DEPARTMENT OF ENERGY,MINES AND RESOURCES
MARINE SCIENCES BRANCH

MINISTÈRE DE L'ÉNERGIE DE MINES ET DES RESSOURCES
DIRECTION DES SCIENCES DE LA MER

CANADA

ATLANTIC OCEANOGRAPHIC LABORATORY

BEDFORD INSTITUTE

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WAVES IN HALIFAX HARBOUR

by

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A.O.L. REPORT 68-3

MAY 1968

PROGRAMMED BY

THE CANADIAN COMMITTEE OF OCEANOGRAPHY

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DARTMOUTH, N.S.

REPORT

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Summary

Phenomena which cause ships to oscillate in Halifax Harbour are described and analysed using semi-theoretical principles. It is concluded that the disturbances are caused primarily by ocean waves, with periods of 4.0 to 8.0 seconds, penetrating into the harbour. These waves spread as arc-shaped curves over the harbour and approach the wharves obliquely with the result that many ships oscillate with large response factors. Since the natural periods of oscillation of a wide range of ships are similar to those of the predominant ocean waves, resonance or near resonance motion of the ships will occur. This response is probably the main cause for severe disturbances in the harbour.

Significant design concepts are formulated which will guide the layout of future harbour developments. Recommendations are submitted to improve the layout of the proposed Pier "C". A proposal is included which would permit undisturbed container handling.

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WAVES IN HALIFAX HARBOUR

1.0 INTRODUCTION

Halifax Harbour is one of the most important deep sea harbours on the Canadian Atlantic seaboard (Fig.1). It has all the desirable properties essential for a modern port - good shelter, immediate access to the open Atlantic Ocean, natural depths in excess of 70 feet, moderate tides, a port city and in addition direct access to Bedford Basin, which is more than 200 feet deep and of very large area. Although shoals and islands at the mouth of the inlet provide good protection, ocean waves enter the harbour particularly during winter storms from the south and make loading of ships at the Ocean Terminals difficult and occasionally impossible. A new pier, (Pier "C"), designed to handle container carriers in addition to general cargo carriers is to be constructed between the breakwater at Point Pleasant Park and Pier "B" (see Fig.11).

"Containerization" is a system of transshipment by which cargo is transported within uniform Van-Containers interchangeably by different forms of transportation, the container ship being a waterborne link in this system. The economy of this type of transshipment lies mainly in the standardization of the shipping unit and in the speed of handling. The units are large sealed boxes, weighing 20 to 30 tons. Lowering them into ships must be done speedily, precisely and gently to prevent damage. To achieve this, the movements of the ship during loading or unloading must be kept to a minimum or the movement of the container must be controlled so that no damage occurs through impact.

The Office of the National Harbours Board in Halifax, which is responsible for operating the harbour and constructing the proposed Pier "C", asked the Bedford Institute for advice and suggested that a study be conducted on the problem of swell and its possible prevention.

This report should be considered only as an introduction to the problem and not a comprehensive investigation. The explanations and ideas submitted are preliminary.

2.0 WIND GENERATED WAVES AND OCEAN SWELL

There are many kinds of waves differing greatly in origin, form, velocity and direction approaching the entrance of the inlet to Halifax Harbour. Some are generated directly by the wind. Kinetic energy is transferred to the water surface, which in turn results in waves. The transfer of energy is not steady but probably occurs with random stress fluctuations initiated by atmospheric eddies and velocity fluctuations . The waves thus generated have irregular shapes and periods.

The prevailing winds on the Atlantic Coast are off-shore. The on-shore winds are on the average 5 to 10 m.p.h. weaker than the off-shore winds and less than one half percent of the on-shore winds are in excess of 35 m.p.h. The waves generated by these winds propagate toward the coast but, due to the configuration of the Inlet (see Fig.2), only those from the south and the south-east are able to enter the Inlet. The strength of the winds from these two directions and their durations during the quarterlies are plotted on Fig.4. The analysis is very general and the wind date used were obtained from the wind diagram at Saint John, N.B. The wind data of Shearwater (at the Inlet to Halifax) has not been used because the compilation did not contain the individual durations of the winds

The most common winds are those with velocities of the order of 8 to 15 m.p.h. They occur more frequently in the summer than in the winter and their direction is more often from the south than from the south-east. Winds in excess of 15 to 20 m.p.h. occur more frequently in the winter than in the summer and their direction is more often from the south-east than from the south. The south-easterly direction is also more closely in line with the centre of the channel to Halifax Harbour.

From this data, and Bretschneider's wave forecasting curves, wave periods and heights which might be expected from this sector were calculated. The duration of their occurance during the different months of the year is shown in Fig.5. While these curves indicate only general trends, they show that waves with periods of 4.5 to 5.5 seconds should be present an average of 20 to 50 hours per month while 5.5. to 7 second waves should occur more frequently during the summer than during the winter season. Smaller waves, i.e., waves with heights of about 2 to 3 feet, are infrequent during the winter but frequent in the summer with a peak duration of 160 hours in July. Waves of 4 to 5 feet height are quite evenly distributed throughout the year but larger waves of 6 to 7 feet height normally occur only from October to March. It appears therefore that these waves, which have periods of 6 to 7 seconds, are wind generated and cause the major disturbances in the harbour during the winter season.

Waves from exceptionally severe and long lasting storm fields in the Atlantic are not included in the graph. Their periods may be up to 14 seconds and their heights in excess of 35 feet. However, such storms occur so infrequently that the disturbances they may cause in the harbour have not been considered.

Another type of wave present in the ocean is that referred to as swell. As wind generated waves move out from under the storms which produce them, their crests become more rounded, their slope less steep, and they approach a sine wave in form. They propagate as groups with similar periods and heights; their usual period in the Atlantic Ocean being in the range of 6 to 14 seconds. These waves can travel over long distances with little loss of energy. When the larger waves, with periods in excess of 10 seconds, approach the Continental Shelf, where the depth of the water is less than half of their length, they "touch" bottom and undergo changes in length and direction.

In this process the wave fronts tend to become parallel to the underwater land contours and thus to the coast line. Since the inlet to Halifax Harbour is located normal to the coast, it appears that many of the long period swell which propagate over the Continental Shelf will approach Halifax Inlet directly. Swell with periods of less than 8 seconds are undisturbed by the Shelf since their half wave lengths are less than the depths of the water in this area and can therefore approach the Inlet from any direction.

From this brief review of the potential wave pattern at the entrance to Halifax Inlet, it appears that the prevailing wave form is probably a composite wave consisting of a swell or a set of swell which have, depending on the on-shore wind condition, wind generated waves of approximately 4.5 to 7 second periods superimposed on them. If the wind generated waves have periods of 6 to 7 seconds and wave heights of 6 to 7 feet, they will dominate the wave pattern.

3.0 WAVE PROPAGATION INTO HALIFAX HARBOUR

As described above, the waves at the entrance to Halifax Inlet are the result of combining a number of generally sinusoidal wave trains; each having its own characteristic period, length, height and direction. In the analysis of the wave propagation, wave trains having periods of 14 seconds, 10 seconds and 6 seconds were considered individually. The 14 second and 10 second waves represent the long and intermediate swell while the 6 second waves represent the short period swell and the dominant wind-generated waves. It was assumed that the waves were sinusoidal although it is known that this does not apply to wind-generated waves.

Halifax Harbour is funnel-shaped, with shoals and islands so located that waves from the Atlantic Ocean can enter the harbour directly only through the channel between McNabs Island and the west shore. As shown on Fig.2, the channel is 4000 to 4500 feet wide with its narrowest section between the outer end of Maugher's Beach on McNabs Island and York Redoubt on the mainland. The centre line of this channel was chosen as the direction of approach for the waves entering from the ocean. Waves approaching from other directions were investigated, but it was soon found that there was little chance of their entering the harbour.

It has been mentioned briefly that waves propagating into shallow water are modified through refraction. As different segments of the wave travel in different depths, those in shallowest water move slowest. Thus crests bend and the wave fronts become progressively curved. In a generally deep section, such as in the channel to the harbour, the waves tend to diverge, and, conversely, over the shoals and ridges they tend to converge. The graphical representation of the changes in direction of a wave front is called a refraction diagram.

Refraction diagrams were plotted for Halifax Inlet and Halifax Harbour for the three representative wave periods, as shown on Figures 6, 7, 8 and Figures 9, 10 and 11 respectively. Huygens wave propagation principle was used which is based on assuming each point on the wave front to be a point source of circular waves and then considering the new wave front to be the envelope of these circular fronts.

The 14 second and 10 second waves with half wave lengths of 500 feet and 250 feet respectively are influenced by the bottom before entering the Inlet where depths of the order of 180 feet prevail. However, this modification to the direction of the wave fronts was considered insignificant and straight wave fronts off Chebucto Head were considered. The 6 second waves with a half wave length of 90 feet begin to be influenced by the bottom within the Inlet.

The configuration of the wave fronts demonstrates (see Figures 6, 7 and 8) the effect of the deep channel, the ridges, shoals and the shore. Portuguese Shoal, Rock Head Shoal and finally Thrumcap Shoal in front of McNabs Island progressively slow the advancing wave fronts until they nearly envelope the south tip of the island. On both sides the wave fronts continue, becoming increasingly curved as the wave progresses. As expected, the wave fronts of the 6 second wave are curved least.

These features can be demonstrated more clearly with orthogonals, which are rays normal to the wave fronts showing the direction of their motion. In addition, their spacing indicates the distribution of wave energy and the relative amount reaching various points of the Inlet.

The orthogonals on Figures 6, 7 and 8 demonstrate clearly that the major part of the wave energy is refracted toward the south tip of McNabs

Island, where the waves break on the shallow beaches. The orthogonals of the 14 and 10 second waves are bent more strongly toward the island than those of the 6-second waves.

The portion of the wave front, which progresses through the channel between McNabs Island and the coast, is shown shaded on the diagrams. From these, it can be seen that very little of the 14-second and the 10-second wave progresses through this section, suggesting that most of their energy is diverted to other areas. In contrast, a relatively large part of the 6-second wave front appears to propagate through this section.

It can be assumed therefore, that waves with periods longer than 8 to 9 seconds,which approach and enter the Inlet to Halifax Harbour, are refracted by the topography of the Inlet so that most of their energy is expended through breaking on the shoals and shores, while waves with periods less than 8 seconds appear to have increasingly less difficulty in entering the inner region of the Inlet.

For this area another set of refraction diagrams was constructed to a larger scale (Figures 9, 10 and 11). Although the previous diagrams showed that little energy of the long period waves would probably reach this section, refraction diagrams for these waves were included to see how they would behave should they enter the harbour.

The initial wave fronts in diagrams 9, 10 and 11 were obtained from Figures 6, 7 and 8 respectively. The new orthogonals are not an extension of the orthogonals of Figures 6, 7 and 8. They have been constructed on the assumption that the wave energy is equally distributed along the curved wave front. They are added mainly to indicate the wave direction.

Again, the 14 and 10 second waves are strongly refracted toward the shore of McNabs Island and even more strongly toward Point Pleasant Shoal. The shaded areas show that, in this part of the Inlet, only a small portion of the energy of these waves would be able to enter the harbour area. In contrast the 6 second waves show little dispersion and most of the energy which propagates through the channel between McNabs Island and the coast enters the harbour.

In summary, the wave diagrams indicate that the swell and wind waves of greatest importance to Halifax Harbour, are those with periods in the neighborhood of 6 seconds. As soon as the 6 second wave passes through the opening between Ives Point on McNabs Island and Point Pleasant on the south tip of Halifax Peninsula, it spreads over the harbour area as shown in Fig. 11 approaching the wharves of Imperoyal directly and the Ocean Terminals obliquely.

It may be seen that the waves converge toward the Ocean Terminals and Point Pleasant Breakwater. Removing the Middle Ground Ridge which causes this convergence would change this situation and would permit this part of the wave to enter the inner area of the harbour. Evidently, the location and layout of Pleasant Park Breakwater were well chosen.

A second type of wind-generated waves can be present; those created locally by winds over the harbour. Excluding the direction through the entrance channel from the open sea, the maximum fetch length is from Shearwater, a distance of approximately two miles. According to Bretschneider's wave forecasting curves, a 35 M.P.H. wind from this direction would create waves at the Ocean Terminals having periods of approximately 3 seconds and heights of the order of 2 to 3 feet. This was verified by observations from Pier "B" on September 24, 1967 when this wind condition prevailed. These waves were superimposed on an ocean swell of 5 to 6 seconds, which was difficult to observe on the highly agitated water surface.

4.0 EFFECT OF WAVES IN THE HARBOUR

As shown in Chapter 3, the most disturbing waves which enter the harbour from the ocean are probably those with periods in the 5 to 7 seconds range. Their lengths can be derived from the equation :

$$\lambda = \frac{gT^2}{2\pi} \tanh \frac{2\pi d}{\lambda} \qquad (1)$$

where λ is the wave length, g the earth's gravitational acceleration, T the period of the wave and d the depth of the water.

For waves with periods of 5 to 7 seconds in water 42 feet deep, (the depth in the existing basins of Ocean Terminals) and 60 feet deep (the depth at proposed Pier "C"), the lengths are between 125 and 211 feet and between 125 and 233 feet respectively. For a 6-second wave, representative of this group, the length is approximately 170 feet.

Evidently waves of these characteristics, if regular and in trains, should create little pitching motion in ships longer than 300 feet, i.e. which are larger than approximately 4000 tons, and are moored normal to the wave crests. However, the same waves approaching sideward will impart rolling and pitching motions to a wide range of ship sizes; thus the direction of the fronts of these predominant waves should determine the layout of berths in the harbour. Where possible the wharves should be arranged so that vessels are moored facing the approaching waves, suggesting that the berthing facilities of Imperoyal be normal to the shore while these for the Ocean Terminals be parallel or slightly oblique to the shore; the opposite of the present layout (see Fig.11). While little can be done to rectify the present situation, it is recommended that the direction of the approaching waves be taken into consideration in designing future harbour extensions and developments.

4.1 Standing Waves and Resonance.

Waves are reflected from vertical walls with little loss of energy; the incident and the reflected waves producing a pattern of standing waves. The amplitude of these waves is twice the amplitude of the incident waves. In Coastal Engineering the term Clapotis is frequently used to designate this type of wave.

Many patterns and forms of standing waves are possible in the basins of the Ocean Terminals. The surface may oscillate longitudinally, transversely or diagonally. The oscillations may also increase in amplitude with a very small supply of energy from outside the basins provided this energy or "excitation" is supplied at one of the natural frequences at which the basins oscillate. The problem is then essentially one of resonance. Longitudinally the basins are closed at the landward end and open at the seaward end while transversely they are closed at both sides. The characteristic periods of resonance for both directions can be derived from "Merian's formula" as follows:

For the longitudinal direction

$$T_m = \frac{4 \cdot l}{m \cdot c}; \; m = 1, 3, 5, 7 \cdots \qquad (2)$$

while for the transverse direction,

$$T = \frac{2 \cdot W}{n \cdot c}; \; n = 1, 2, 3, 4 \cdots \qquad (3)$$

In these equations l is the length and W the width of the basin and m and n are the modes of oscillation in the longitudinal and transverse directions respectively. The wave celerity c can be obtained from the equation:

$$c = \sqrt{\frac{g\lambda}{2\pi} \tanh \frac{2\pi d}{\lambda}} \qquad (4)$$

where λ is the wave length and d the depth of the water in the basin.

The natural periods of oscillation in the basins at the Ocean Terminals which are 1,250 feet long, 360 feet wide, 42 feet deep and open at one end, are listed in the following tables.

Longitudinally.

Mode	1.	2.	3.	4	5.	6.	7.	8
m	1	3	5	7	9	11	13	15
T_m(sec)	136	46	28	20	16	13.1	11.3	10.0

Transversely

Mode	1.	2.	3.	4.	5.	6.	7.
m	1	2	3	4	5	6	7
T_n(sec)	20.2	10.6	7.7	6.3	5.5	4.9	4.5

Obviously, resonant conditions in the longitudinal direction for periods less than 8 to 10 seconds can only be achieved by higher modes of oscillation than those listed. The wave lengths of these oscillations are less than 300 feet and ships larger than 10,000 tons should be little disturbed as shown on Fig.12.

In the transverse direction conditions are quite different and disturbing resonant oscillations occur (Fig.13) on the second, third, fourth, fifth and sixth modes with periods ranging from 10.6 to 4.9

seconds. This indicates that ships even with very large beam (this includes 100,000 ton vessels) could be brought into rolling motion by any of these oscillations.

It may be concluded, therefore, that resonance in the transverse direction may play an important role in the formation of standing waves in the basins and in ship motions.

4.2 Oblique Reflection.

As indicated on the refraction diagrams and in Fig.14 waves usually approach the Ocean Terminals obliquely. Under these circumstances the waves reflect at an angle which is equal to the angle of incidence. The surface pattern of such a wave field is not parallel with the pier walls but the initial and reflected waves form oblique, criss-cross, pattern. The amplitude of the waves along the walls will still be twice that of the incident waves but the apparent wave length along the wall is increased to:

$$\lambda_\alpha = \frac{\lambda}{\sin.\alpha} \qquad (5)$$

Where λ_α is the apparent wave length along the wall, λ is the length of the incident wave and α is the angle of the crest of the incident wave with the wall.

The apparent lengths of a 6-second wave at varying angles of incidence are plotted on Fig.15. For a perpendicular approach, or an angle of incidence of zero degrees, the apparent wave length approaches infinity which means that the wave crests are parallel with the wall, while, for an angle of 90 degrees, the wave crests are normal to the wall and the apparent wave length is the same as the real wave length or 165 feet for a 6-second wave in 42 feet deep water. For angles of incidence of 15 or 10 degrees the apparent wave lengths are approximately 650 feet and 1,000 feet respectively. This would explain the pitching motion of large ships moored on the south side of Pier "B".

4.3 Oscillatory Motions of Ships.

Under the action of waves, ships may pitch, roll, heave or move with a combination of these motions. Pitching is the longitudinal oscillation about a transverse axis, rolling the transverse oscillation about a longitudinal axis and heaving the vertical rising and falling of ships. Pitching occurs in waves approaching from almost any direction while rolling primarily occurs when the waves approach broadside. According to Rossel and Chapman (1939), pitching does not cause rolling but rolling generally induces pitching. Heaving may be caused by the same conditions that set up either rolling or pitching, or both. It is caused by buoyancy lost or gained amidships when the wave moves along the ship.

The magnitude of these motions depends primarily upon the size of the waves and their period with respect to the natural frequencies of the ship's oscillations. The interplay between these forces and factors is complex and will be described only to the extent necessary for understanding the behavior of the vessels moored at the wharves.

The principle properties which characterize the size of a wave are its length and height. In starting an oscillation of a moored ship, the wave length is of greater importance in the initial stages than the wave height. Only after an oscillation has been initiated will the wave height influence the magnitude of the oscillation.

A ship begins to respond to the disturbing forces of waves at a definite ratio of wave length to ship length and increases its response to a maximum as the wave length increases. This is demonstrated on Fig.17 (Abkowitz and Vassilopoulos, 1966) which shows the pitch and heave response of a cargo ship in terms of the ratio between the length of the wave and the length of the ship; the maximum response occuring when this ratio is about 1.0. The response of a ship decreases very rapidly as the wave length decreases; being only about one tenth of its maximum when the wave length is halved.

From the relationship that maximum response occurs when the wave length and ship length are equal, a graph (Fig.18) was derived for Pier "B" which shows the lower limit where ships have maximum response for given wave periods. The graph indicates that maximum response occurs with 5-second waves for ships of about 10,000 tons and with 7-second waves for ships of about 35,000 tons. If 5-second waves prevail, the response factor which is approximately 1.0 for a 10,000 ton ship decreases to 0.25 for a 20,000 ton ship and to less than 0.1 for a 45 000 ton ship.

Therefore, it appears that many vessels at at the Ocean Terminals oscillate with maximum or near maximum response to the waves. Even vessels as large as 50,000 tons may have large response factors because of the oblique layout of the wharves to the predominent 5 to 7-second waves. The effect of waves on the pitching and heaving motions of ships at the Ocean Terminals would likely apply to the rolling motion of ships at the wharves at Imperoyal, however, data to verify this were not available.

Another important factor in the interaction between waves and ships is the natural periods of oscillation of the ships compared with the period of the waves When these periods are equal resonance occurs with the effect shown on Fig.19 (Bell and Walker 1966) which illustrates the results of rolling tests on a model of CNAV "Endeavour". The model was tested on a two-degree wave slope. For waves with periods shorter than 7-seconds and longer than 11-seconds, the roll angle was smaller than 4-degrees but between 7 and 11 seconds the roll angle increased to nearly ten times the wave slope. Full resonance conditions existed at a period of 8.2 seconds. This indicates that if the wave period approaches the natural period of oscillation of the ship severe motions may occur.

From analytical studies and experimental data, first approximations of the probable periods of the principal oscillatory motions of pitching, rolling and heaving, as they would occur in still water following an initial impressed displacement or elevation, can be obtained. According to Saunders (1965) these periods can be derived from the following equations:

Natural pitching period: $$T_P = \frac{2\pi K_{yy}}{\sqrt{g\overline{GM}_L}} \qquad (6)$$

Natural rolling period: $$T_R = \frac{2\pi K_{xx}}{\sqrt{g\overline{GM}_T}} \qquad (7)$$

Natural heaving period: $$T_H = 2\pi\sqrt{\frac{D}{g}} \qquad (8)$$

In these equations K_{yy} and K_{xx} are the radii of gyration of the ship about the transverse and longitudinal axes respectively, $\overline{GM}_L$ and $\overline{GM}_T$ the longitudinal and transverse metacentric heights and D the mean draft of the underwater body. From the analysis of a number of vessels the following approximate values for these factors were derived: $K_{yy} = 0.24L$; K_{xx} between 0.32B and 0.37B for fully loaded and between 0.375B and 0.43B for empty condition; $\overline{GM}_L$ is generally 1.1L, but $\overline{GM}_T$ is respectively 0.05B and 0.11B for cargo vessels loaded and empty and 0.10B and 0.41B for bulk and oil carriers loaded and empty. By substituting these values in equations 6, 7 and 8, and evaluating for various values of L, B and D as given in Fig.20, the natural periods of pitching, rolling and heaving were calculated; these are plotted against the size of the vessels in Fig.21. Because of the simplifications applied it must be understood that these results indicate only general trends.

It can be seen immediately that the natural periods of oscillation for pitching and heaving for all ships, cargo or bulk/oil, range from 3.5 to 5.5 seconds when empty and from 4 to 8 seconds fully loaded. A 20,000 ton cargo ship freely pitches with a period of 5 seconds when empty and with a period of 6 seconds when loaded. Since the periods of the waves which propagate into Halifax Harbour are primarily in this range, it must be concluded that waves and ships in the harbour are quite frequently in resonant or near resonant conditions. This is probably the major reason for the large and sometimes violent pitching and heaving oscillations experienced by ships at the Ocean Terminals.

As shown also on Fig.21, the rolling period for both cargo ships and bulk oil carriers is approximately twice the pitching period. The Ocean Terminals are cargo and passenger terminals and the proposed Pier "C" is to be used for "Container" and general cargo handling. The natural rolling period for vessels of this type would be generally longer than 9 seconds for vessels of 5,000 tons and longer than 12 seconds for ships in excess of 30,000 tons. Since the periods of the predominant ocean waves are in the neighbourhood of 4 to 8 seconds, rolling should be a minor problem to ships at the Ocean Terminals. Furthermore, as shown on Fig 14, the waves do not approach the wharves directly and thus do not provide conditions for rolling to occur, except along the wharves of SHED 20, 21 and 22. As can be seen readily on Fig.11, part of the ocean waves which arrive at the shore and loading facilities of Imperoyal might be reflected and approach the east side of the Ocean Terminals directly. Although these waves would be small, they might be sufficient to induce relatively high rolling on cargo vessels smaller than 10,000 tons under resonant conditions.

At the Imperoyal wharves the conditions are different. Fully loaded tankers should roll, with periods from 9 to 14 seconds and with periods from 7 to 11 seconds when empty. A 20,000 ton tanker arriving at the wharf fully loaded has a natural rolling period of about 11 seconds, but while unloading its natural period decreases until it reaches about 8.5 seconds when empty. Thus, tankers larger than 10,000 tons should be disturbed little by waves entering the harbour if they are fully loaded but their natural rolling period decreases when their load is discharged and approaches the natural harbour wave period. Because rolling induces pitching, some pitching motion must also be anticipated.

From this analysis it can be expected that mooring along the wharves of Imperoyal and discharging oil must, on occasions, be difficult due to the rolling and pitching of the vessels. A change in the layout of the wharves with respect to the approaching waves could stop rolling but not pitching A reduction in pitching could be achieved only if the angle between the waves and wharves could be increased.

Thus it can be concluded, that the motion of a ship is controlled primarily by two harmonic oscillations, that of the wave and that of the natural oscillation of the ship. The dynamic force, resulting from the vessel being moored to the wharf, has not been taken into consideration, though it is known that it can impede the motion.

As has been discussed, regular wave trains are probably the exception rather than the rule in Halifax Harbour, however, they may be present for several days during a year. When they do exist, a ship will oscillate with approximately the same period as that of the wave, though the magnitude of the movement will depend on the natural period of the ship. If the vessel's period is smaller than the period of the wave, the ship will follow the effective wave slope but if the ship's period is longer than that of the wave, its motion will be small in comparison to the wave slope. In cases when the ship's period is similar to that of the wave period, resonant conditions, as already described, occur. The three cases are demonstrated on Fig. 19 where the roll angles of the model of CNAV

"ENDEAVOUR" are shown. For wave periods longer than 12 seconds, the roll angle assumed the slope of the wave while for periods smaller than 7 seconds, the roll angle quickly declined to very small values. Between these periods, near resonance and resonance with very large angles, occurred.

Under normal sea conditions, waves which enter the harbour, have a variety of periods and wave heights, causing the surface of the water to fluctuate in a complex way. Inspite of this, ships in the harbour oscillate quite regularly and with relatively uniform periods. The initial impulse for the motion seems to be supplied by larger forces occurring at random intervals. The action of these forces is demonstrated by sudden and large movements of the ship. Between the "impulses", the ship oscillates with fairly constant periods and with decreasing amplitudes.

There may be several explanations for this behavior. The most rational one is that the composite wave pattern contains waves with periods which are similar to those of the ship's own frequency, thus causing, when they occur, resonance or near resonance oscillations of the ship. These types of waves must exist although they have not been observed or measured. A similar effect results from surges which are solidary types of waves and which have been observed to be present in the harbour. These surges, probably caused by the interference of wind and swell waves, appear to act also as impulse forces. They occurred at quite regular intervals. Between these "excitations" the vessels appear to oscillate primarily under their own natural frequencies.

Finally, it may be concluded that the disturbing oscillations in Halifax Harbour are caused by resonance of the ships in response to the predominant harbour wave.

4.4 Observation of Ship Oscillations.

On a number of occasions, during the fall of 1967, the oscillation of ships was observed at the Ocean Terminals. The periods were always between 4 and 7.5 seconds, although swells were present sometimes at the entrance to the inlet with periods of 10 to 13 seconds. This seems to support the conclusion, derived from the wave diagrams, that the longer period waves are filtered out by refraction.

During a storm from the south on October 18, 1967, four vessels were moored at the Ocean Terminals. Their location, size and movement are shown on Fig. 22. All were pitching with periods from 5 to 7 seconds and the smaller vessels in addition were heaving. Some slight sideward swaying could also be detected.

Through observations from the ends of the piers it was verified that wave fronts, similar to those derived from refraction diagrams, were present on the highly agitated surface of the harbour and were approaching Pier "B" at a small angle. An angle of 16 degrees - the angle which was obtained from the refraction diagram for a 6 second wave - increases the apparent wave length along the wall to more than 600 feet. The ship "MAMFE", which was moored to Pier "B" is approximately 470 feet long and the ratio λ/L of 1.3 indicates that the vessel probably responded fully to the wave slope. The natural periods of pitch and heave according to Fig. 21 were between 4.5 and.5 seconds. The longer periods of the observed oscillations - 6 to 7 seconds - were therefore probably forces oscillations imposed by the wave surges while the smaller oscillations between the surges were probably at the ship's natural frequency. The vertical movements of the bow - an average of 5 to 7 feet but occasionally 8 to 9 feet - were large compared with the height of the waves but they were not steady enough to indicate that they were due to resonant oscillations of the ship.

Similar motions, though slightly smaller, were observed on "HOEGH DENE", a 20,000 ton freighter, the small vessel "CALM" and the fishing trawler "CAPE ALERT". Although these vessels were moored in well protected areas, they exhibited consistent oscillations with periods similar to those of the "MAMFE" indicating that the same type of surges existed in the basins as at the south side of Pier "B".

The oscillations of the water surface, although smaller in the basins than outside, were relatively large and had the appearance of standing waves. They presumably were caused by reflections from the outer south sides of the wharves and diffraction about their ends

The energy transferred into the basins by reflection and diffraction was small and resonance in the basins may have played a significant role in magnifying the oscillations. However, the most probable explanation for the relatively large movements of the vessels, is that the periods of the waves initiating the surface oscillations corresponded closely with the natural periods of pitching and heaving of the ships. These periods, according to Fig. 21, would be between 5 and 6 seconds for the "HOEGH DENE".

5.0 PROPOSALS.

The design of coastal engineering projects, such as Halifax Harbour, requires a proper understanding of the interaction between waves, their environment and the response of the vessels. As shown herein, the interaction is complex and the conclusions derived are generally more qualitative than quantitative. Nevertheless, if they are taken into consideration in the design of new installations, some of the present disturbances can be prevented or their magnitude can be decreased.

Evidently the major problem of Halifax Harbour is that its inlet is not sufficiently protected from ocean waves. This is aggravated by the fact that the periods of the predominant waves which enter the harbour are generally similar to those of the natural periods of oscillation of vessels in the harbour. Thus, it appears that there is frequently sufficient excitation to produce the oscillation of ships in any part of the harbour south of Georges Island, except in the Eastern Passage.

Since the ocean waves are the source of these disturbances, they must either be prevented from entering the harbour or dissipated within the harbour or their effect must be kept to a minimum through a proper layout and design of the wharf facilities. Several proposals which take these aspects into consideration, are submitted. They are designed to improve conditions in the harbour generally and at the proposed Pier "C" of the Ocean Terminals in particular. Their application must be chosen on the basis of present and future requirements.

If "containerization" becomes the predominant form of transshipment and if the handling of containers requires that ships lie nearly motionless during loading and unloading it appears that the only way to achieve this is by closing off the area where container ships are berthed. A proposal to this effect is included.

5.1 Breakwaters.

As shown in the wave analysis of Section 3.0., ocean waves with periods less than approximately 8 to 9 seconds have little difficulty in entering the harbour. Reviewing the refraction diagram of the 6-second wave, which represents this group (Fig.11), it is evident that effective protection from this type of wave could be achieved by two relatively small breakwaters placed on the Outer Middle Ground and the Middle Ground Shoals., as shown on Fig. 23. The Outer Middle Ground Breakwater would protect the Dartmouth and Imperoyal side while the Middle Ground Breakwater would protect the Ocean Terminals on the Halifax side. The existing navigation lanes and thus the free flow of traffic would be effected little.

The two breakwaters would improve conditions appreciably but would not achieve still water conditions in the harbour since a portion of the wave energy would progress around the structures due to diffraction and reflection from the shores. Complete protection from ocean waves could be obtained by a set of staggered breakwaters or an enclosure. Such structures would be large and expensive and their location could be decided upon only after a more comprehensive investigation.

5.2 Modifications to the Layout of Pier "C".

If no breakwaters or wave reducing structures are installed in the inlet to Halifax Harbour, wave conditions at Pier "C" will be generally similar to those experienced at the existing wharves. In the basins on both sides of the pier, diffraction, oblique reflection and resonance will produce fluctuations similar to those in the basins of the present terminals. Since the openings are more exposed to the incoming waves, the heights of the oscillations will probably be greater.

As discussed, the oblique approach of waves at small angles is one of the major causes of the pitching and heaving of large ships. The smaller the angle the greater the ratio of wave length to ship length becomes and thus, according to Fig.17, the response of the ship to the wave slope. On the other hand, the response of the ship to the wave decreases as the angle of incidence increases. This important relationship should be considered in designing marine structures such as wharves.

In the proposed design of Pier "C", the incoming waves approach the south side and the waves reflected from Pier "B" approach the north side at angles less than 10° resulting in apparent wave lengths along the walls in excess of 1,000 feet for 6-second waves. Ships up to 100,000 tons would pitch and heave with full response at these wharves. It is recommended, therefore, that these walls be realigned as shown in Fig.24 or even inclined the opposite way. The final layout depends on foundation and navigation considerations.

The east side of the pier, which is most exposed, will probably be the best side for berthing large ships. Here the waves from the ocean will run along the wall; their crests being nearly normal to it. The apparent length of the waves will be increased little and the wave length of a 6-second wave will be about 170 feet. Under these circumstances ships larger than 5,000 tons should have a very small response to the waves.

This, however, is strictly true only for a regular wave train. As has been described, waves, in nature, are nearly always irregular, with surges occuring in generally regular time intervals. While the modifications suggested would improve conditions appreciably they would be unable to compensate for the effect of surges which would still cause the vessels to oscillate. Loading and unloading conditions would therefore be improved but completely calm conditions would not be provided on any side of the pier.

5.3 Still Water Basin at Pier "C".

Sufficient excitation will probably always be present to promote the oscillations at ships moored along the wharves as long as ocean waves can enter the harbour. Therefore ships, regardless of their size, will oscillate on occasion though the amplitude of these oscillations might be reduced by the methods indicated in the preceding section.

Pier "C" is to handle container cargo as well as general cargo. At the existing terminals, general cargo handling appears to have been difficult on only 10 to 20 days annually. Container handling, however, requires that ships lie nearly motionless during loading and unloading. It appears also that this form of transshipment is becoming more common and may become the predominant form. If this occurs and Pier "C" is to handle this type of cargo until special container facilities are developed, the question arises as to whether such calm conditions can be provided. The only way in which a complete calm can be achieved is by providing an enclosed basin where waves are prevented from entering.

Such an arrangement is shown in Fig.25. The shape of the pier should be modified to a rectangular form in which the east wall is parallel to the existing wharves. The basin between Pier "B" and Pier "C" which would be similar to the existing basins, could be closed by a floating structure. This structure would reflect the waves so that only an insignificant part of their energy would be able to enter the basin. A laid-up vessel, a large barge or a specially built floating concrete structure might be used as a closure.

For most of the year, when the ships are undisturbed by waves, the basin would remain open and the mobile closure would be moored off Point Pleasant Park Breakwater as an extension to the breakwater. In this position, smaller ships berthed at the south side of the pier would receive increased protection particularly against the locally generated waves. As soon as loading in the basin becomes difficult, the mobile closure would be towed to the opening and the basin closed off. After the disturbance had subsided the closure would be returned to position at the breakwater.

The draft of the floating structure should be approximately half the depth of the entrance to the basin or about 30 feet. However, a depth of 20 feet would intercept more than 70% of the energy of larger waves and practically all the energy of smaller waves. A simple passively-controlled anti-roll tank might improve its performance.

Implementing this proposal would provide Halifax Harbour with a pier at which all-year-around container loading would be possible. At the remaining sides of the proposed pier, loading could occur under the same conditions as now prevail at the existing terminals. The floating structure could also be used to close off other basins of the Ocean Terminals, thus providing added protection to the existing facilities when needed.

5.4 Low Reflection Wall.

In the proposed design the pier is to be enclosed by cribs which are box-like structures of reinforced concrete. The individual cribs are to be 117 ft. long, 48 ft. wide and between 43 ft. and 57 ft. high, and consist of a bottom slab, plain front, middle, back and side walls and a number of dividing walls. They are to be floated into position and filled with rubble and soil.

Waves would be reflected from the plain vertical walls of these cribs as described in section 4.1 and incident and reflected waves would form standing waves, the height of which would be approximately twice that of the incident waves. These reflections and the effects resulting from oblique incidence, diffraction and resonance are considered to be the main reasons for the relatively large oscillations of the water surface in the present basins.

Waves of this nature can be damped effectively by walls with low reflective values, i.e.

a wall in which part of the wave energy is absorbed. A very effective wall is one which is perforated and incorporates a resonant chamber behind it. The hydraulic characteristics and efficiency of which have been studied by Jarlan (1961). The design comprised a chamber about 30 feet wide formed by two walls; the seaward wall being perforated with a void area of approximately 20 to 40 percent of the face area.

When waves surge against this type of wall, water pours through the perforations into the chamber behind and energy is dissipated through friction and turbulence. As the wave recedes, the flow is reversed and the jets of outflowing water have a damping effect on the approaching waves.

In model tests the wave heights have been reduced by approximately 50 percent. These results were verified by similar investigations reported by Boivin (1963) in which slotted perforations were used. According to his tests with slots in a wall of 33 percent void ratio, the height of a 6-second wave in 45 feet of water would be reduced from 5.0 feet to 2.5 feet and from 8 feet to 4.5 feet.

The cribs enclosing the proposed Pier "C" could be modified, without great difficulty, to include such a low-reflection wall. The outer walls of the cribs would be perforated and fill omitted from the outer section to form the resonant chamber. The general design of the structure is shown on Fig.26.

The openings in the wall could be made easily by rearranging the reinforcing steel. A major addition to the structure would be a deck slab designed to support the loads which occur in handling cargo. In the proposed design, the calculations for the stability of the crib were evidently based on the assumption that soil and water would fill both the front and rear section of the crib. Omitting the fill from the front section would reduce the downward load on the structure in this region. If necessary, the bottom slab could be extended to compensate for this reduction.

The low reflection walls should be used on all sides of the pier. However if this is felt to be too costly it is suggested that at least the east half of the walls on the south and north side be modified to this type of wall.

The application of this damping arrangement to the existing structures appears to be impracticable on account of the expensive modifications required.

In summary, a low reflection wall would substantially reduce the waves and movement of vessels along the pier.

5.5 Crane Control System.

The main problem is not so much the protection of ships from waves but the prevention of damage which occurs during loading and unloading when the ships oscillate under the wave action. Therefore, the question arises whether the problem should be solved entirely through modifications to reduce ship motions or through improvements in the loading facilities. A combination of both would probably provide the optimum solution to the problem.

Cranes for the transshipment of cargo or containers can be stationed either on land or on ships. For heavy loads, land based cranes are preferable since they operate from a stable base.

At the Ocean Terminals the predominant motions are vertical movements in the order of 5 to

6 feet, with slight sideward sways and average periods of 5 to 7 seconds. The rate of vertical movement can be as much as 3 to 4 feet per second. The power of impact between the ship and a container weighing 30 tons and hanging motionless above the ship, could be as much as 120 foot-ton per second but if the load were lowered with the same speed at which the ship rises, the power of impact would double.

Obviously, the problem to be solved is to reduce the impact between the ship and the load to a minimum to prevent damage. This might be achieved through a mechanical or an electronic control on the crane.

In principle the system would work as follows: A device, mounted either on the ship near the point where the load is to be placed or attached to the load itself, would sence the distance between the descending cargo and the loading area on the ship. As soon as a certain distance was reached - approximately 6 to 7 feet - an electronic control on the crane would be activated. This sensor would gently lower the cargo into the ship's hold while continually compensating for the motions of the vessel. Thus the "movement" of the ship would be indirectly minimized by an electronically guided hoist which would automatically adjust itself to the vertical displacement of the ship.

It is not known if this or similar proposals have already been investigated or tried. The author is not qualified to properly evaluate the applicability of the system but feels that it should be investigated. It might even be useful in other places where loading conditions are more difficult than in Halifax Harbour.

The concept of the control was suggested by E. S. Turner from the National Research Council and is described in the Appendix.

6.0 SURVEY.

Practically no data and very few visual observations were available for this investigation. The conclusions derived herein warrant, therefore, some form of verification through field observations.

The initial step would be a survey of ocean waves propagating into Halifax Harbour and the confirmation or disproof that only waves with periods smaller than 8 to 9 seconds are able to enter the harbour. For this purpose the wave spectrum should be observed and traced from a station off the mouth of the inlet to the harbour. The observation points may consist of both moored and shore-based gauges.

In the harbour, the data of particular interest in addition to wave height and period, are wave directions with respect to existing and future harbour developments. Such data are difficult to obtain and are obscured by reflection, residual agitation and resonance. Nevertheless, with gauges placed at key positions and photographs from elevated points or from the air, the distribution of the wave energy and the direction of the waves might be obtained with reasonable accuracy.

Bedford Basin is probably unaffected by ocean waves. This open body of water, however, may develop, in addition to wind generated waves, longer period waves and seiches initiated by atmospheric disturbances. This could be studied with a few shore-based observation points.

If larger container handling facilities should be required, the question of where and how to place them to achieve optimum still water conditions will arise. Such requests and others concerning the harbour in general could be answered more quantitatively with the results of a survey of this type.

Waves form only one of the forces acting on the water of the system. There are also tides which raise and lower the water and create alternating currents, density currents which are initiated by haline and thermal differences, and wind driven currents. All the forces of these currents and oscillations interact . Therefore none can be properly surveyed and understood unless viewed and measured in relationship to the environment in which they exist. Hence it is suggested that the wave survey be extended into a comprehensive investigation of all the hydrodynamic properties of the system.

7.0 CONCLUSION.

The wave problem in Halifax Harbour has been analysed by applying systematic interpretations based on theoretical principles, to formulate significant design concepts which would guide the layout of future harbour developments and provide recommendations for improving the design of the proposed Pier "C".

The conclusions are :

1. The predominant ocean waves which enter the harbour are swells and wind generated waves with periods probably in the order of 4 to 8 seconds. The prevailing wave pattern is a composite formed by these waves and by waves generated in the harbour. On occasions regular wave trains may occur.
2. The ocean waves spread in arc-shaped curves over the harbour approaching the wharves of the Ocean Terminals obliquely and those of Imperoyal directly, causing ships to pitch and heave at the former and to roll at the latter.
3. Since the apparent wave length along wharves depends upon the angle of incidence of the wave and since the response of a ship to the wave slope in turn depends upon the ratio of the wave length to the ship length, it follows that wharves should be located so that they are nearly normal to the wave crests. Therefore, in Halifax Harbour, wharves should be arranged parallel to the

to the coast on the west side and normal to the coast on the east side.

4. Ships berthed in the harbour are usually excited by resonance waves and surges of the composite wave. Between these "excitation" the ships oscillate predominantly under their own natural periods of oscillation. If the ship's period coincides with that of a regular wave train, resonant oscillations of large amplitude will occur. This resonant or near resonant condition is probably one of the main causes for severe ship motions.
5. It appears at the present that there is no area in the harbour south of Georges Island, except in the Eastern Passage which is sufficiently protected from ocean waves so that ships would not be disturbed. This applies also to the basins of the Ocean Terminals where the protection of the piers is partly cancelled by resonance and reflection in the basins.
6. Several proposals are submitted. They include two breakwaters which would provide

improved protection for the entire harbour, the modification of Pier "C" so that the oscillation of ships would be no worse than in the existing terminals and the installation of perforated walls along the wharves to absorb reflections and resonant oscilla= tions. A crane control system is suggested which should improve the loading mechanically.

Each of these proposals can be applied individually or in combination. Optimum protection would be provided when all the proposals were implemented.

If containerization should become the prevailing form of transshipment on Pier "C", a semi-enclosed basin as outlined in the third proposal, is suggested to provide the required stillwater condition.

7. A number of factors determining the wave propagation in Halifax Harbour are still not well understood and warrant further investigation through systematic observations. The study should be extended into a comprehensive investigation of all the hydrodynamics properties of the system.

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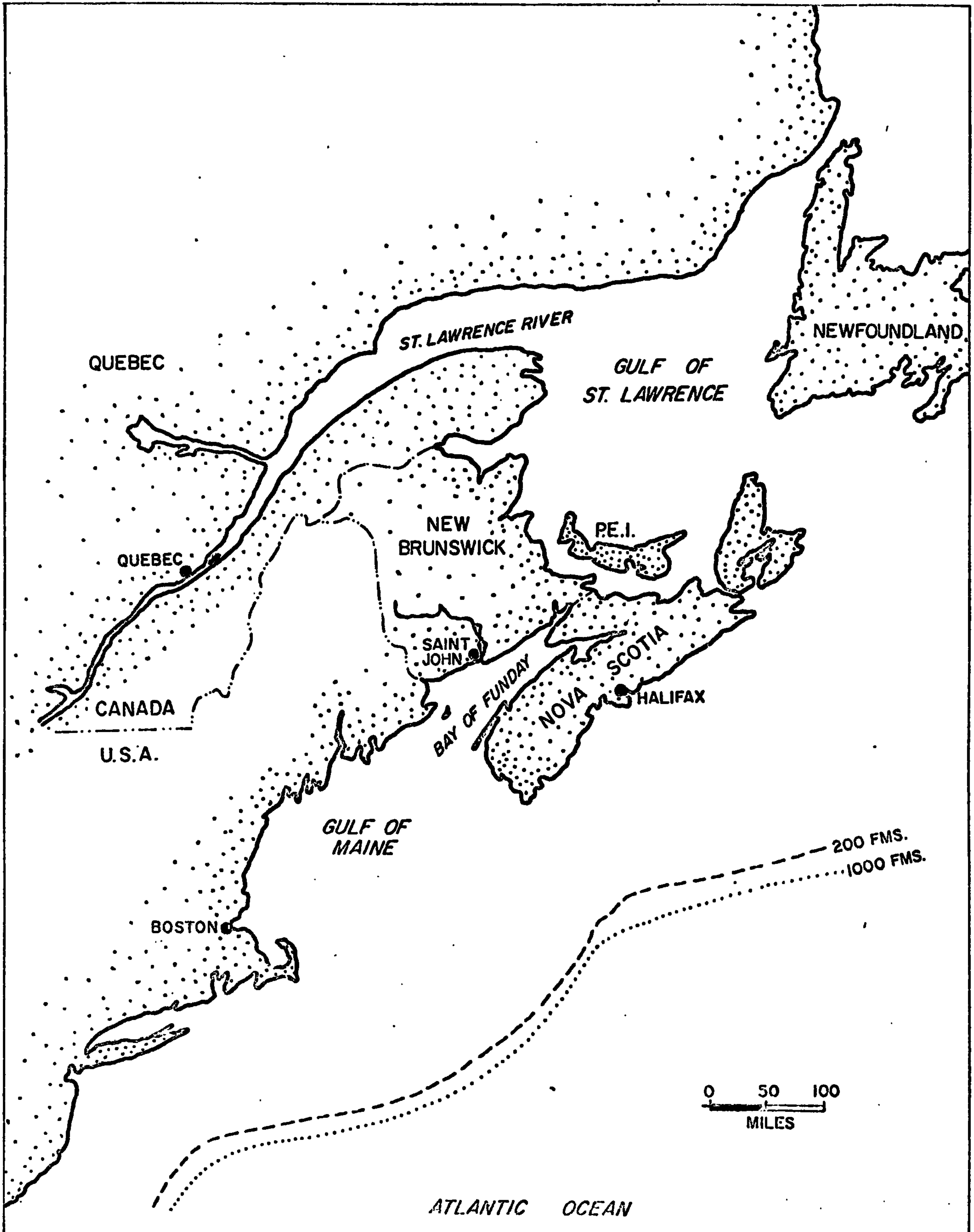


REGIONAL MAP OF ATLANTIC COAST
SHOWING LOCATION OF HALIFAX HARBOUR, N.S.

FIG. 2

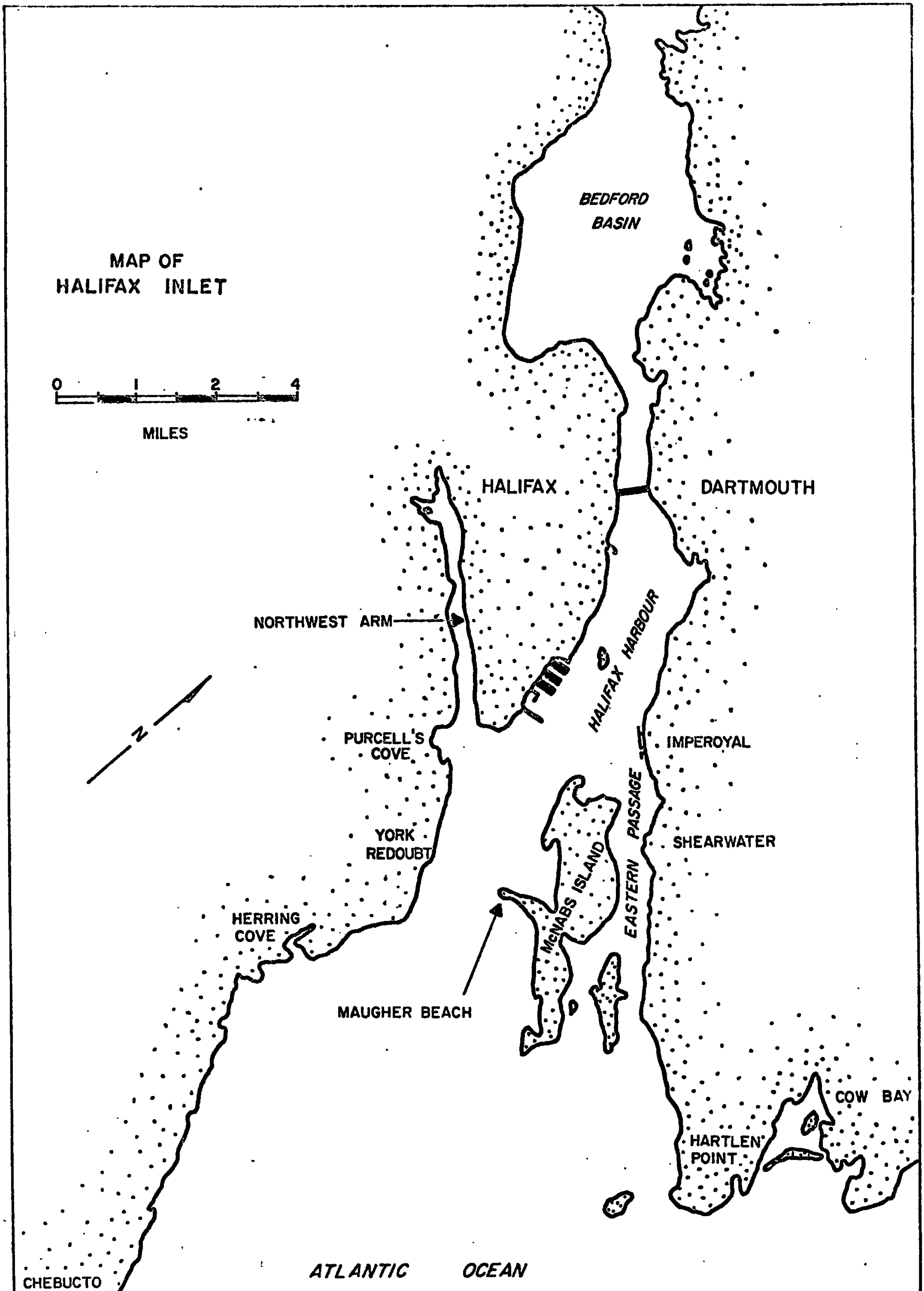
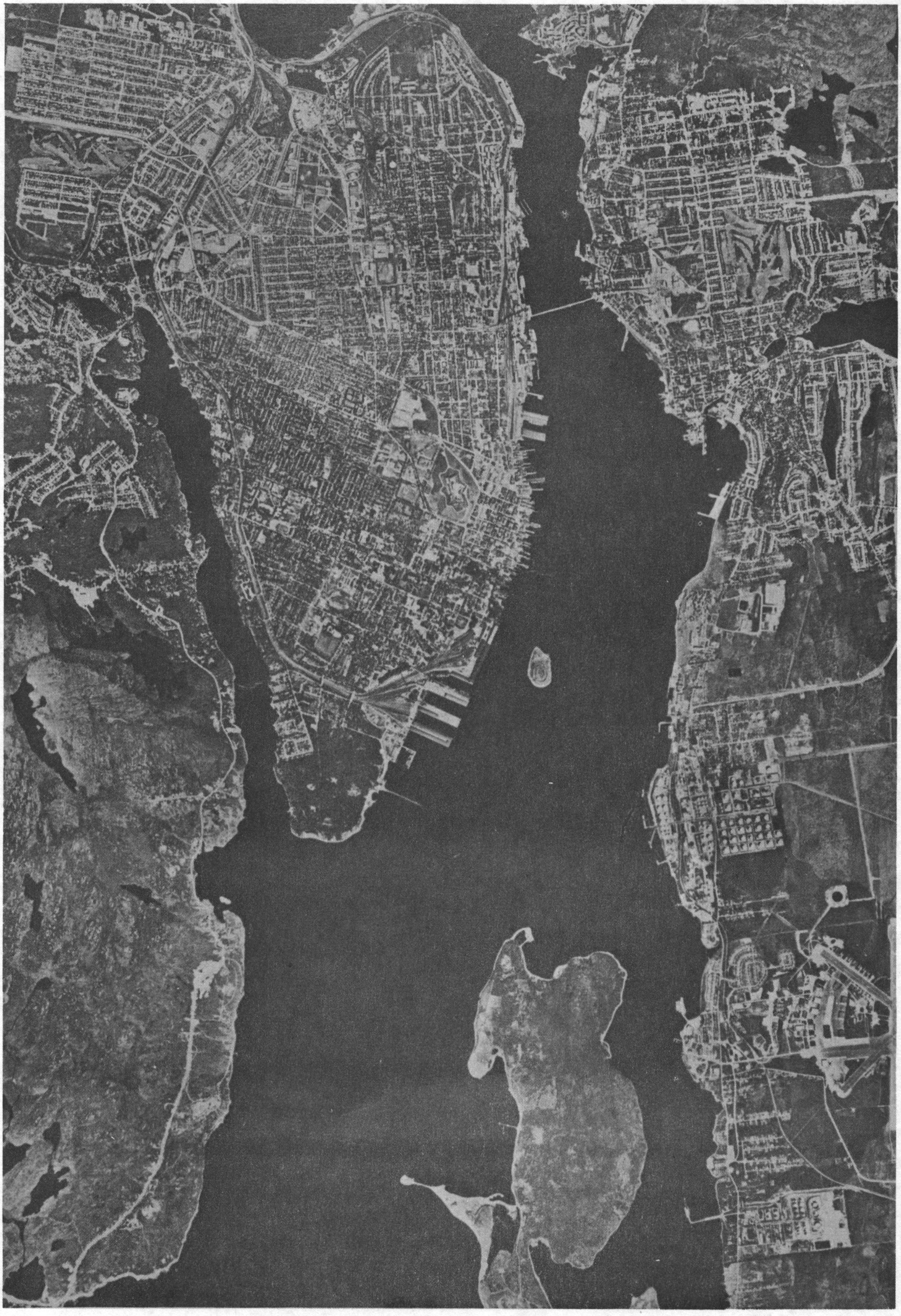

MAP OF
HALIFAX INLET
0
1
2
4
MILES
N
BEDFORD
BASIN
HALIFAX
DARTMOUTH
NORTHWEST ARM
HALIFAX HARBOUR
PURCELL'S
COVE
IMPEROYAL
EASTERN
PASSAGE
YORK
REDOUBT
SHEARWATER
McNABS ISLAND
HERRING
COVE
MAUGHER BEACH
COW BAY
HARTLEN
POINT
ATLANTIC OCEAN
CHEBUCTO
HEAD

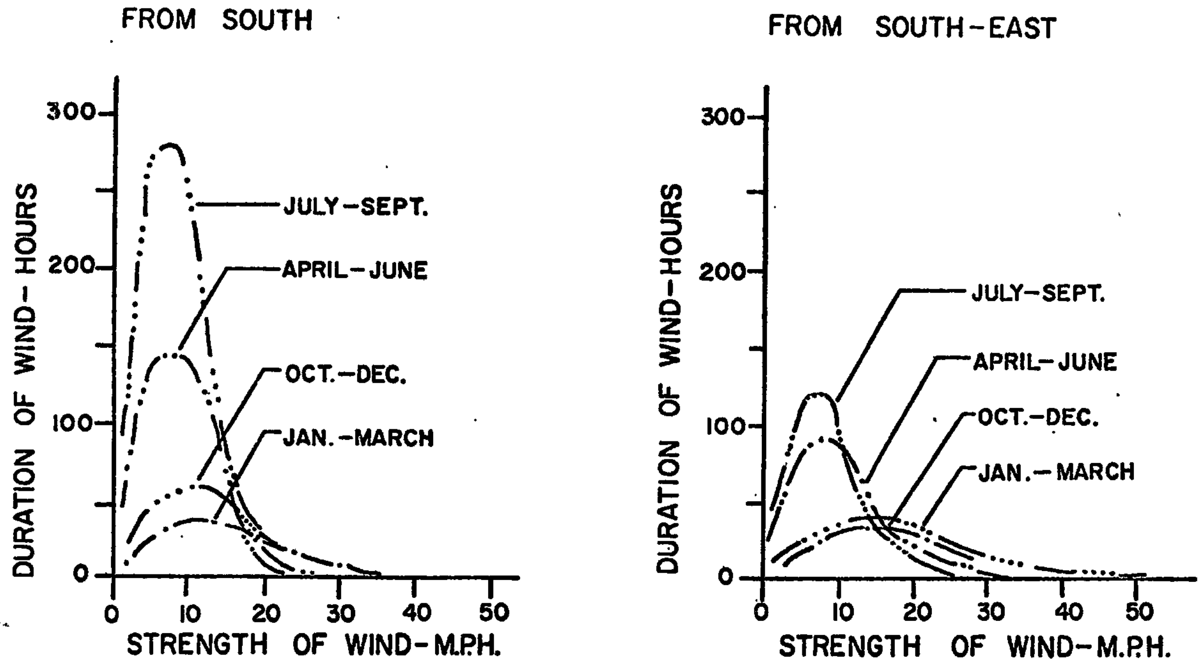
FIG. 3



AERIAL PHOTOGRAPH OF HALIFAX HARBOUR

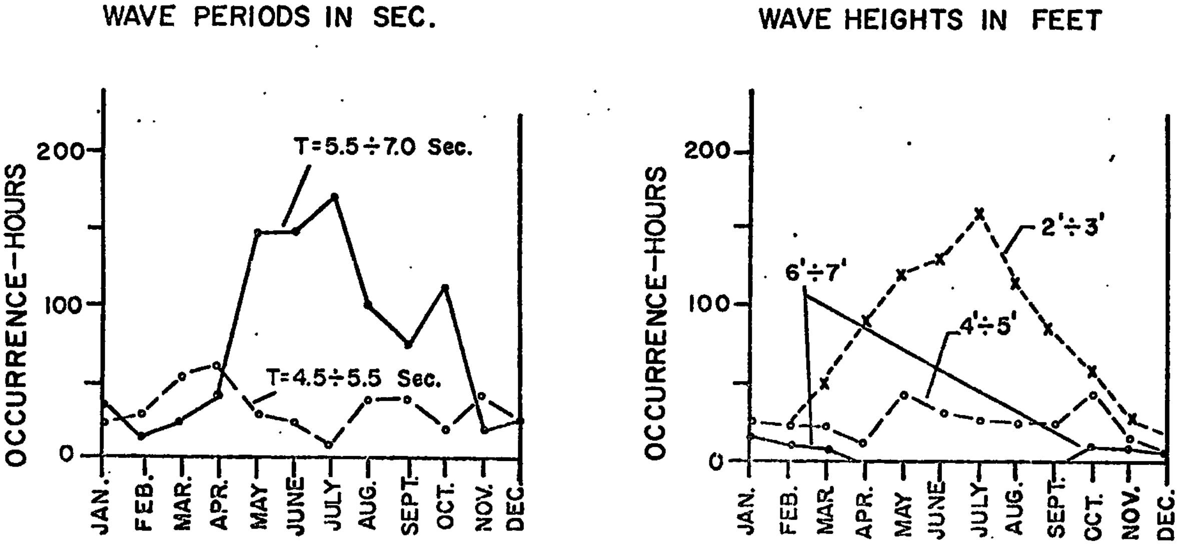
Photo: Atlantic Air Survey Ltd.
Dartmouth N.S

FIG. 4



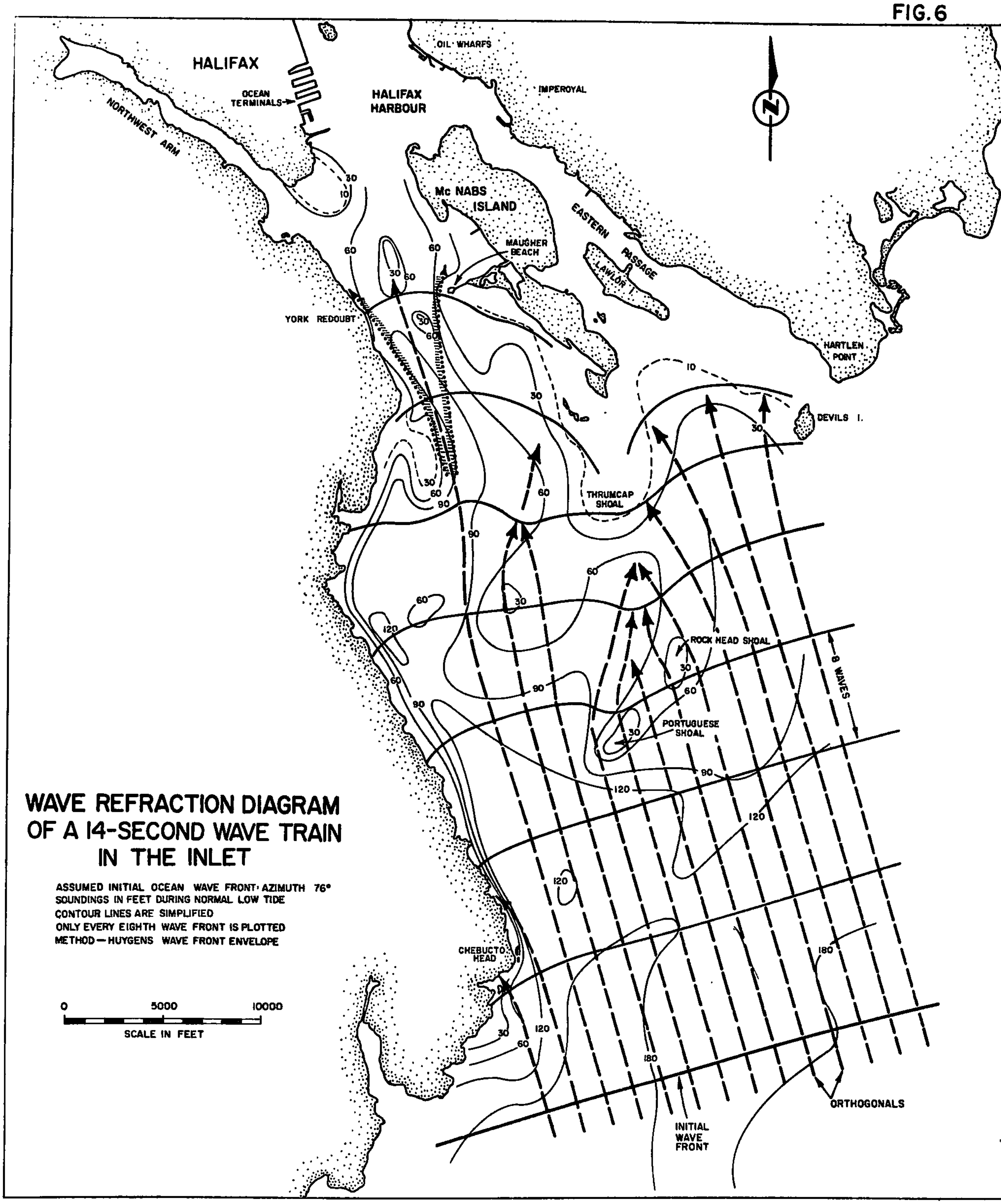
WIND STRENGTH AND DURATION DURING QUARTERLIES

FIG. 5



AVERAGE OCCURRENCE OF WAVE PERIODS & WAVE HEIGHTS FROM SECTOR SOUTH TO SOUTH-EAST
(BRETSCHNEIDER)

FIG. 6



WAVE REFRACTION DIAGRAM OF A 14-SECOND WAVE TRAIN IN THE INLET

ASSUMED INITIAL OCEAN WAVE FRONT: AZIMUTH 76°
SOUNDINGS IN FEET DURING NORMAL LOW TIDE
CONTOUR LINES ARE SIMPLIFIED
ONLY EVERY EIGHTH WAVE FRONT IS PLOTTED
METHOD — HUYGENS WAVE FRONT ENVELOPE

FIG. 7

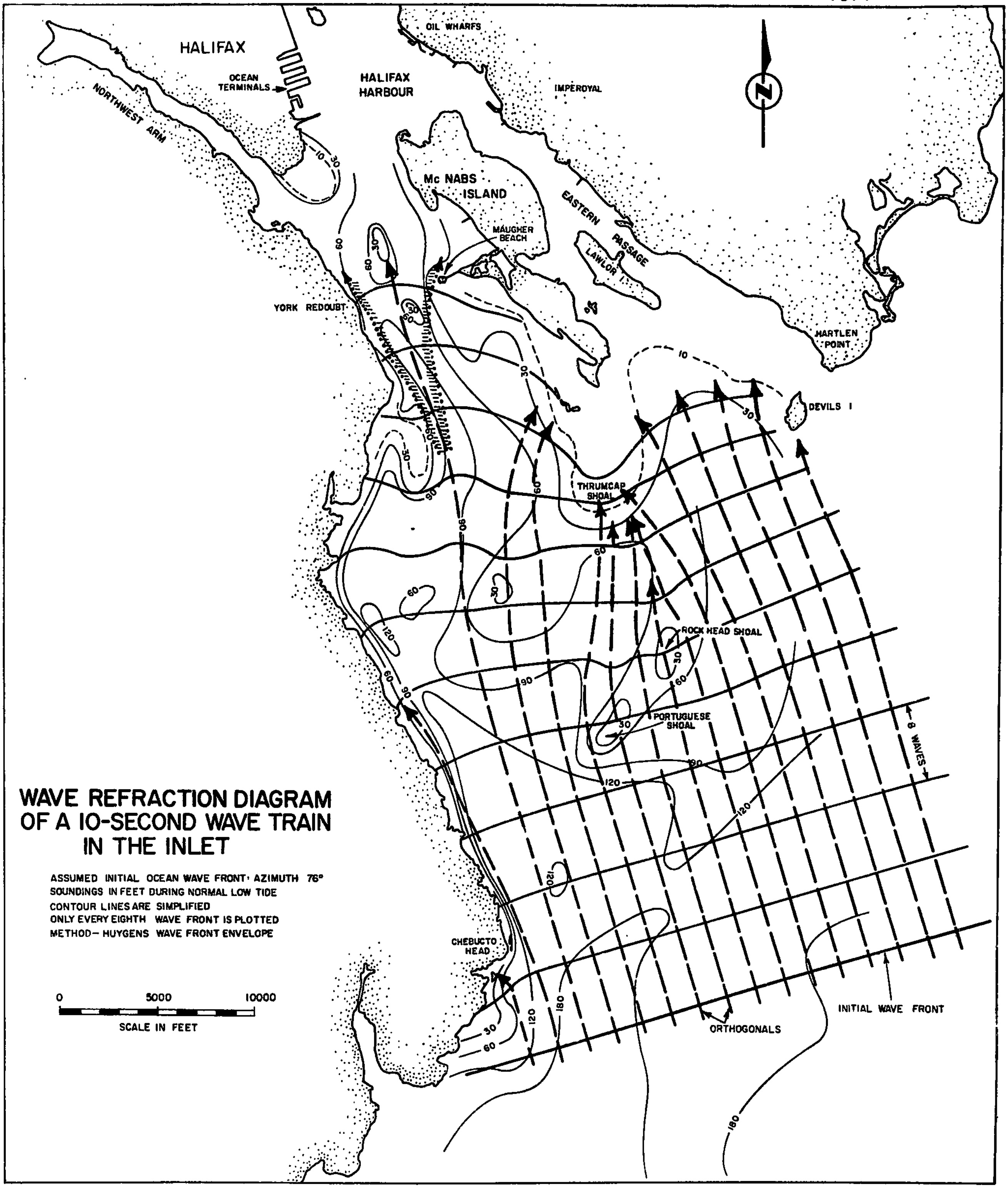
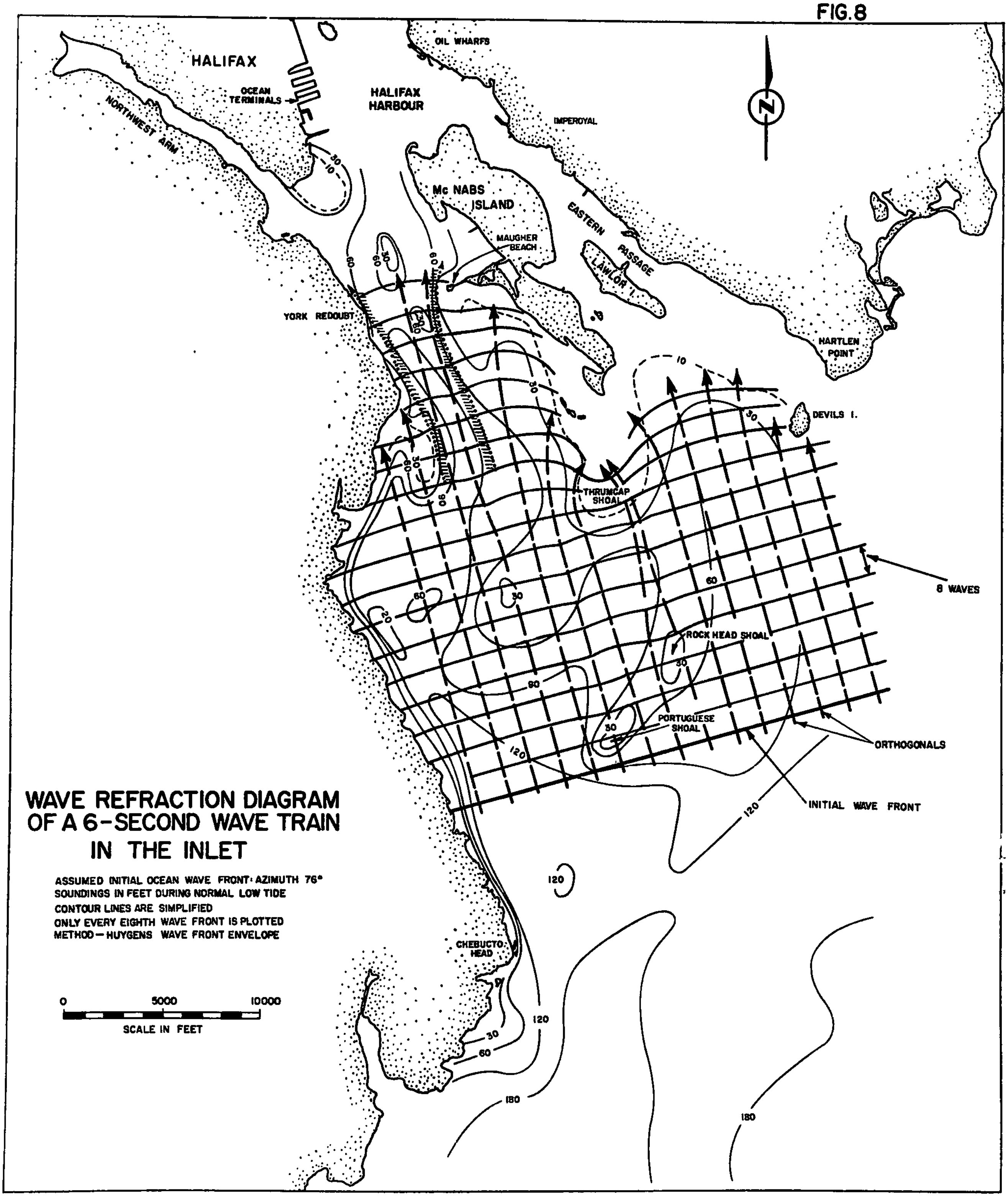

WAVE REFRACTION DIAGRAM
OF A 10-SECOND WAVE TRAIN
IN THE INLET
ASSUMED INITIAL OCEAN WAVE FRONT AZIMUTH 76°
SOUNDINGS IN FEET DURING NORMAL LOW TIDE
CONTOUR LINES ARE SIMPLIFIED
ONLY EVERY EIGHTH WAVE FRONT IS PLOTTED
METHOD- HUYGENS WAVE FRONT ENVELOPE
0
5000
10000
SCALE IN FEET
HALIFAX
OCEAN TERMINALS
HALIFAX HARBOUR
OIL WHARFS
IMPEROYAL
NORTHWEST ARM
Mc NABS ISLAND
MAUGHER BEACH
EASTERN PASSAGE
LAWLOR I.
YORK REDOUBT
HARTLEN POINT
DEVILS I
THRUMCAP SHOAL
ROCK HEAD SHOAL
PORTUGUESE SHOAL
CHEBUCTO HEAD
8 WAVES
INITIAL WAVE FRONT
ORTHOGONALS

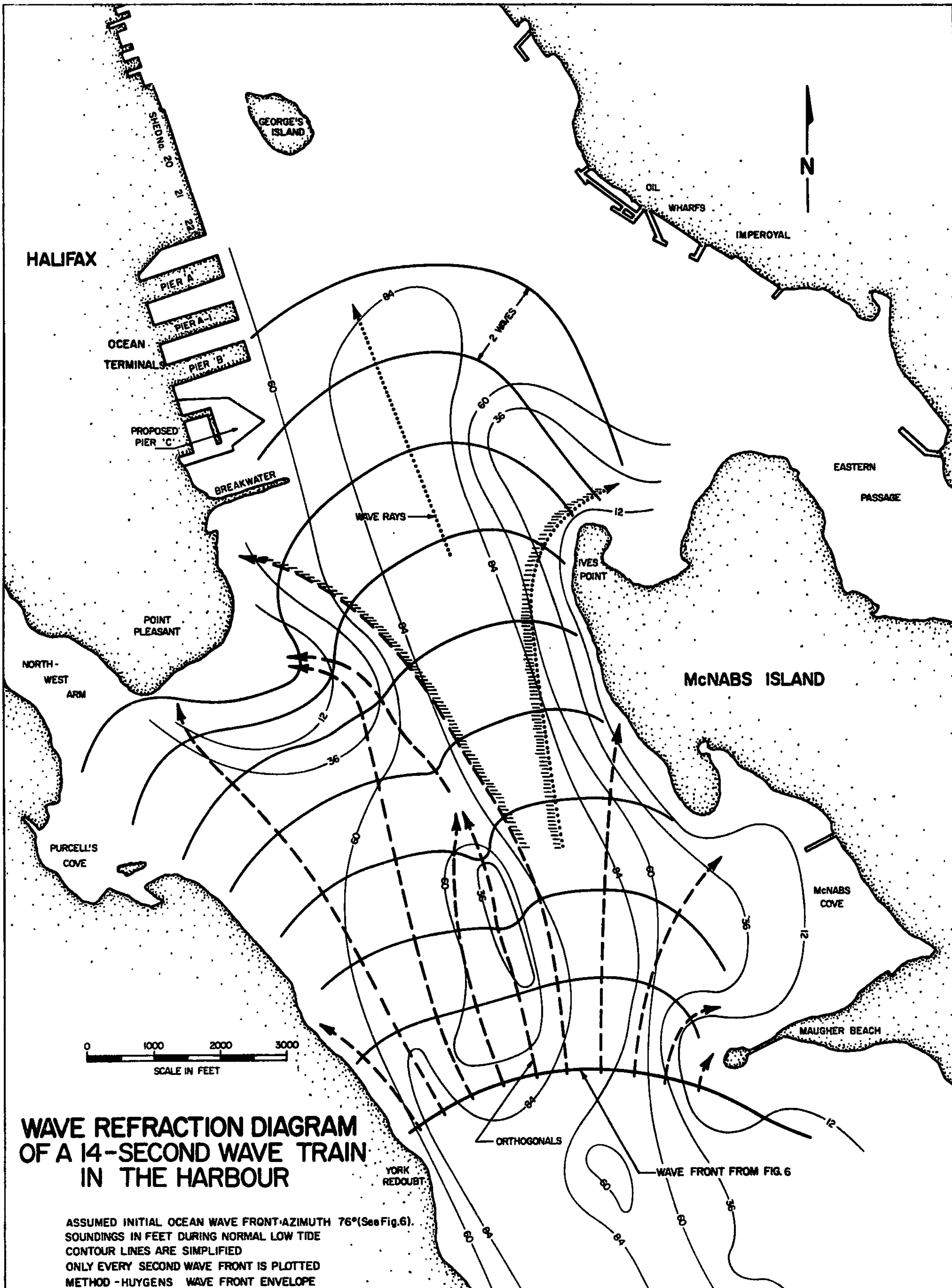
FIG. 8



WAVE REFRACTION DIAGRAM OF A 6-SECOND WAVE TRAIN IN THE INLET

ASSUMED INITIAL OCEAN WAVE FRONT: AZIMUTH 76°
SOUNDINGS IN FEET DURING NORMAL LOW TIDE
CONTOUR LINES ARE SIMPLIFIED
ONLY EVERY EIGHTH WAVE FRONT IS PLOTTED
METHOD — HUYGENS WAVE FRONT ENVELOPE

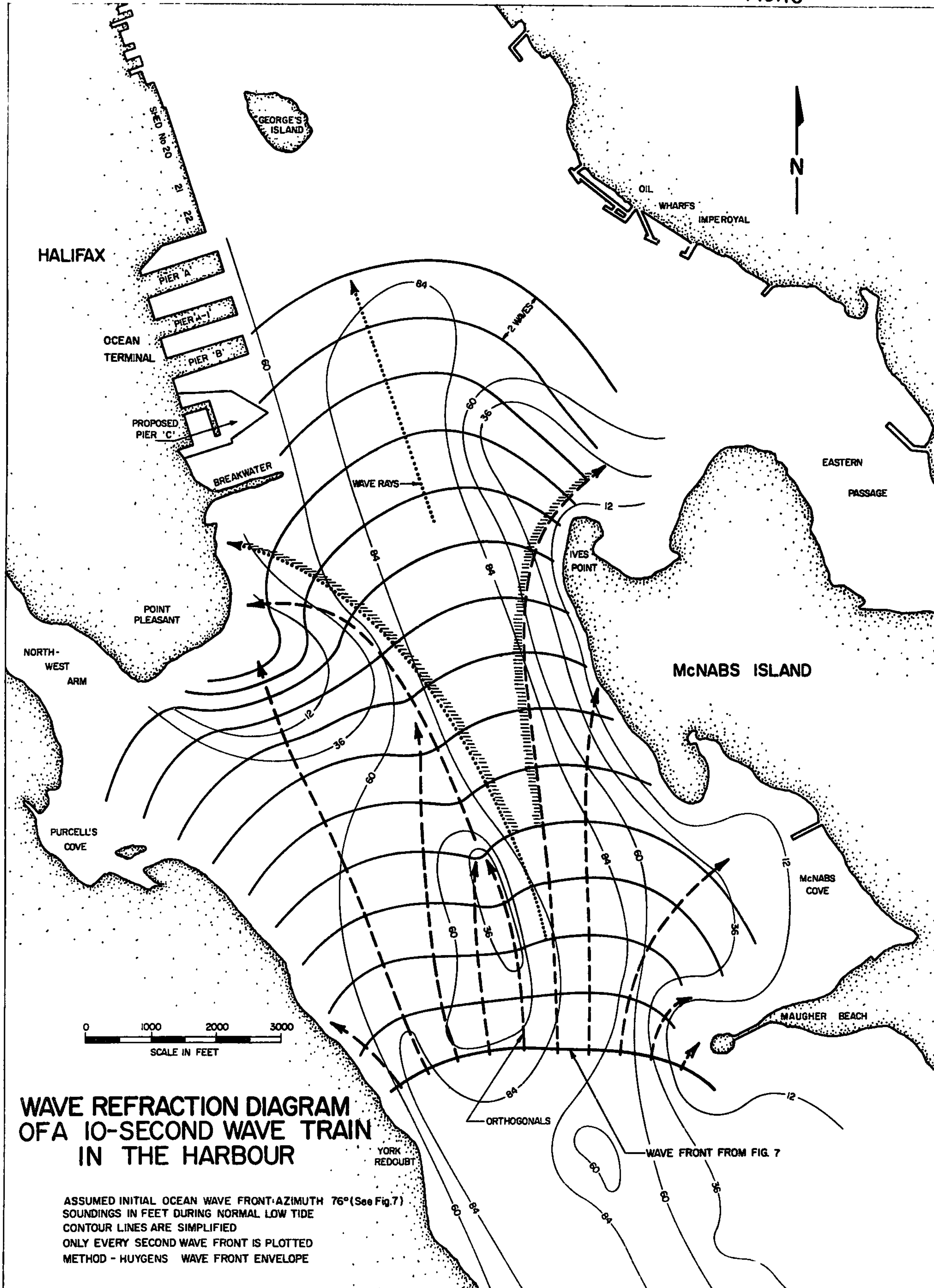
FIG. 9



WAVE REFRACTION DIAGRAM OF A 14-SECOND WAVE TRAIN IN THE HARBOUR

ASSUMED INITIAL OCEAN WAVE FRONT AZIMUTH 76° (See Fig. 6).
SOUNDINGS IN FEET DURING NORMAL LOW TIDE
CONTOUR LINES ARE SIMPLIFIED
ONLY EVERY SECOND WAVE FRONT IS PLOTTED
METHOD - HUYGENS WAVE FRONT ENVELOPE

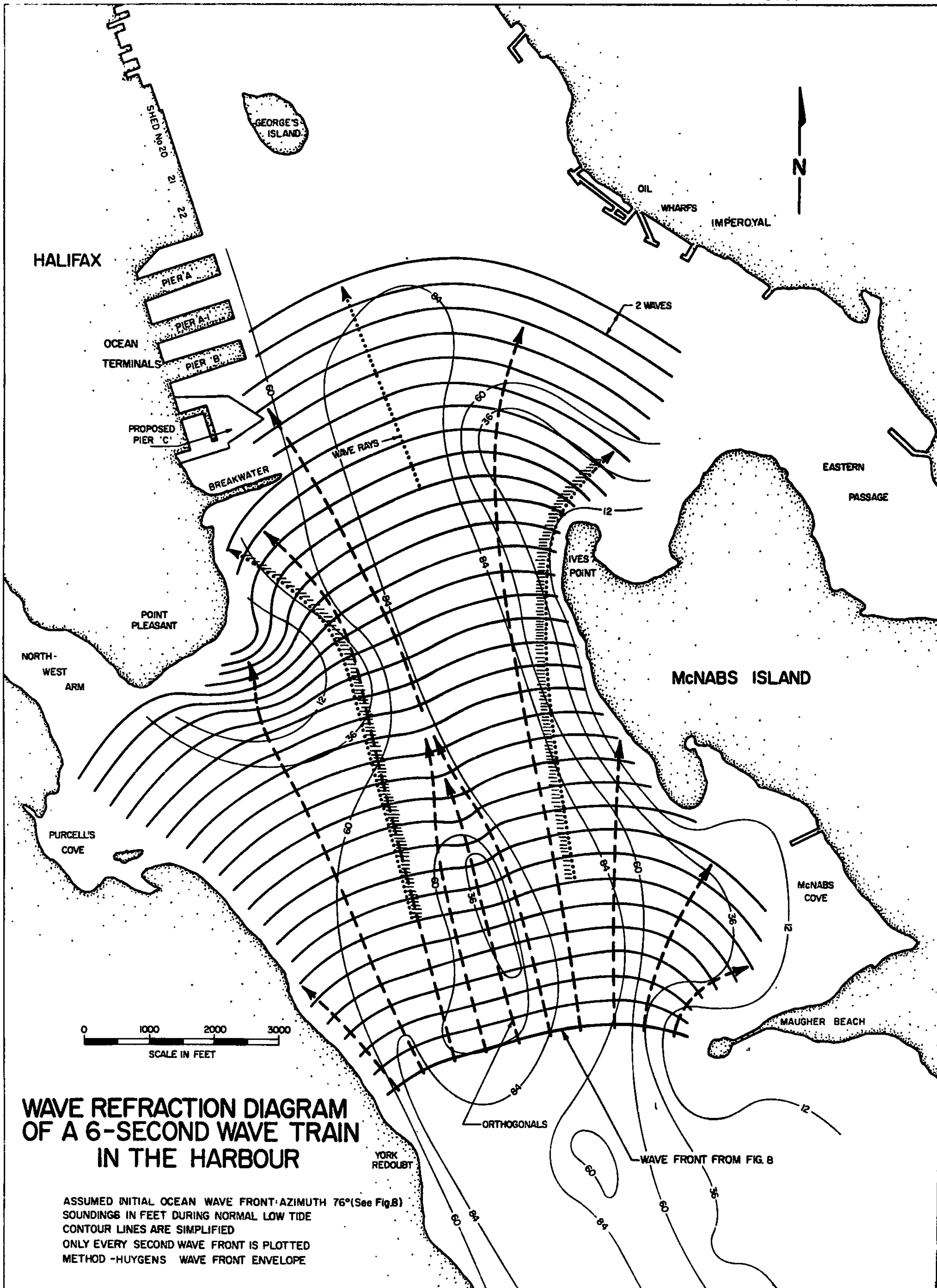
FIG. 10



WAVE REFRACTION DIAGRAM OF A 10-SECOND WAVE TRAIN IN THE HARBOUR

ASSUMED INITIAL OCEAN WAVE FRONT-AZIMUTH 76° (See Fig. 7)
SOUNDINGS IN FEET DURING NORMAL LOW TIDE
CONTOUR LINES ARE SIMPLIFIED
ONLY EVERY SECOND WAVE FRONT IS PLOTTED
METHOD - HUYGENS WAVE FRONT ENVELOPE

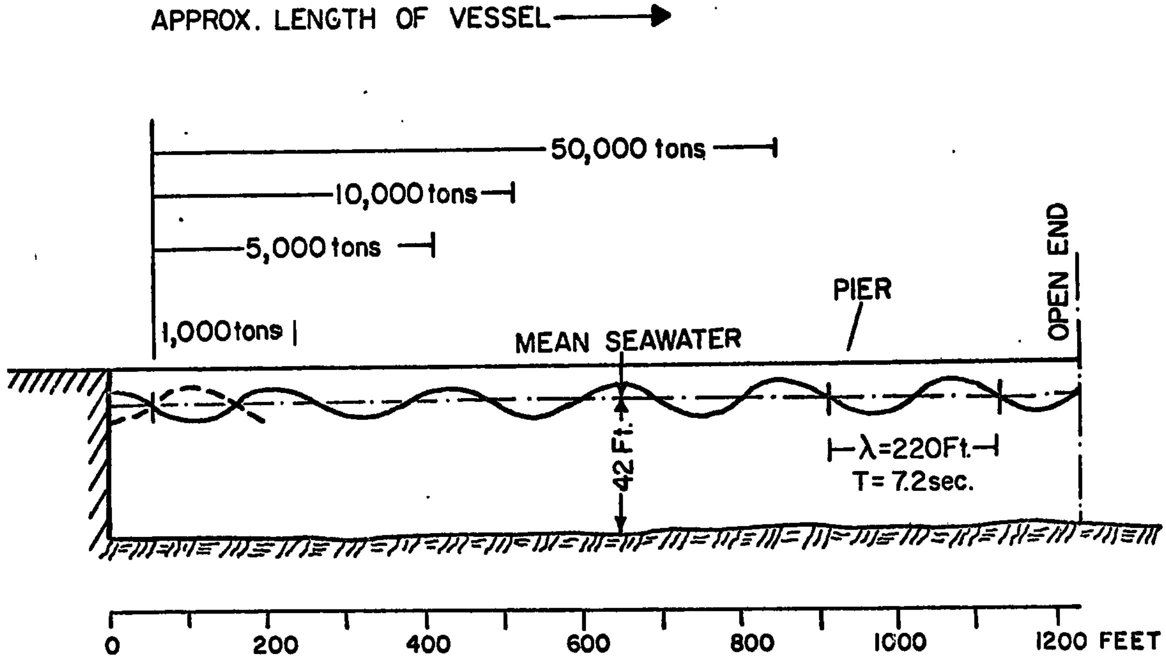
FIG. 11



WAVE REFRACTION DIAGRAM OF A 6-SECOND WAVE TRAIN IN THE HARBOUR

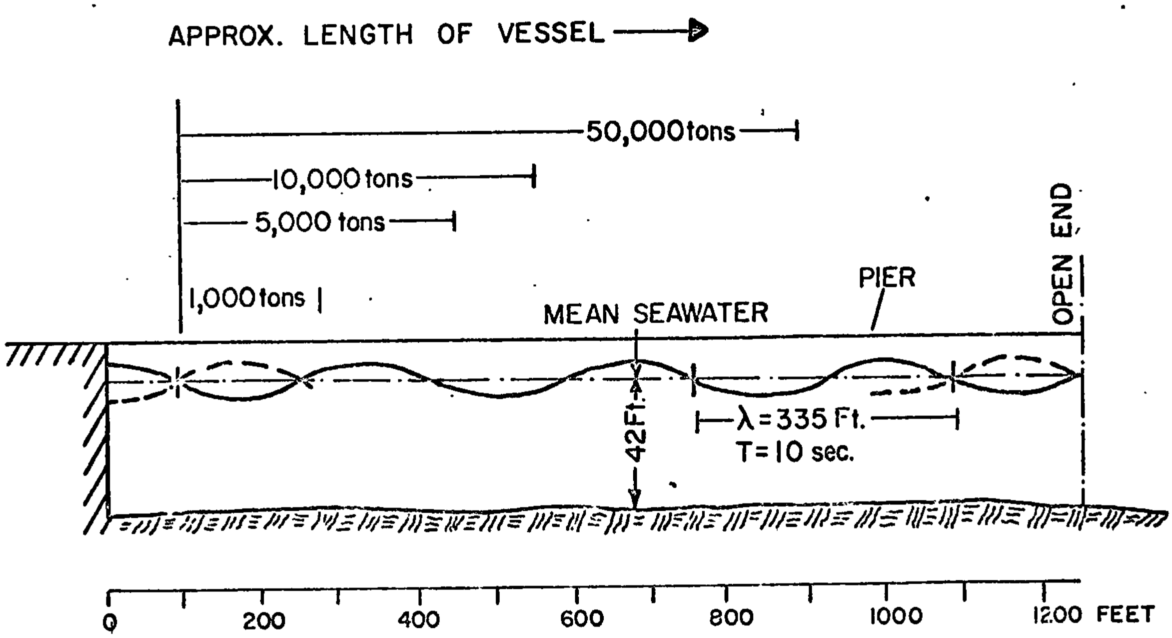
ASSUMED INITIAL OCEAN WAVE FRONT: AZIMUTH 76° (See Fig.8)
SOUNDINGS IN FEET DURING NORMAL LOW TIDE
CONTOUR LINES ARE SIMPLIFIED
ONLY EVERY SECOND WAVE FRONT IS PLOTTED
METHOD - HUYGENS WAVE FRONT ENVELOPE

FIG. 12



TWELFTH MODE

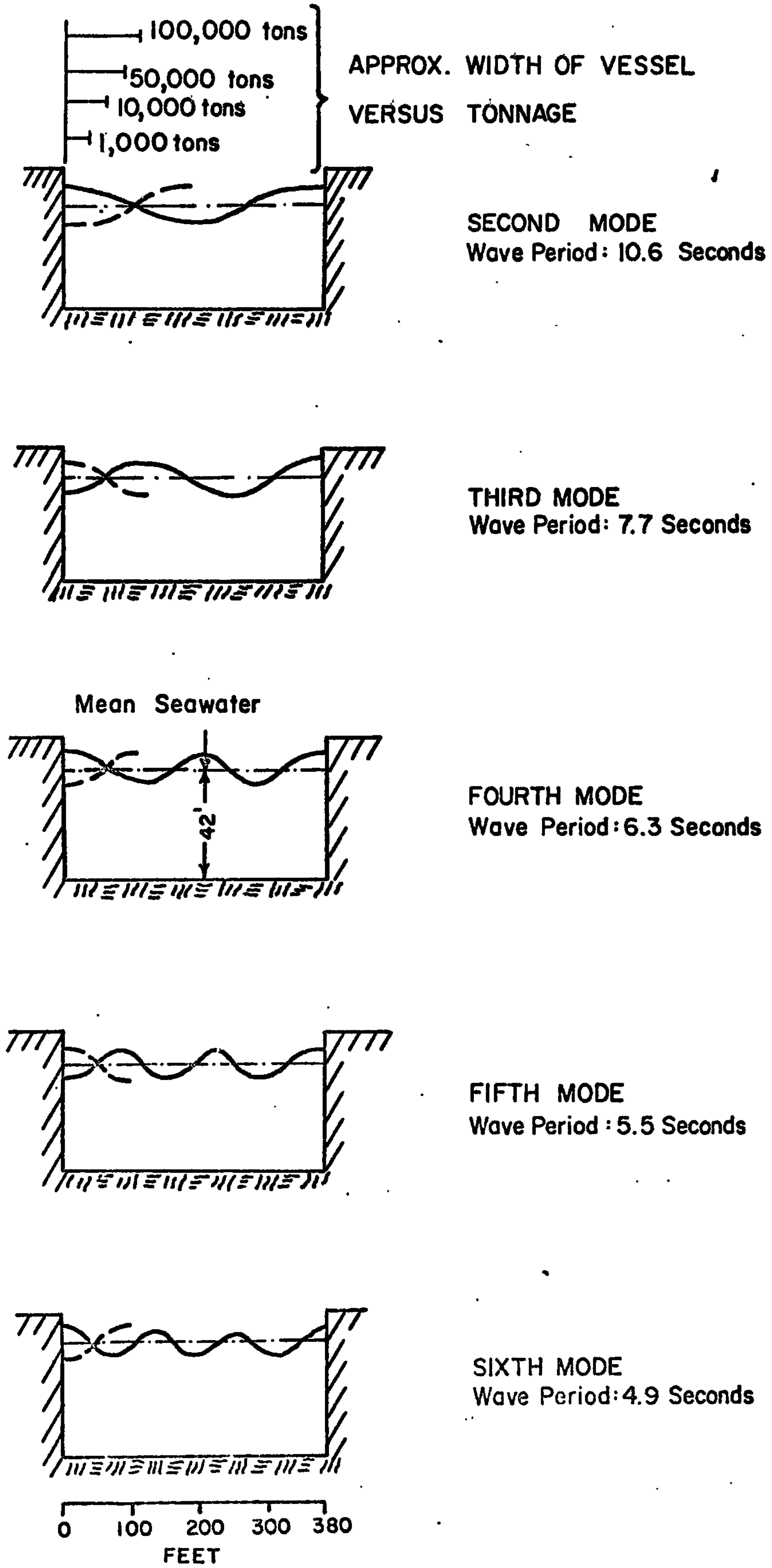
PERIOD OF OSCILLATION: 7.2 Seconds



EIGHTH MODE

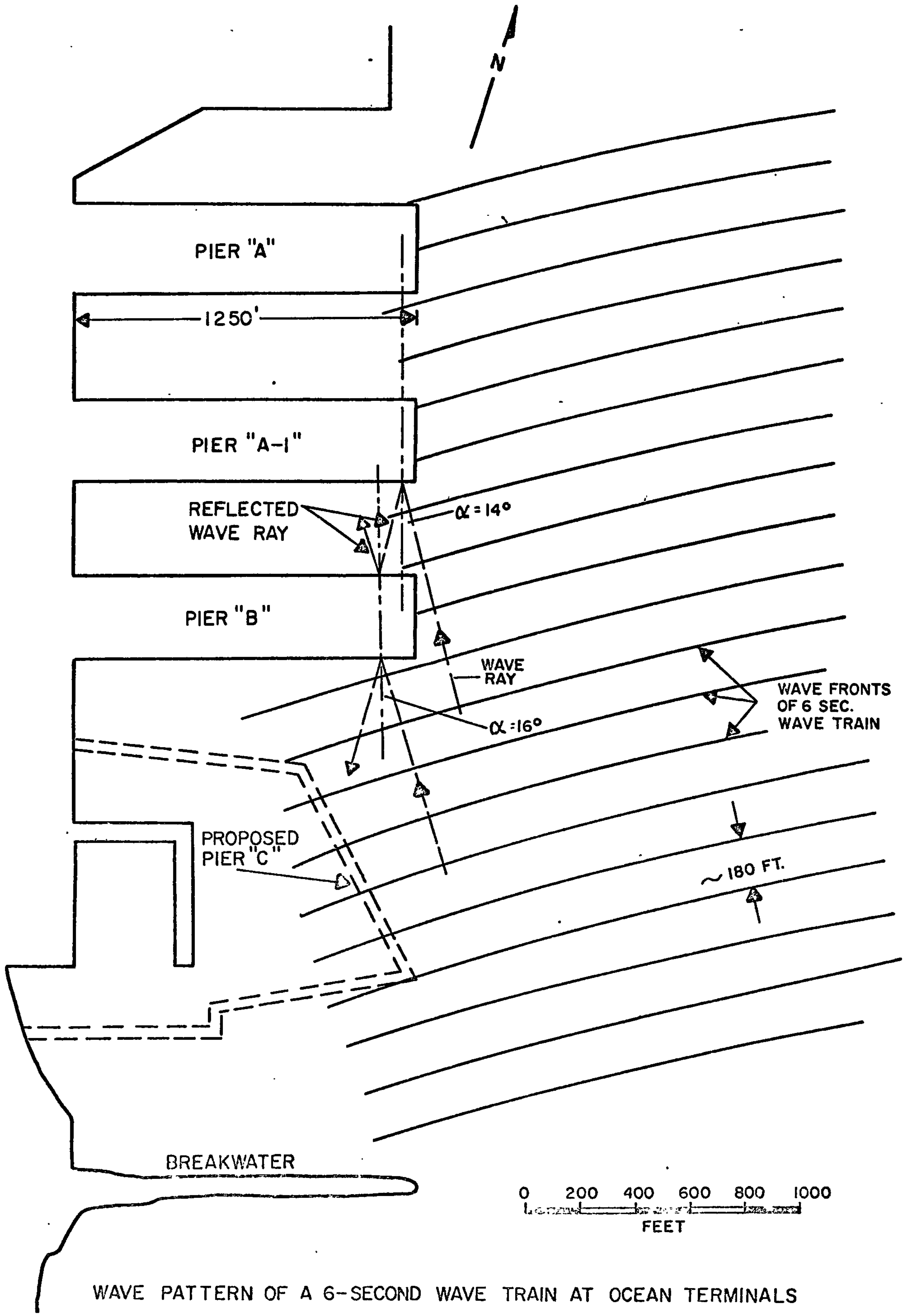
PERIOD OF OSCILLATION: 10 Seconds

LONGITUDINAL NATURAL OSCILLATIONS IN BASIN OF OCEAN TERMINALS



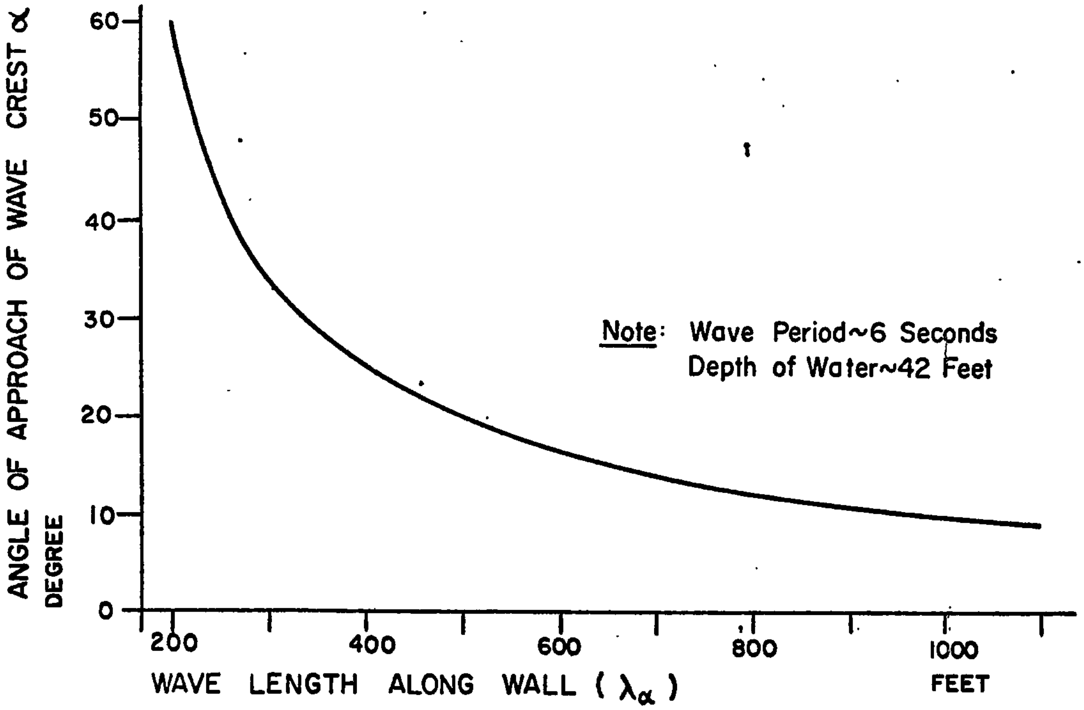
TRANSVERSE NATURAL OSCILLATIONS IN BASIN OF OCEAN TERMINALS

FIG. 14



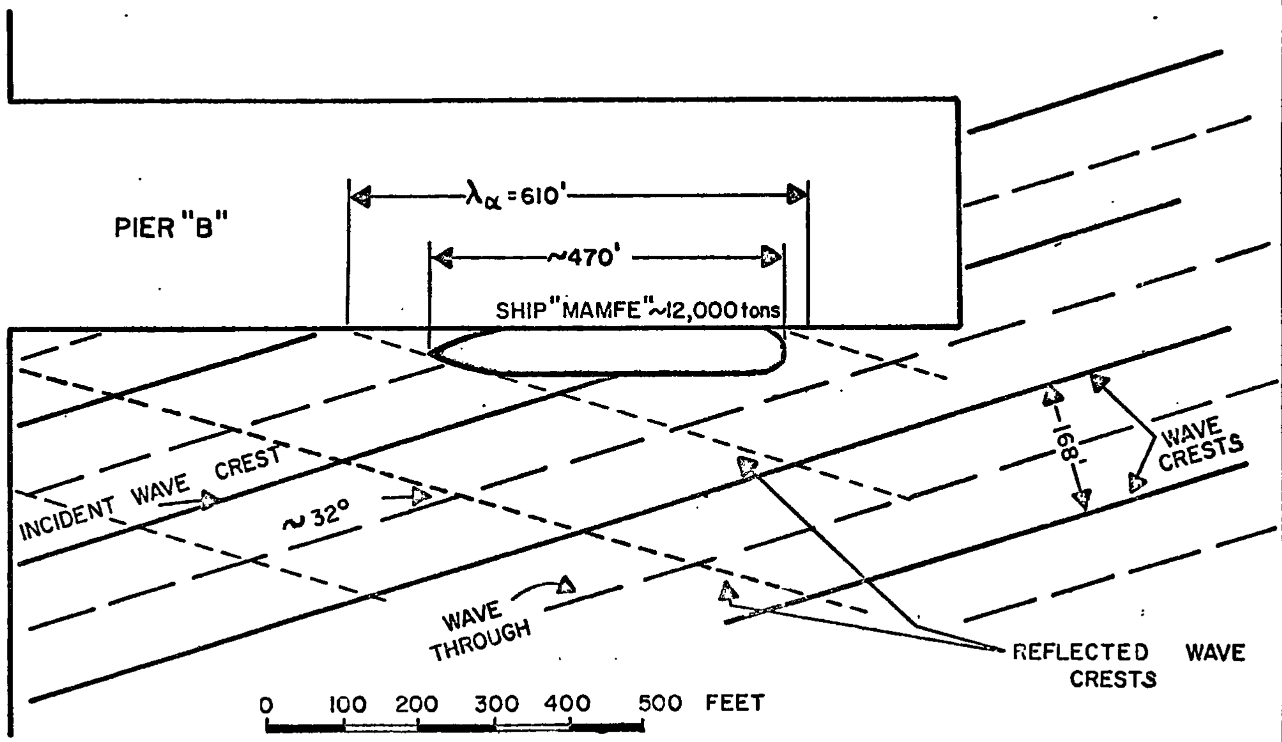
WAVE PATTERN OF A 6-SECOND WAVE TRAIN AT OCEAN TERMINALS

FIG. 15

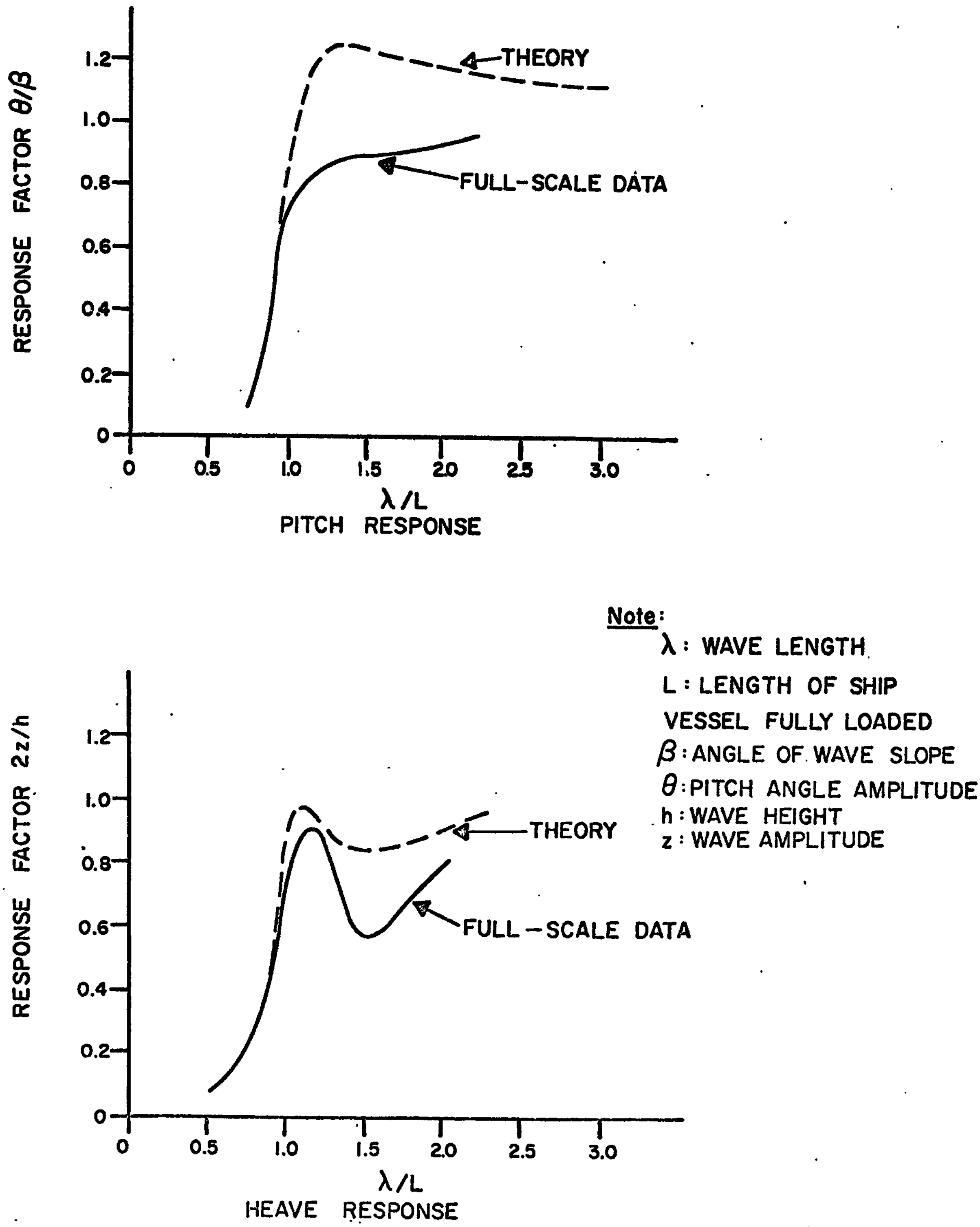


APPARENT WAVE LENGTHS AT OBLIQUE INCIDENCE

FIG. 16

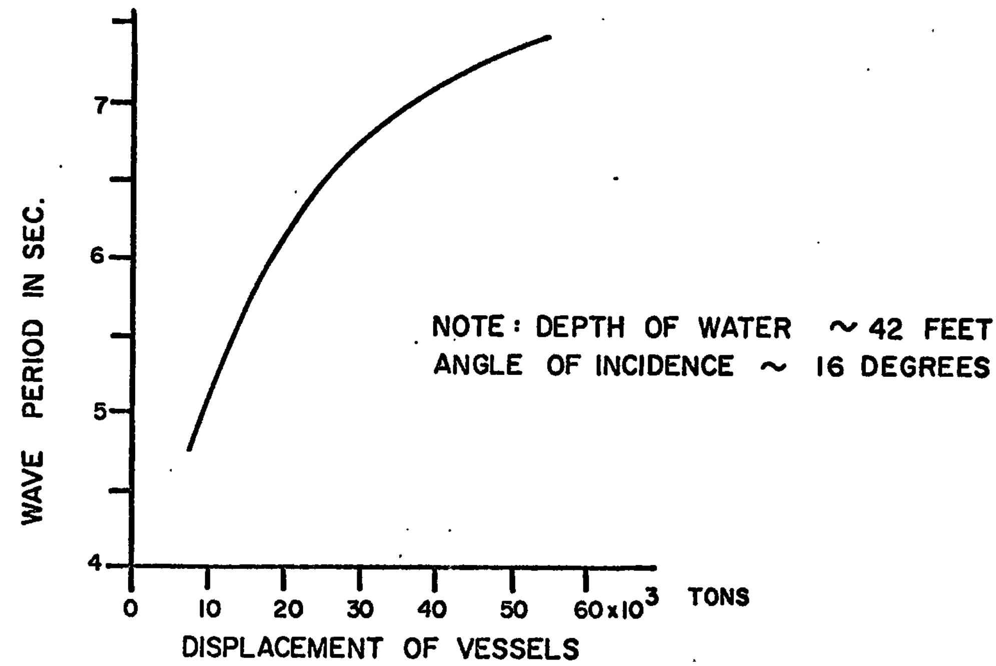


OBLIQUE INCIDENCE OF A 6-SECOND WAVE TRAIN AT PIER "B"



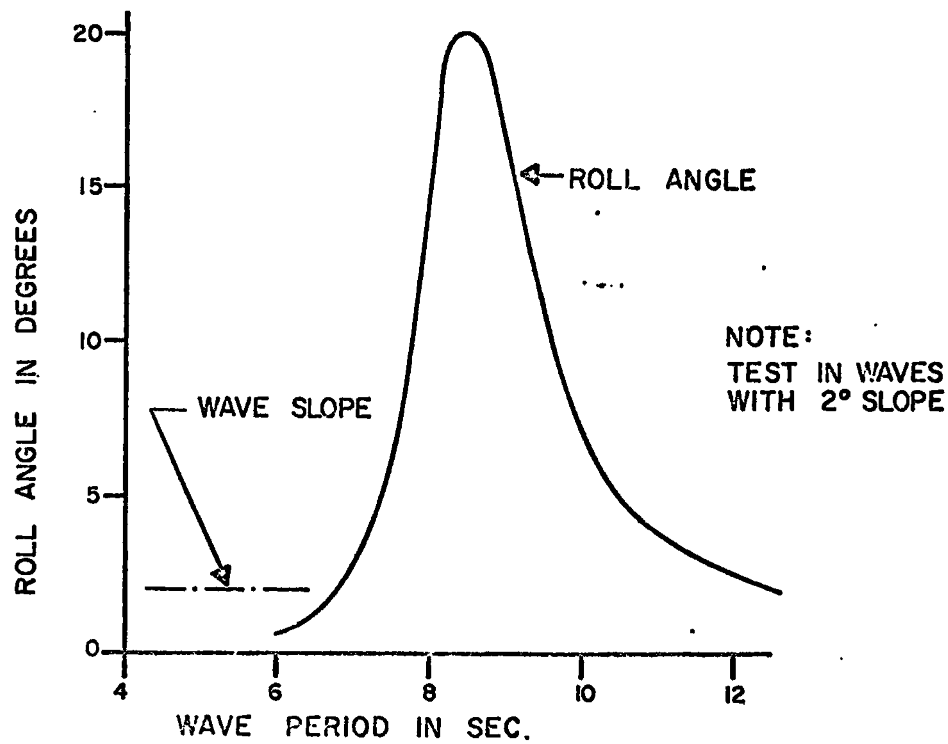
PITCH AND HEAVE RESPONSE FOR M.V. JORDAENS

FIG. 18

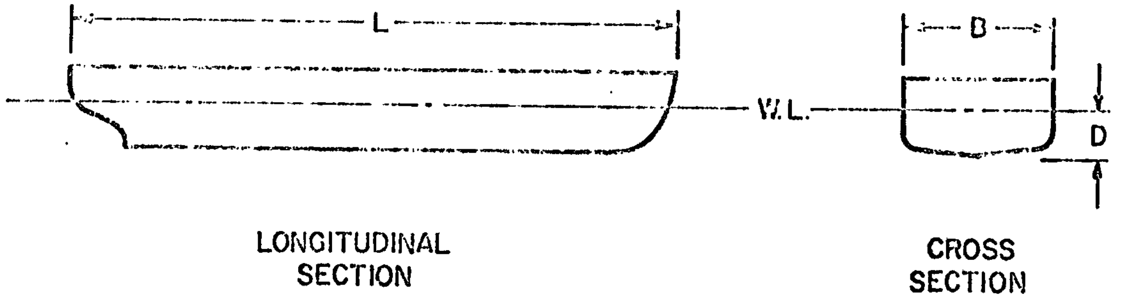


MAXIMUM PITCHING AND HEAVING RESPONSE AT PIER "B"

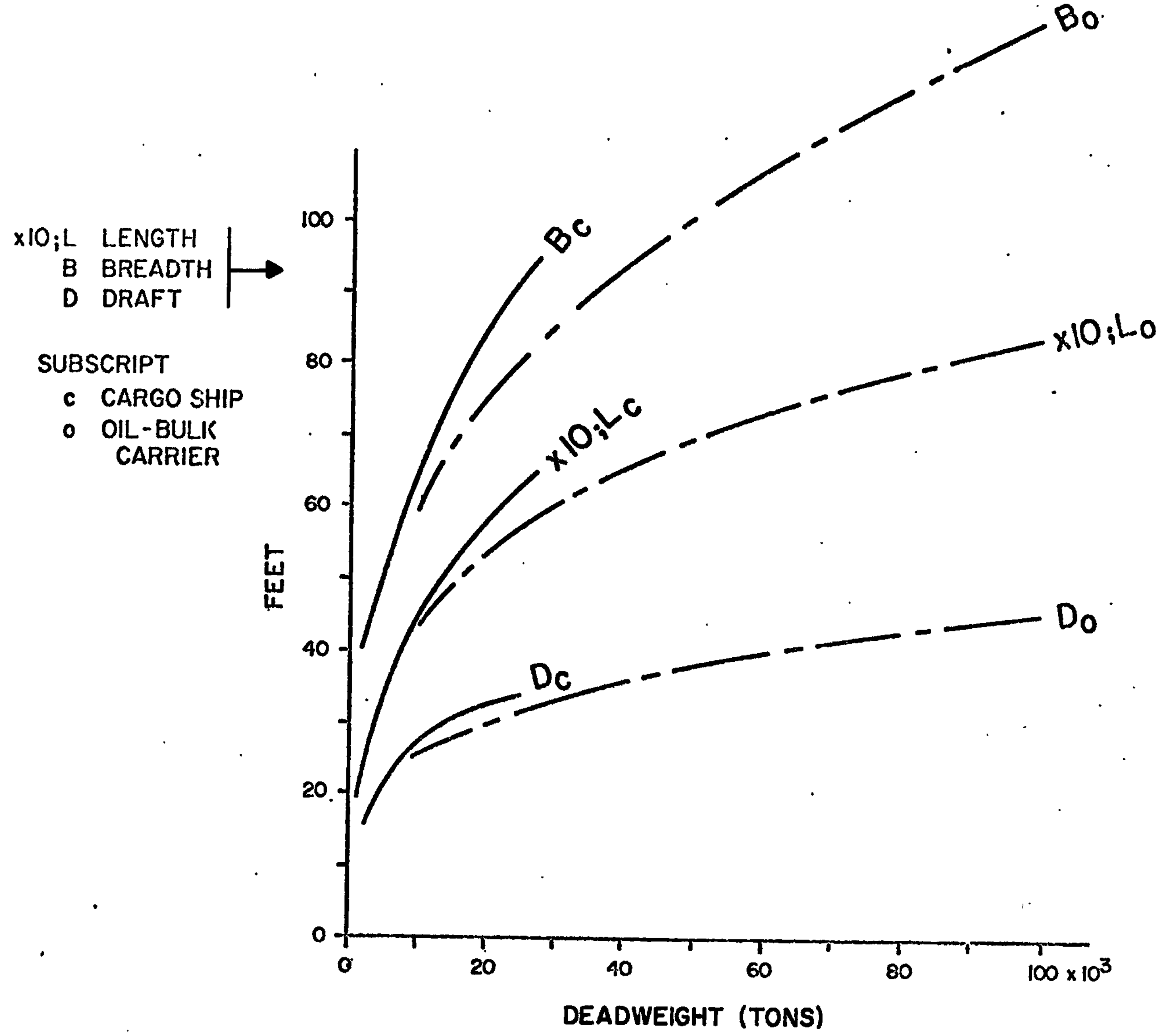
FIG. 19



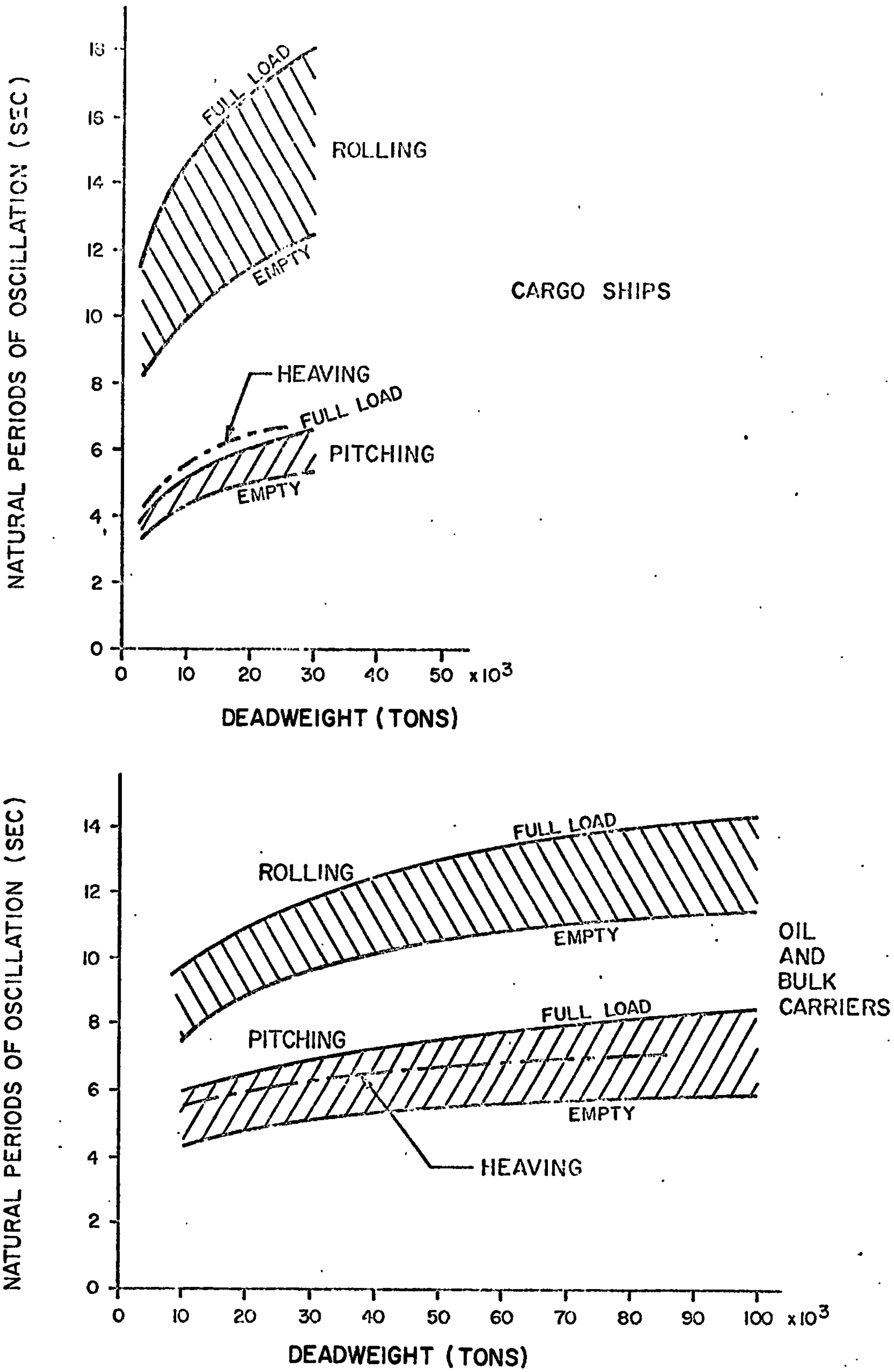
MODEL ROLLING TESTS OF CNAV "ENDEAVOUR"



SYMBOLS OF SHIP DIMENSIONS

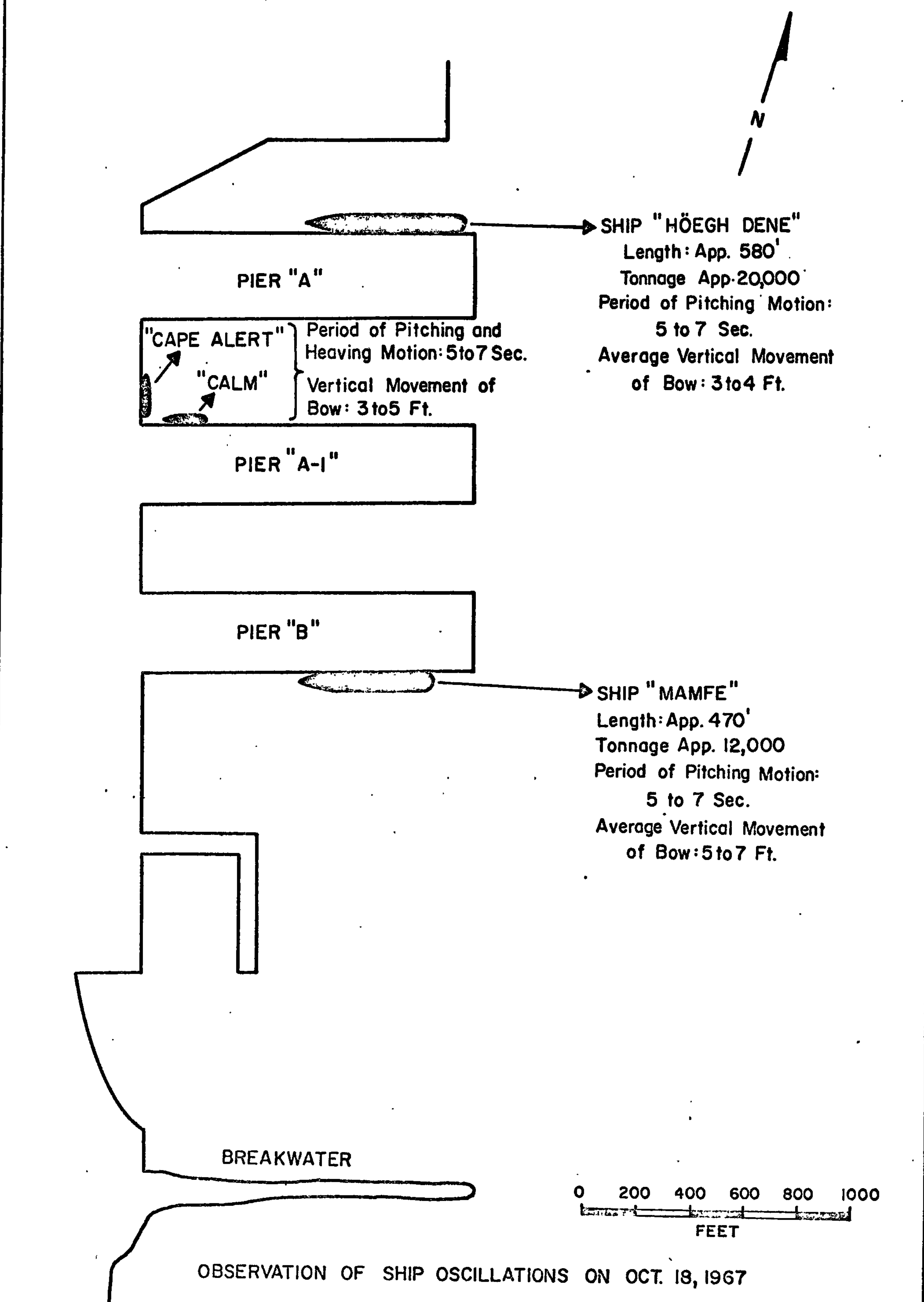


APPROXIMATE RELATIONSHIP BETWEEN LENGTH, BREADTH, AND DRAFT OF VESSELS.



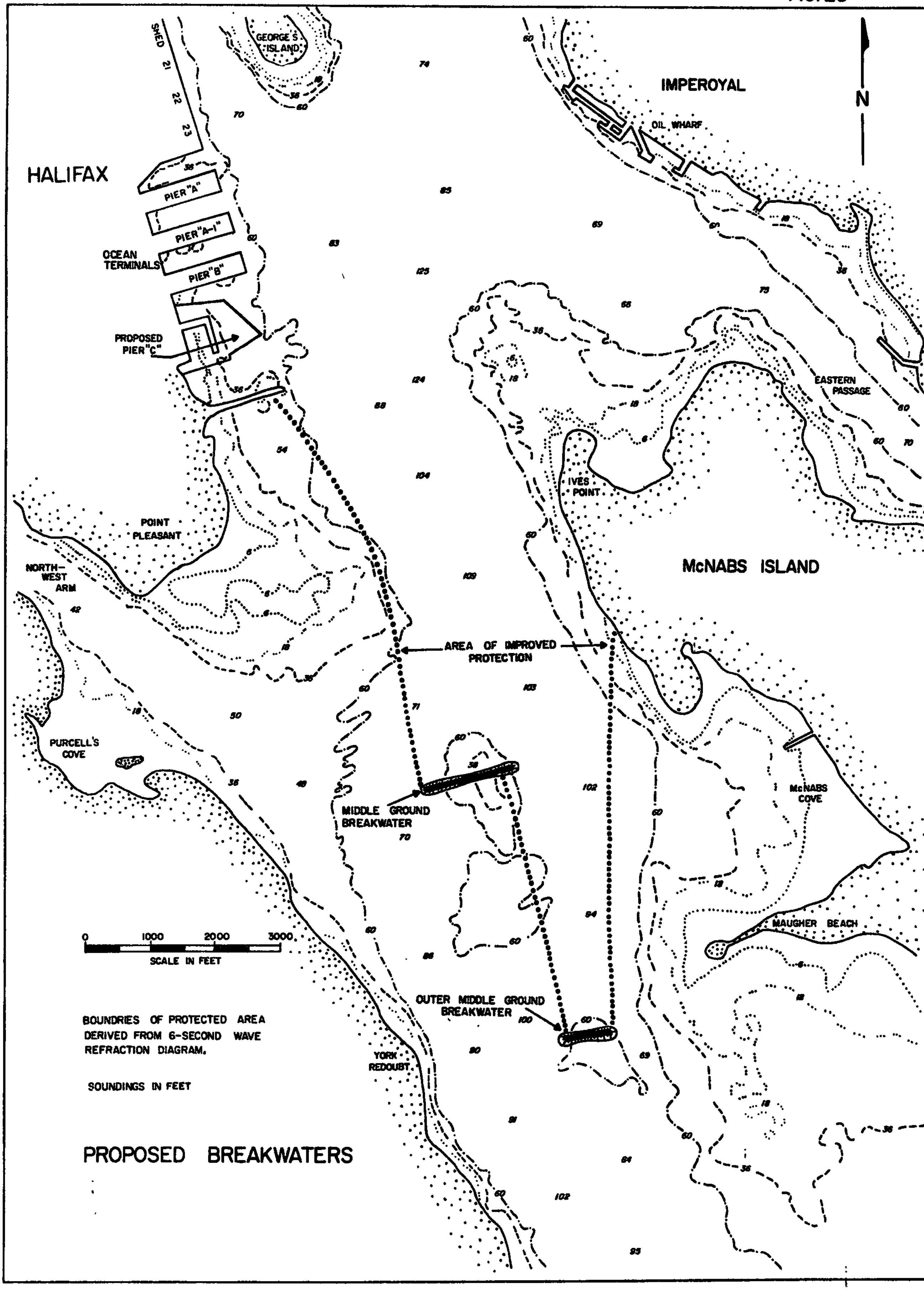
COMPUTED NATURAL PERIODS OF PITCH, HEAVE, & ROLL OF VESSELS

FIG. 22

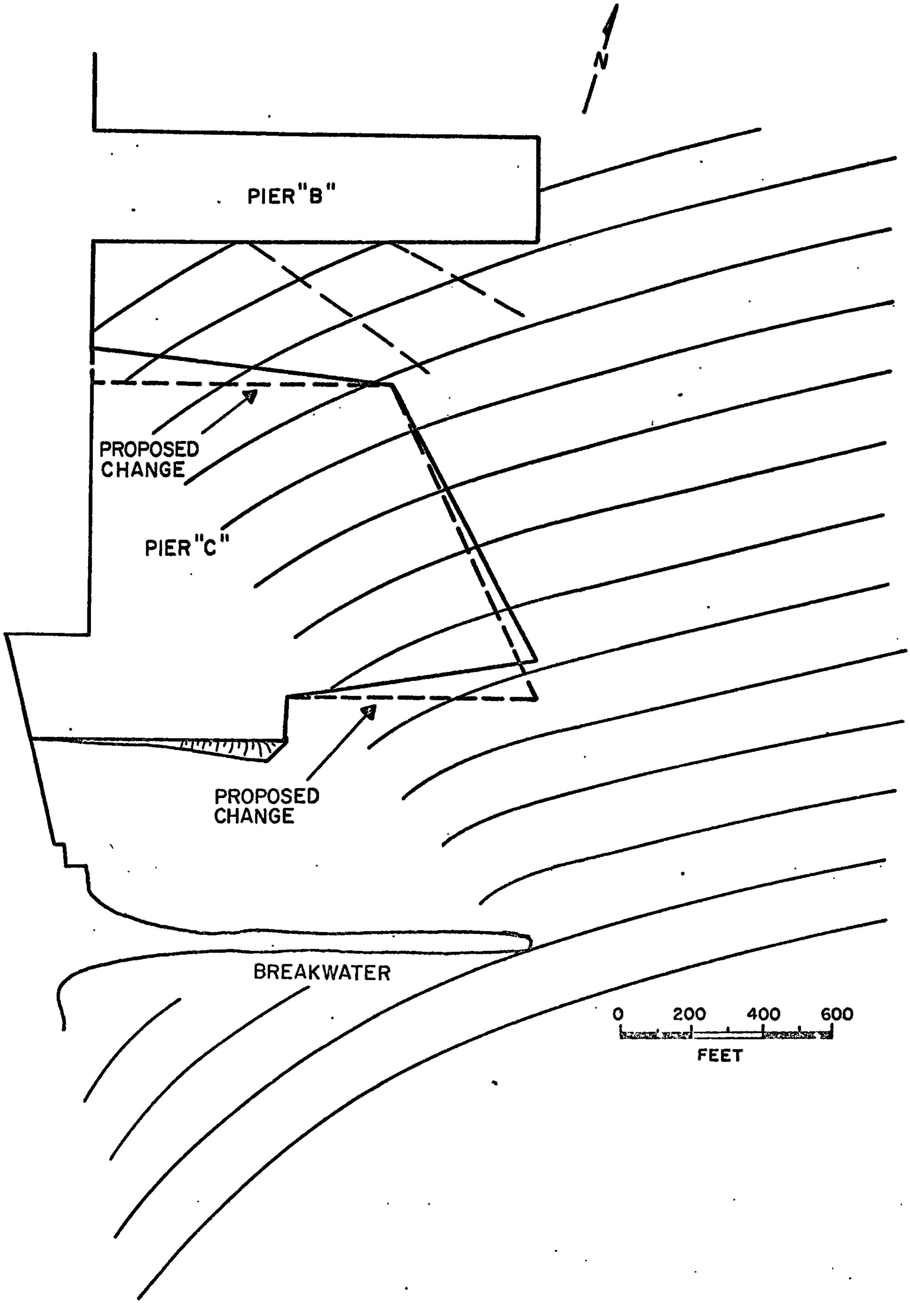


OBSERVATION OF SHIP OSCILLATIONS ON OCT. 18, 1967

FIG. 23

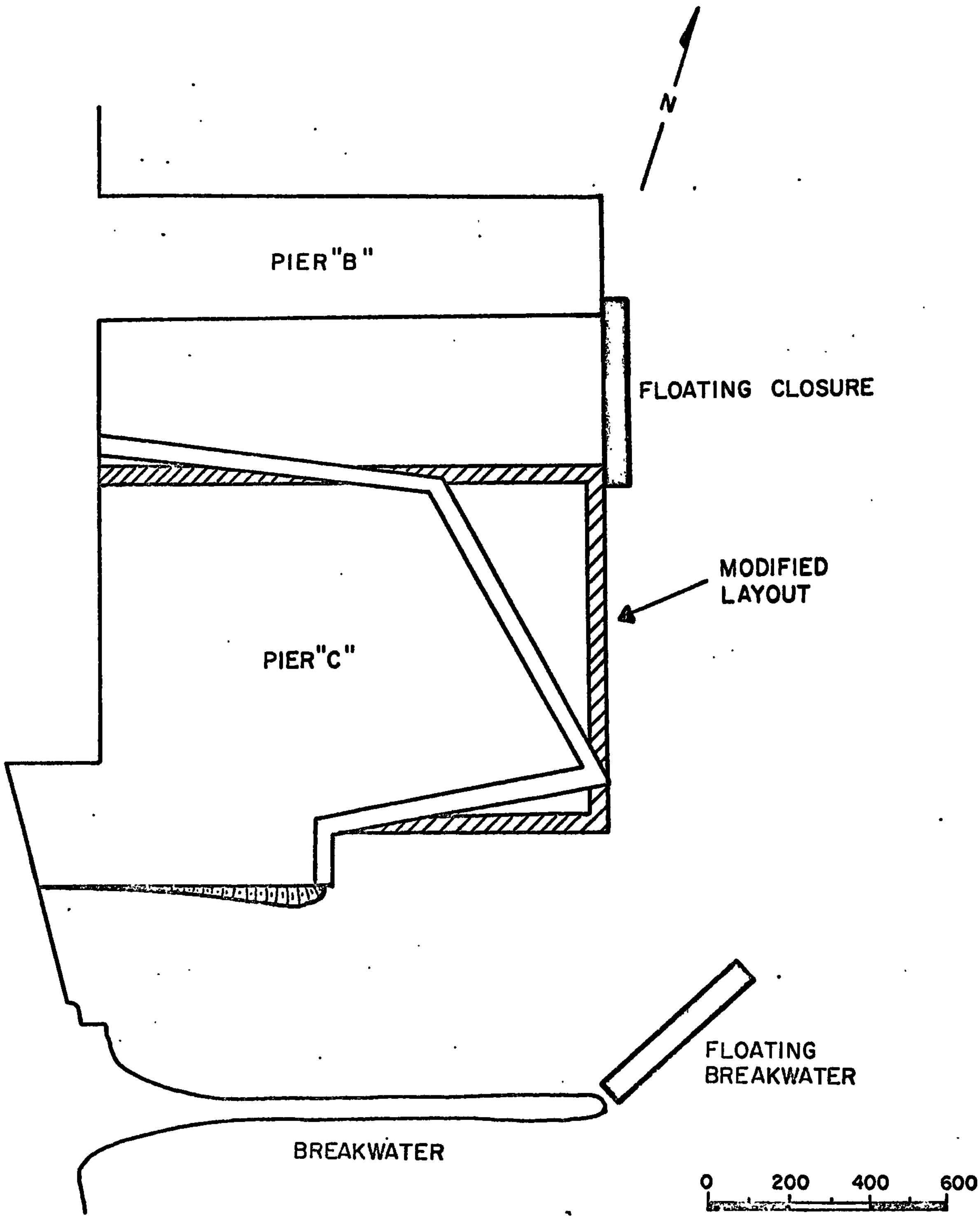


PROPOSED BREAKWATERS

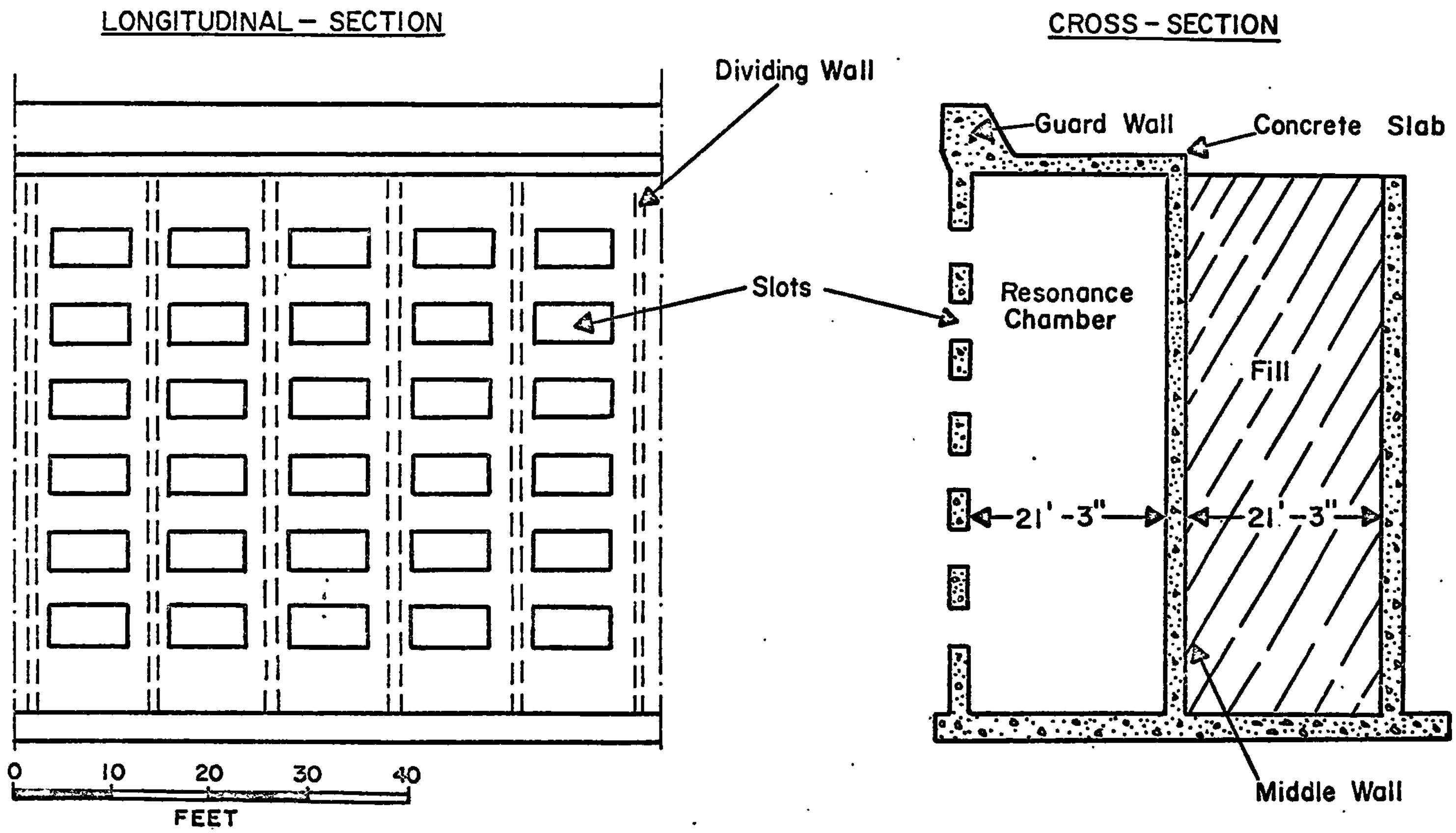


PROPOSED CHANGES IN LAYOUT TO PIER "C"

FIG. 25



INTERCHANGEABLE FLOATING CLOSURE—BREAKWATER



PERFORATED WALL

FIG. 26

9.0 APPENDIX.

Crane Control System

by E. S. Turner

The problem is to load and unload a ship moored to a wharf as it rises and falls in a swell. It is assumed that the vertical motion is about five feet and that the ship does not roll.

Consider the arrangement shown in Figure 1.

A portable box or cabinet "A" containing an accelerometer. power supply and transmitter would be placed on the deck of the ship. The accelerometer would be mounted on a vertical slide up and down which it could be moved at a controlled rate. With the accelerometer fixed on the slide, a signal having a frequency proportional to the vertical acceleration of the ship would be transmitted.

A similar accelerometer and transmitter would be fixed in a stout link supported from the crane hook at the bottom of which the cargo hook would be attached. This equipment would transmit a signal with a frequency proportional to the vertical acceleration of the crane hook.

A receiver "C" would be located on the crane to receive the signals from the two transmitters. The operation of the equipment in loading a ship would be as follows :-

The load would be picked up from the dock area and lowered into the hold of the ship in the usual way, stopping when the minimum distance between the ship and cargo was about 4 to 5 feet. The electronic control would be activated at this minimum distance and the signals from "A" and "B" would be continuously compared, integrated and amplified to control the hoisting machinery so that the load followed the vertical motion of the ship. The control on the cabinet "A" would then be operated to lower the accelerometer slowly and the load would likewise be lowered. On releasing the load, the crane hook would be raised initially by raising the accelerometer in "A" in readiness for the next load, then manually by switching off the electronic control.

The portable units "A" and "B" would be stored when not required.

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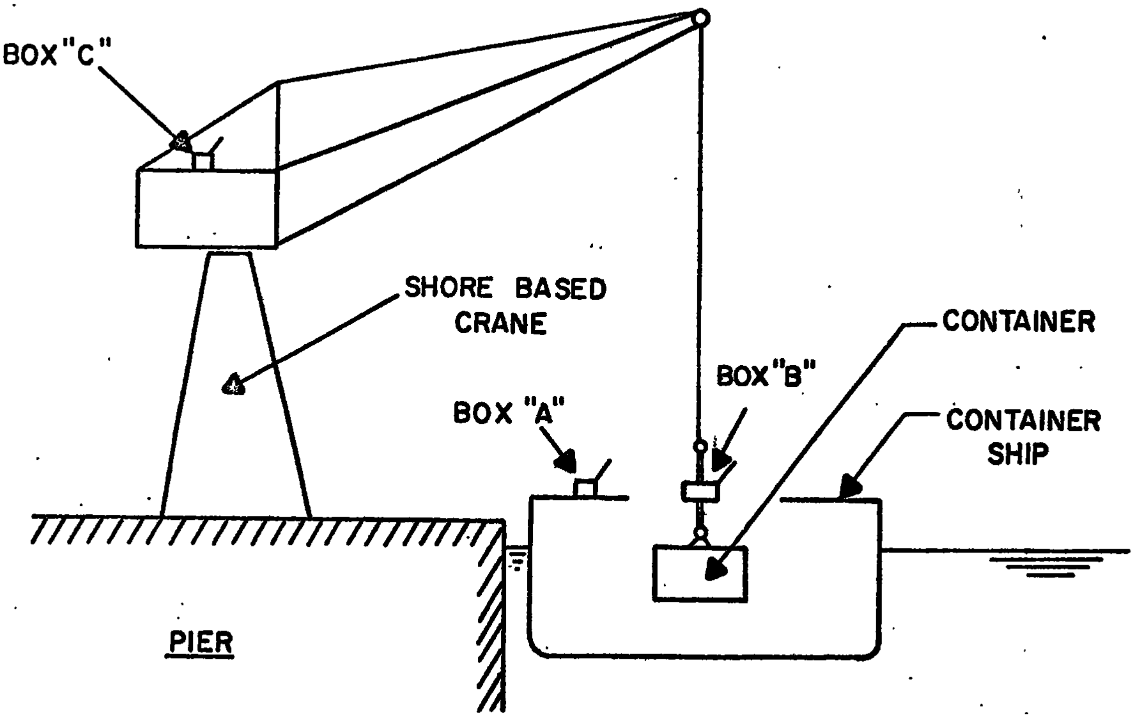
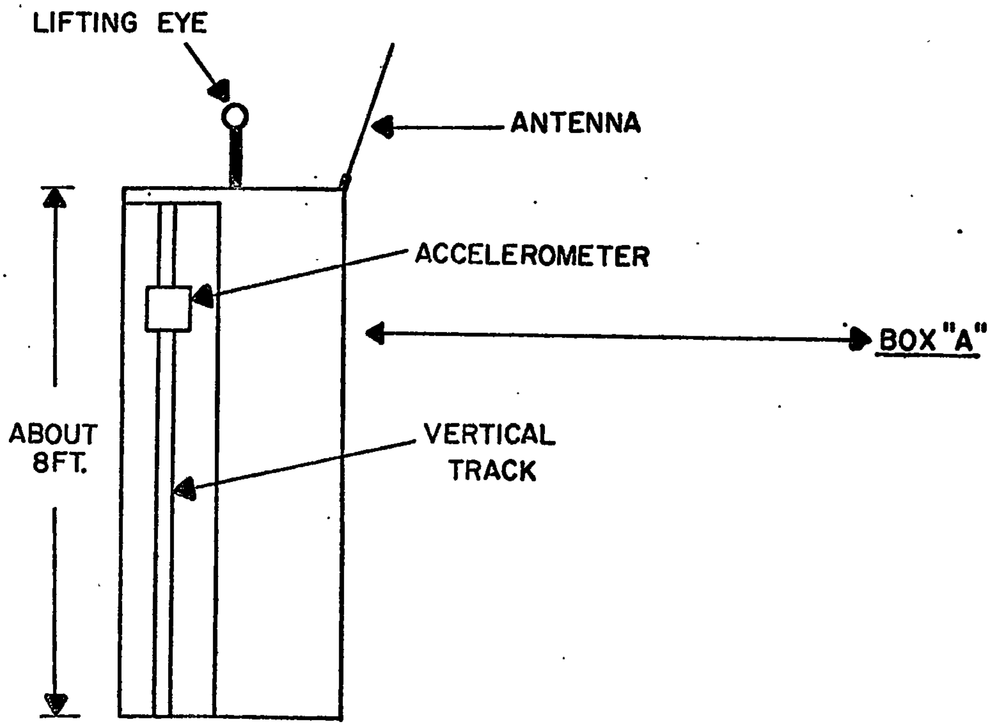


GENERAL ARRANGEMENT



CRANE CONTROL SYSTEM

E.T. (5/9/67)