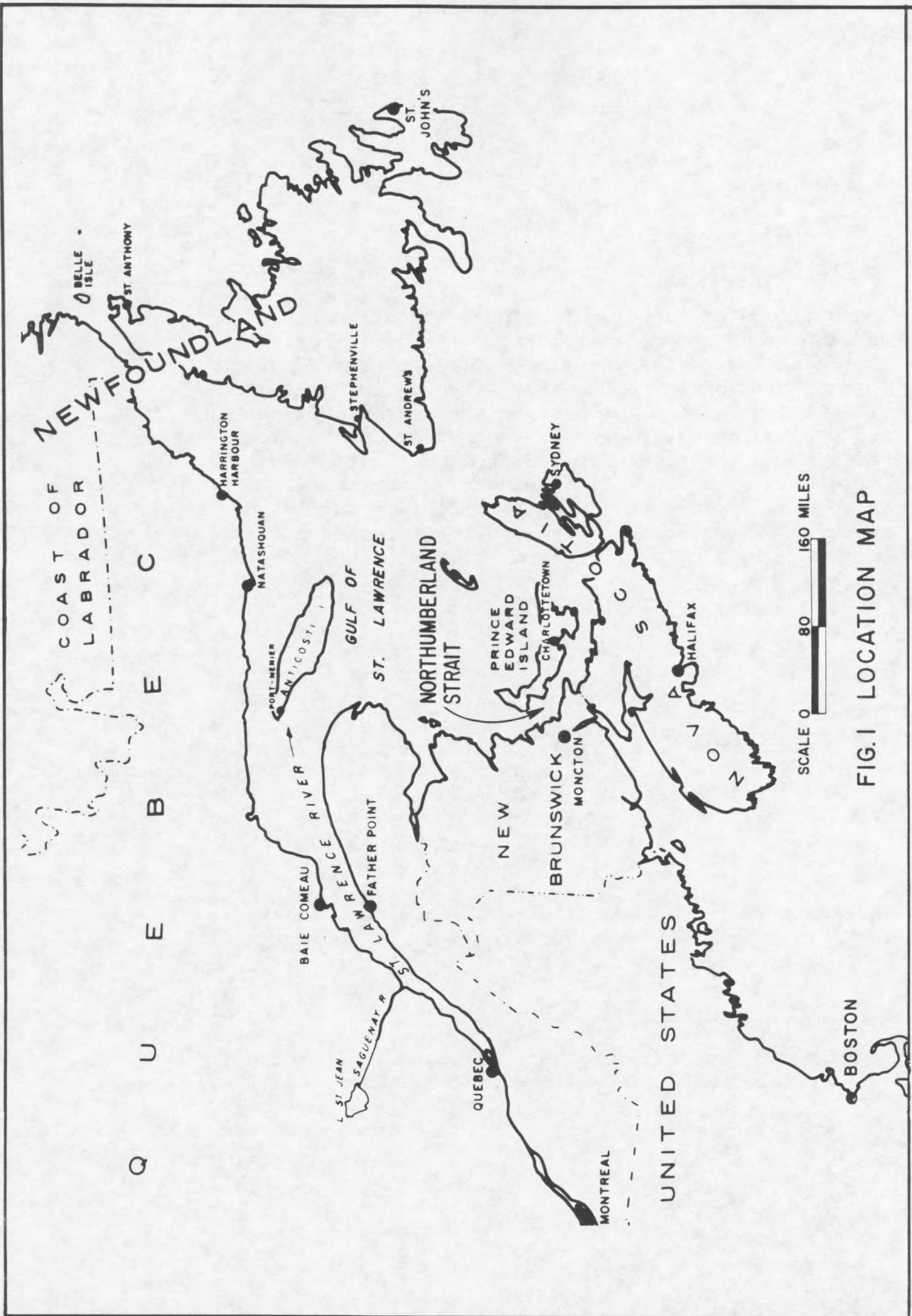


FIG.1 LOCATION MAP

complex tidal regime which results in tidal currents of up to 2 knots at the narrowest point. The Canadian Government is presently considering construction of a permanent crossing of the Strait at this point to replace the existing ferry service.

Although the climate of this area is moderate by Canadian standards, ice conditions in the Northumberland Strait are exceptionally severe. From January to March each year the Strait is so dominated by ice that navigation is restricted almost exclusively to icebreaking vessels. The icebreaking ferry Abegweit has been delayed as long as 13 hours in making the 9 mile crossing.

The reversing tidal currents prevent the formation of a continuous sheet of ice over the Strait. As sheets form they are broken up by the wind and the tides and driven against the shores and stationary ice sheets which do persist in sheltered areas. In the process the ice is extensively remoulded, ridged and thickened so that reliable reports of thicknesses as great as 20 feet are not uncommon. The ice coverage and degree of compaction varies greatly from day to day in response to changing wind conditions. The prevailing westerly wind maintains a long-term net movement of ice to the eastward and results in the introduction of some ice from other parts of the Gulf of St. Lawrence into the Strait from the west. In April the rotting ice fields usually pass out of the Strait at the eastern end. The persistence and severity of ice conditions varies greatly from one season to another depending on temperature, snowfall and wind conditions. Examples of some of the ice forms found in the Strait are shown in Figures 2 to 6.

## 2 - BASIS OF THE MODEL STUDY

The interaction between ice fields made up of individual floes of many shapes and sizes transported by reversing tidal currents and the piers which would support a

FIG. 2 ICE PANS VIEWED FROM THE AIR



FIG. 3 LEADS IN A CONSOLIDATED ICE FIELD





FIG. 4 A FIELD OF REMOULDED ICE AND RIDGES VIEWED FROM THE AIR

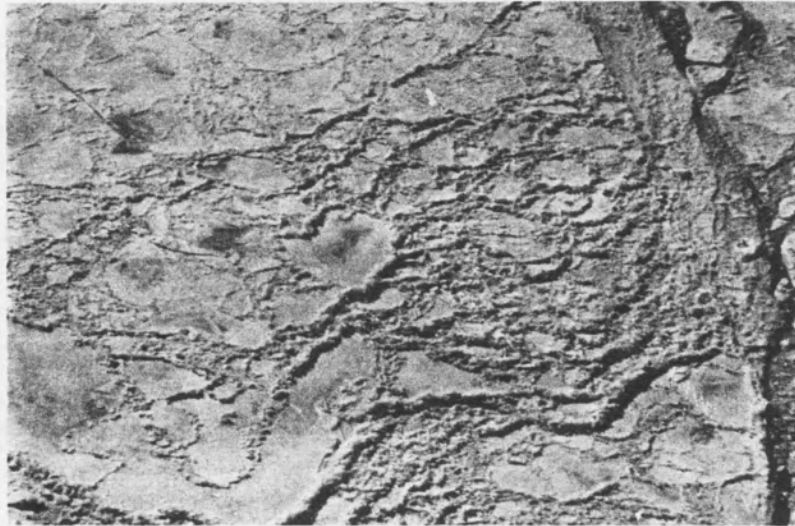


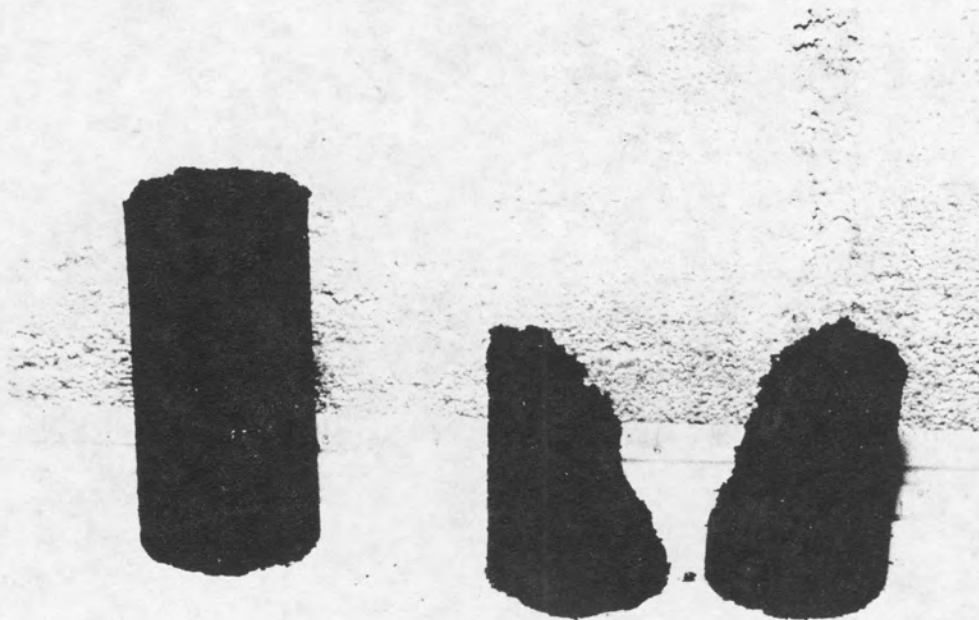
FIG. 5 AN ICE RIDGE VIEWED FROM THE AIR



FIG. 6 AN ICE RIDGE VIEWED FROM THE GROUND



FIG. 7 COMPRESSION TEST SAMPLE OF MODEL ICE



bridge crossing was studied in a 1:60 scale hydraulic model. The model was based on Froude scaling relationships which ensure that accelerations in the model are to the same scale as the acceleration due to gravity. In such a model, water movements and hydraulic forces are to scale and, if a material with the same density as ice is used, the dynamic response of individual ice pieces to these forces is also reproduced.

Because the loads to be withstood by the bridge piers depend on the strength of the ice fields as well as on the hydraulic conditions, an analysis of model scale relationships was made to determine under what conditions the breakup of ice might be reproduced in the model. It was established that if the strength of the material used to represent ice in the model were reproduced to the scale of the hydraulic forces, and other physical properties were related in an appropriate way, the deformation and breakup of the ice and hence the loads on the piers would also be reproduced. With an ideal material forces associated with weight, buoyancy, acceleration, and stress waves in tension, compression and shear, would all be simulated correctly in the model ice. Flexural stress waves would not be reproduced to scale, a factor which would impose limitations at extremely high rates of loading.

The specifications for a material which would comply completely with the desired physical properties at a given scale are very difficult to satisfy. This difficulty is compounded by the fact that the appropriate values of these properties for sea ice under field conditions are not well known. In the material developed for this study only the key parameters of density and strength were systematically controlled. Other properties such as elasticity and friction were less well reproduced and it was necessary to make allowances for them in interpreting the results.

The model material adopted employed paraffin as a binder, oil as a weakening agent, and granulated charcoal as a filler to prevent segregation of the other ingredients. Small amounts of sand were added as required to adjust the density. Figure 7 shows compression test samples of the model material.

The "ice" was black. It had a texture and appearance much like that of paving asphalt. With the 1:60 model scale it was required to have a very low strength; the tensile strength (measured as a modulus of rupture in bending) was 2 psi.

A set of control experiments was carried out to check the ability of this material to reproduce the mode of failure and the failure loads of an ice sheet. A large sheet of model ice floating freely in still water in the model basin was broken by a vertical point load applied at one edge. The pattern of failure was similar to that found analytically by Meyerhof <sup>(1)</sup> for the case of a semi-infinite plate on an elastic foundation. The failure loads were within 20 per cent of those predicted by Meyerhof's theory. These results gave confidence that, in spite of its limitations, the model material would be useful in studying the more complex situation of ice action against piers.

### 3 - THE EXPERIMENTS

The model tests were carried out in a 20-foot wide flume formed as an oval circuit in a 45-foot by 100-foot by

---

(1) "Bearing Capacity of Floating Ice Sheets", A.S.C.E. Engineering Mechanics Division paper 2629, October, 1960.



FIG. 8 AN INSTRUMENTED MODEL PIER

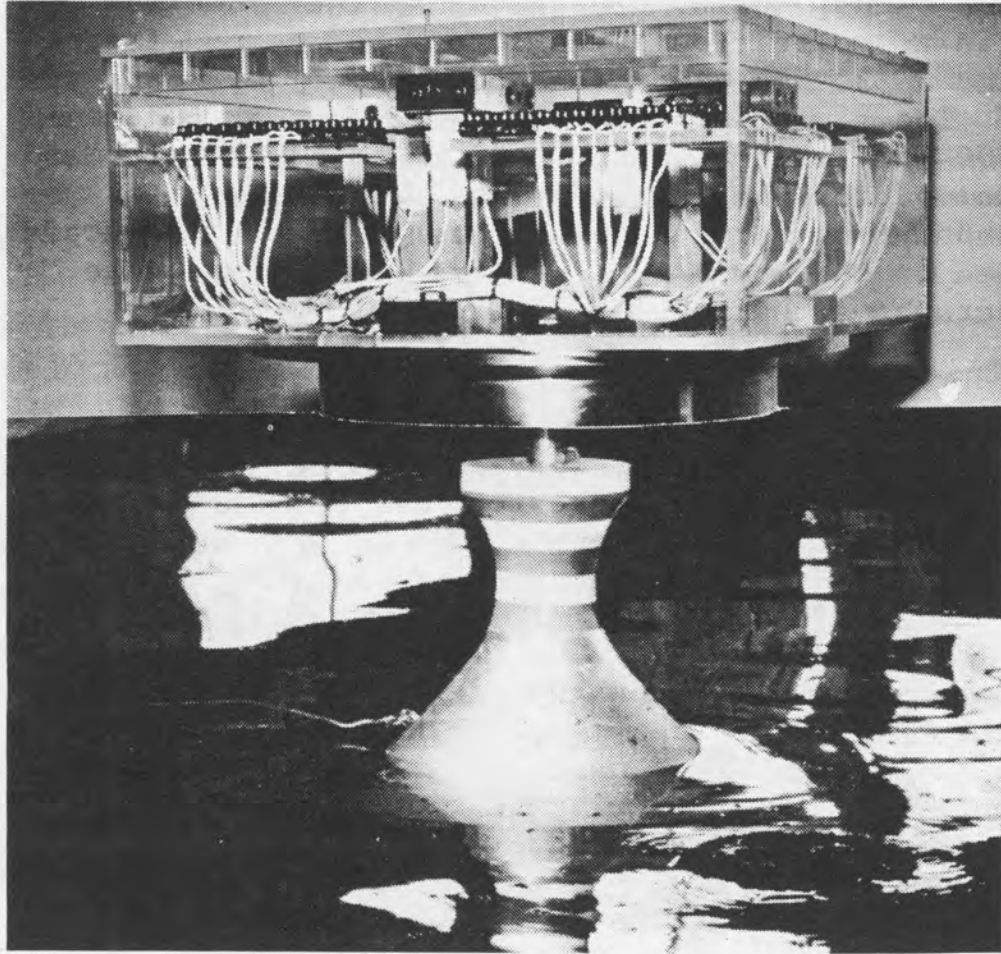
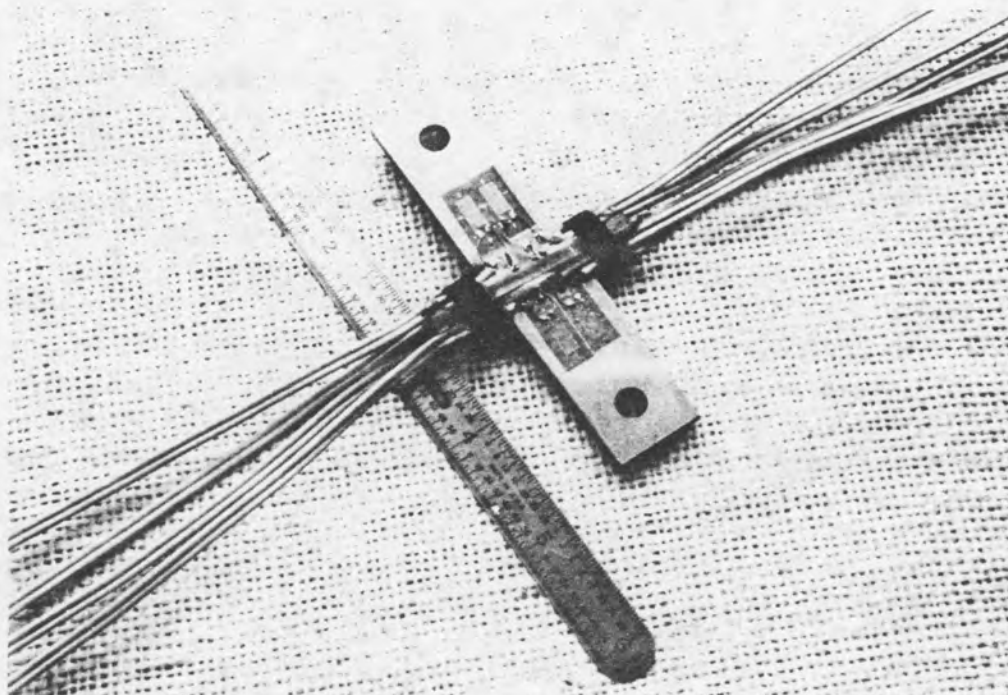


FIG. 9 ONE DYNAMOMETER SENSING ELEMENT

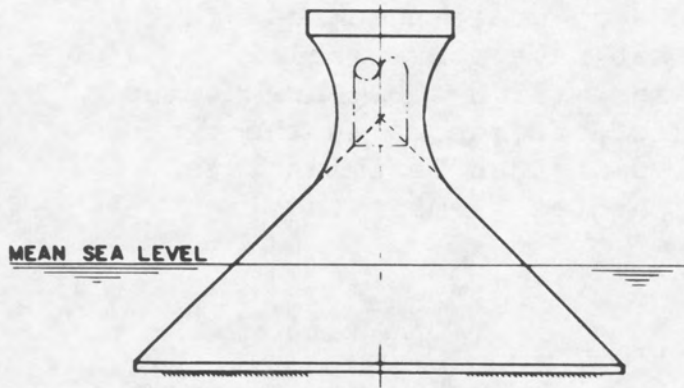


20-inch deep basin. The water in the flume was circulated at velocities up to 1 foot per second (representing approximately 8 feet per second) by means of jets. The flume width was sufficient to accommodate two 500-foot bridge spans. One instrumented pier and two dummy piers were used. The instrumented pier was suspended from a dynamometer which measured the loads applied by the model ice. Figure 8 is a composite photograph of the model pier and dynamometer.

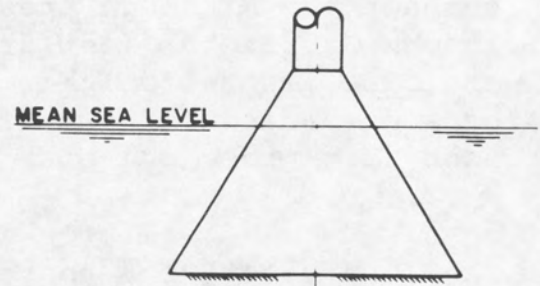
Figure 9 shows one of 12 load cells within the dynamometer. The load cells were arranged in such a way that 5 load components were reported simultaneously. By resolving these components, the resultant force, its point of application and direction were obtained.

The most severe loads on the pier were produced by impacts from large ice fields. The inertia of ice fields in nature is so enormous that sheets of ice in contact with a pier will be cracked and broken apart a number of times without appreciably reducing the rate of advance. A procedure for simulating these circumstances in the model was developed in which a sheet of model ice was allowed to drift with the current in front of a heavily weighted raft until it broke on the instrumented pier. In these tests the record of loads from the dynamometer was supplemented by synchronized slow motion films.

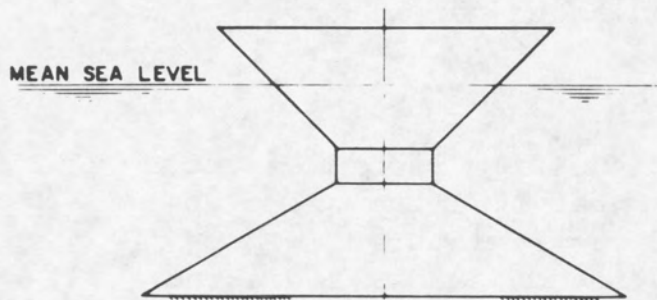
The four pier shapes shown in Figure 10 were tested in the model. The concept behind the sloping faced piers was that reduced loads would be produced by breaking the ice sheets in bending rather than by crushing. Because of the width of the Strait, ice driven by wind can attack the bridge from almost any direction and so only conical and cylindrical shapes were studied. Pier shape 1 was found to result in the most favourable ice loads and so the most extensive tests were carried out on this shape. In all tests using pier shapes 1 and 2 extensive rideup of broken ice pieces on the model structures was observed. The expanding top of pier shape 1



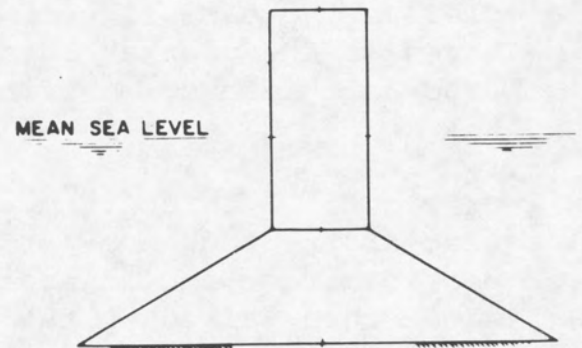
PIER SHAPE 1



PIER SHAPE 2



PIER SHAPE 3



PIER SHAPE 4

FIG.10 ILLUSTRATION OF PIER SHAPES



was developed to limit the height of this rideup. This action is shown on Figure 11.

Load tests were conducted with ice sheets representing thicknesses of up to 15 feet. It has since been established that ice formations of such great thickness in the Northumberland Strait do not have appreciable strengths. Although these cases will not be encountered in the Strait the most dramatic differences in the types of loads imposed on the model piers can be illustrated by a comparison of two different tests employing 15-foot thick ice.

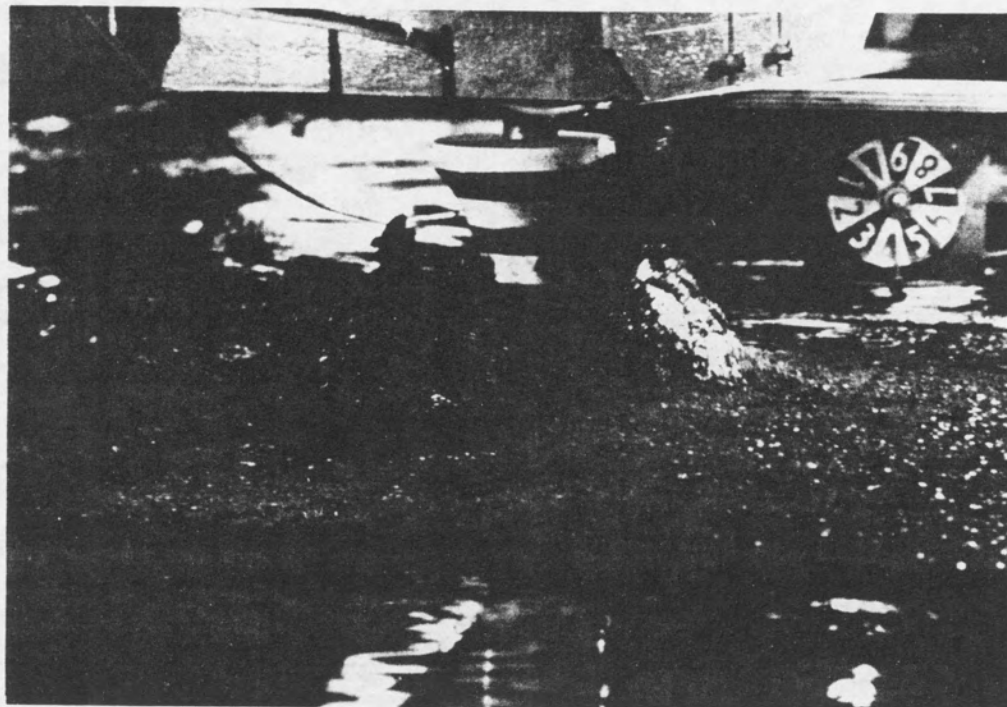
The load record for the case of a wide 15-foot thick ice floe striking pier shape 1 is reproduced on Figure 12. The resultant load on the pier has been computed at model time intervals of 0.2 seconds and these forces are tabulated and shown as vectors on a sketch of the pier on the same figure. The way in which the load moved on the pier as the ice advanced can be traced from this record.

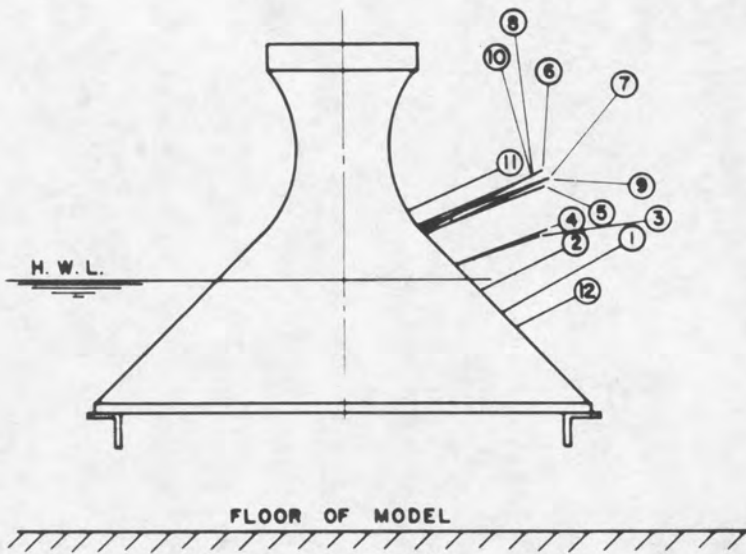
On Figure 13 three frames from the film record of this test are reproduced. At time interval 1 the sheet appeared intact and a large load was registered. The sheet thus failed by the formation of cracks radiating from the point of contact with the pier, and subsequent breakup of fragments along a roughly semicircular line about the pier. At the time, of time interval 9, broken fragments of ice were being deflected at the top of the pier but the load vectors continued to act downward on the pier as was intended for this shape.

Figures 14 and 15 illustrate the load record and frames from the film record of a similar test using a narrow 15-foot thick ice floe. The mode of ice failure in this case was strikingly different. The ice broke initially as a beam some distance from the pier under a much smaller load. Because of the great thickness of the ice, this broken fragment was able to remain intact



FIG. II ICE ACTION ON PIER SHAPE I



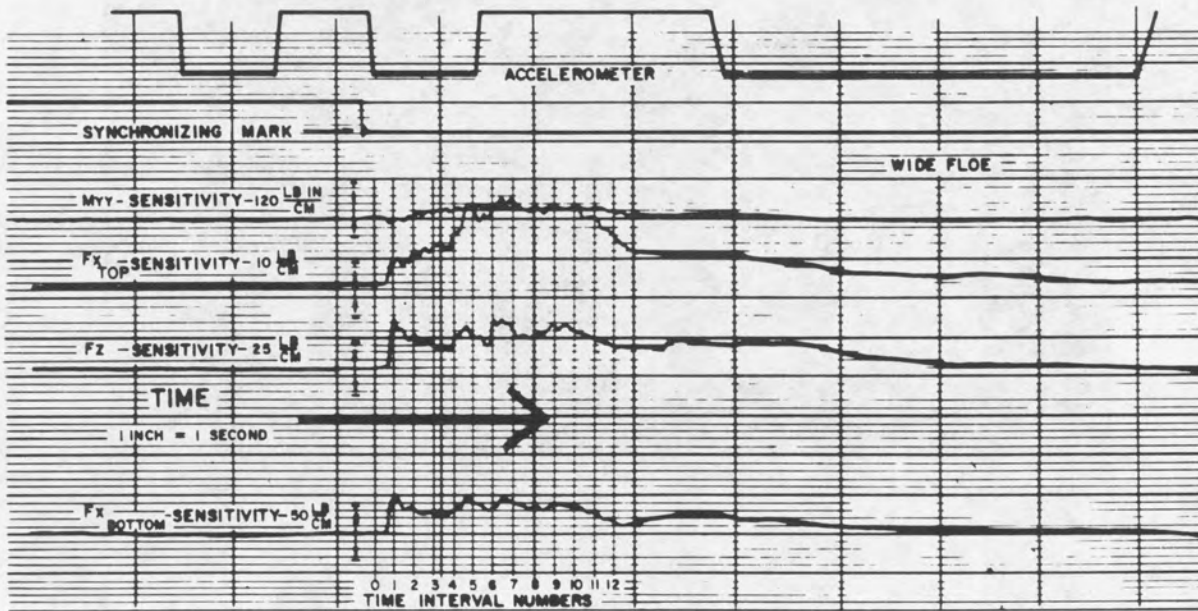


TIME INTERVAL NUMBER	T I M E		RESULTANT	
	MODEL (SEC)	PROTOTYPE (SEC)	MODEL (LB)	PROTOTYPE (KIPS) *
1	0.05	0.388	63.0	13,600
2	0.25	1.94	43.7	9,940
3	0.45	3.49	37.4	8,070
4	0.65	5.04	45.4	9,800
5	0.85	6.59	59.7	12,900
6	1.05	8.14	64.4	13,900
7	1.25	9.69	64.8	14,000
8	1.45	11.24	57.4	12,400
9	1.65	12.79	63.9	13,800
10	1.85	14.34	57.0	12,300
11	2.05	15.89	46.3	10,000
12	2.25	17.44	30.6	6,600

PIER SHAPE I  
TIME SEQUENCE OF RESULTANT LOAD VECTORS

TIME SEQUENCE OF RESULTANT LOADS

\* ICE THICKNESS - 15 FEET  
MODULUS OF RUPTURE 119 PS.I.



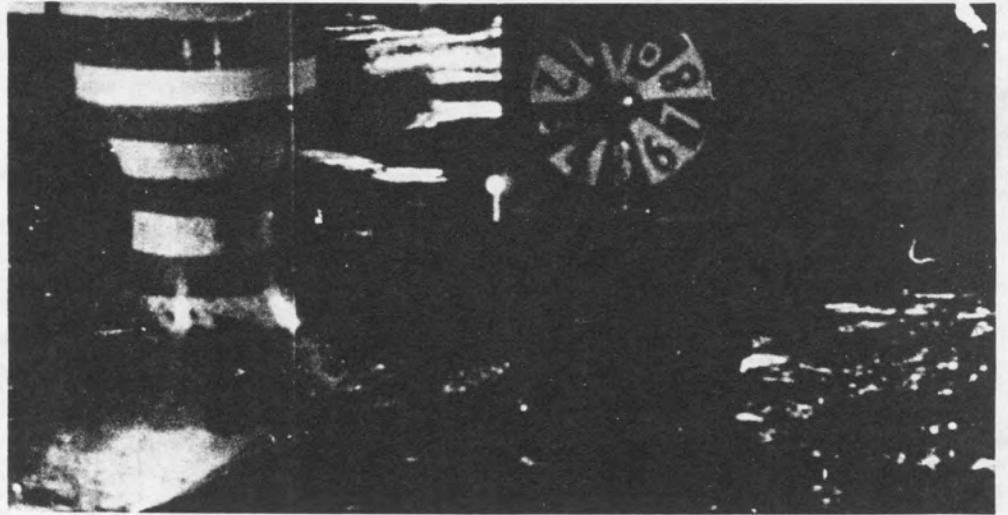
REPRODUCTION OF OSCILLOGRAPH TRACES

FIG.12 LOAD RECORD FOR A WIDE FLOE

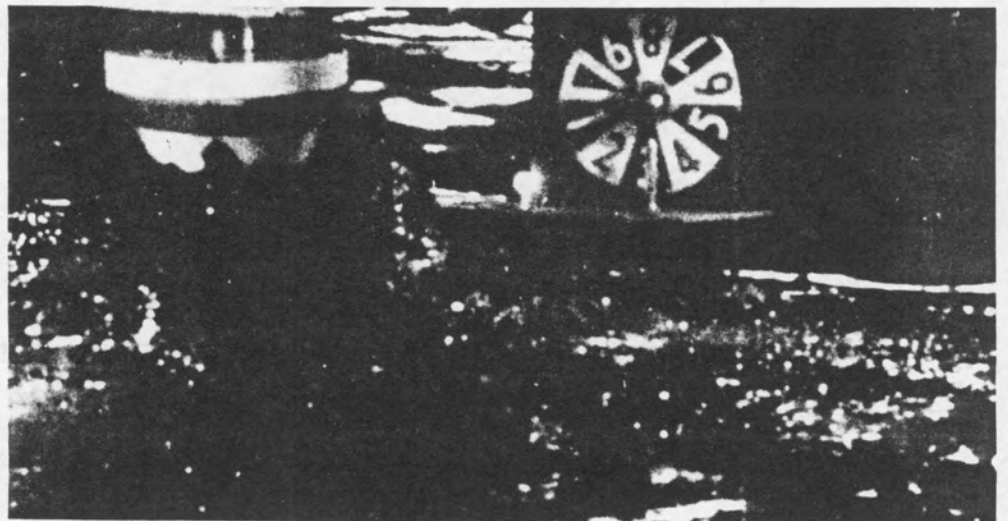
FIG. 13 SEQUENCE OF EVENTS IN A WIDE FLOE TEST

TIME INTERVAL NUMBER

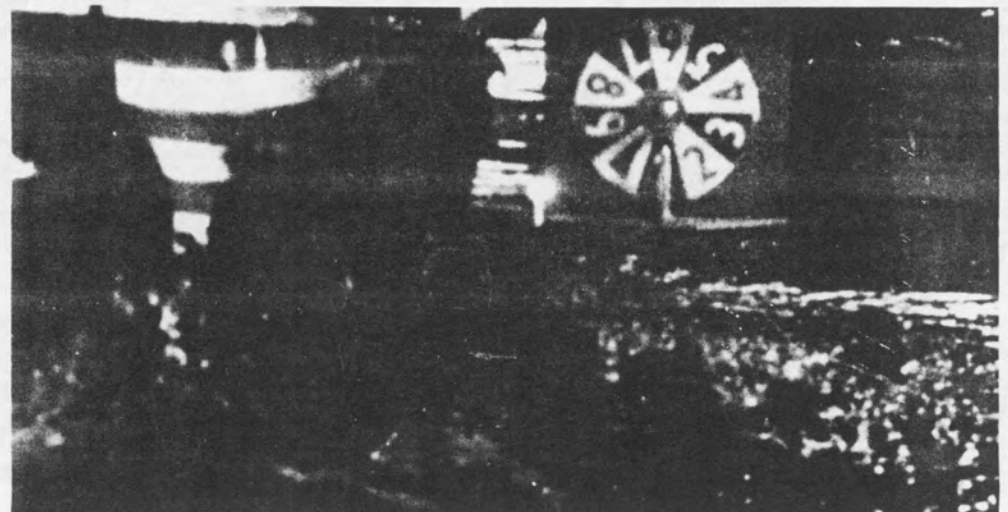
1



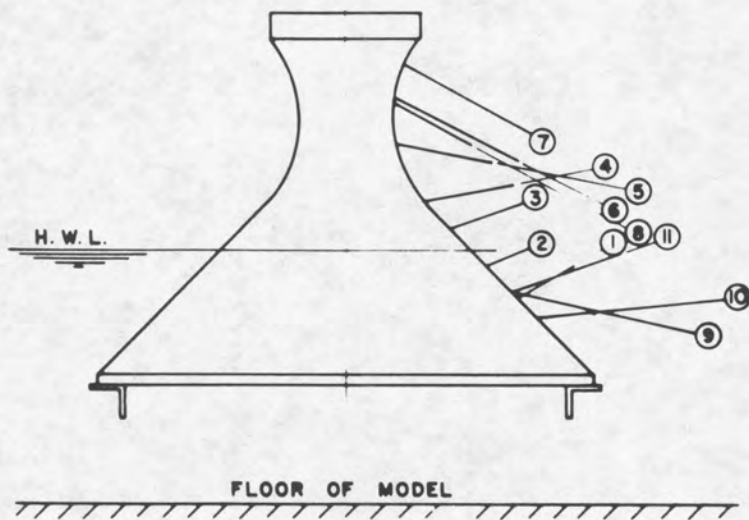
5



9





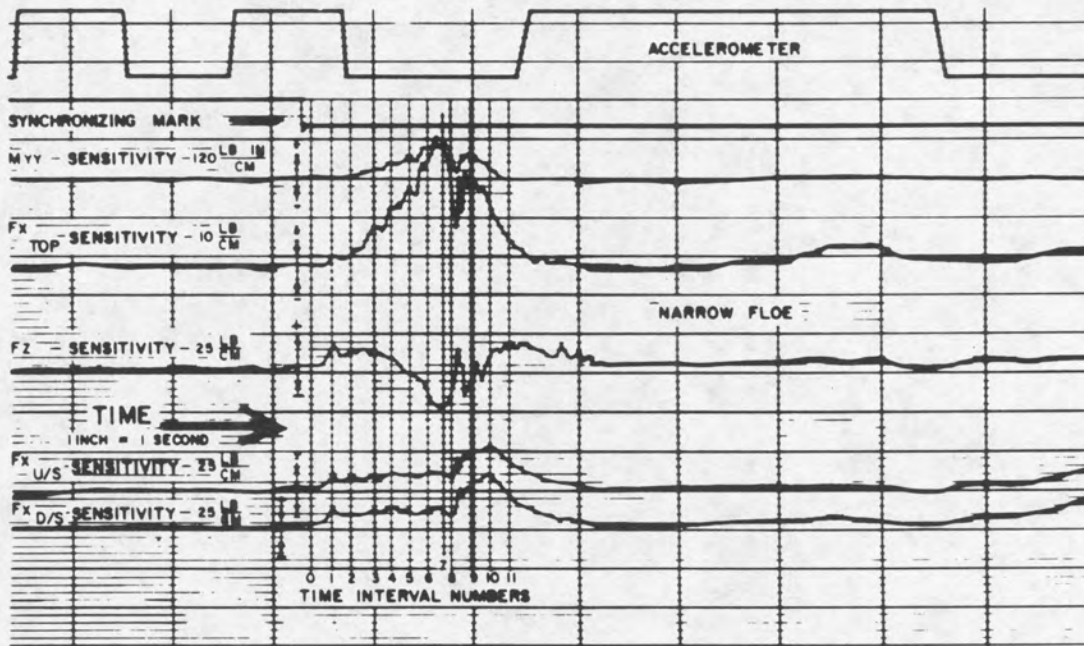


TIME INTERVAL NUMBER	T I M E		RESULTANT	
	MODEL (SEC)	PROTOTYPE (SEC)	MODEL (LB)	PROTOTYPE (KIPS)*
1	0.08	0.62	30.1	6,500
2	0.28	2.17	22.9	4,950
3	0.48	3.72	35.9	7,750
4	0.68	5.27	41.6	9,000
5	0.88	6.82	45.9	9,900
6	1.08	8.37	63.9	13,800
7	1.15	8.92	66.6	14,400
8	1.28	9.92	40.0	8,650
9	1.48	11.47	86.5	18,700
10	1.68	13.02	87.0	18,800
11	1.88	14.57	53.7	11,600

PIER SHAPE I  
TIME SEQUENCE OF RESULTANT LOAD VECTORS

TIME SEQUENCE OF RESULTANT LOADS

\* ICE THICKNESS - 15 FEET  
MODULUS OF RUPTURE 101 PSI



REPRODUCTION OF OSCILLOGRAPH TRACES

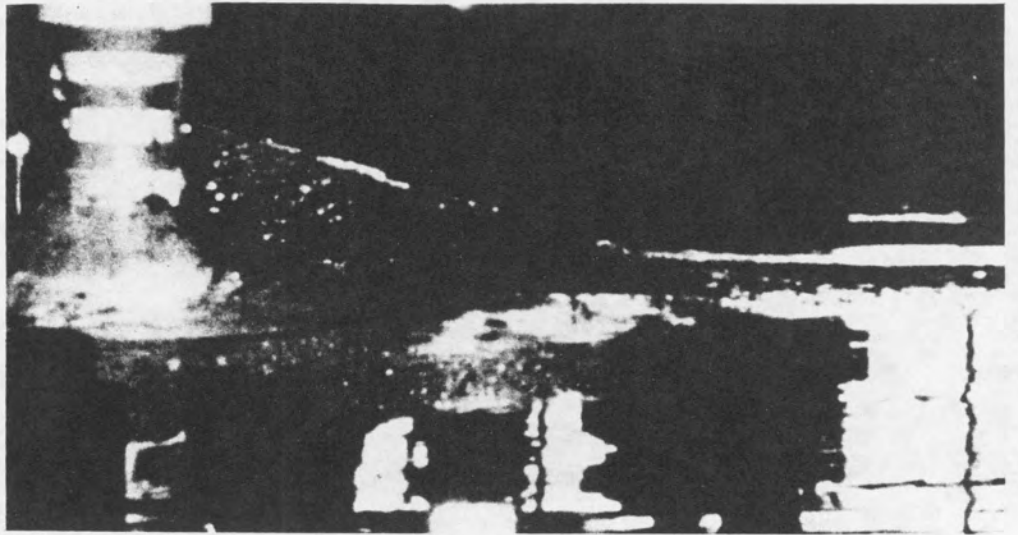
FIG. 14 LOAD SEQUENCE FOR A NARROW FLOE



FIG. 15 SEQUENCE OF EVENTS IN A NARROW FLOE TEST

TIME INTERVAL NUMBER

5



7



10



while it was propelled up the pier until, at time interval 7, it was forced to crush against the pier causing a very large and unfavorable load. This is an instance when the largest (widest) ice sheet would not cause the most severe loading condition. It is emphasized that this type of load does not apply to ice conditions which could be experienced in the Northumberland Strait.

#### 4 - CONCLUSION

It is likely that this type of hybrid model, which has proved to be useful in the study of the action of sea ice on structures, might profitably find application to other problems in which the hydraulic loads are intimately linked with the response they produce. This study has demonstrated that if the mechanical properties of the materials involved are adequately reproduced, quantitative conclusions can be drawn from measurements made on the model.