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COLLEGE OF ENGINEERING
Department of Meteorology and Oceanography

Final Report

WAVE FORCES ON THE EAST BREAKWATER SHOREARM AT LORAIN, OHIO

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INTRODUCTION

Direct measurements of the pressures of waves incident on a breakwater in Lake Erie were made to produce data for an evaluation of existing theoretical and empirical wave pressure formulations. Measurements of meteorological and limnological parameters were taken concurrently for correlation with the wave pressure data and as input for evaluation studies.

The East Breakwater Shorearm at Lorain, Ohio was the site of the field studies which were initiated in September, 1968. The formation of ice on the breakwater and on the tower instrumentation terminated the field measurement program in December, 1968. Data were taken during November and December, 1968.

To evaluate the theoretical expressions for wave pressure, concurrent measurements of the following parameters are necessary during those times that waves approach normally to the breakwater:

a) Wave pressure profile on the breakwater.

b) Maximum height of the clapotis on the face of the breakwater.

c) Wave heights before the waves are affected by reflection from the breakwater.

d) Wave lengths for the undistrubed waves.

e) Depth of the water at the base of the breakwater.

During the few occurrences of waves approaching normally to the breakwater, one or more of the instruments was not operational so that simultaneous measurements of the above parameters were unobtainable.

Despite the lack of any complete sets of data, the form of the vertical wave pressure pattern was measured on 9 December 1968, when incident waves approached along a direction normal to the breakwater. The profiles of wave pressure from these data appear to verify the Sainflou form rather than the other empirical or theoretical profiles.

THEORETICAL AND EMPIRICAL RELATIONS

Early Measurements. Thomas Stevenson (Minikin, 1963) at Dunbar measured wave pressures of 3.2 tons/ft^2 or approximately 48 lbs/in^2 on a vertical wall. Minikin gives no details as to the location of Stevenson's wave dynamometer or to the distribution of forces or pressures over the face of the wall. As the height of the waves are not given, the above value of wave pressure only indicates the magnitude that might be expected.

Following the distruction of the East Genoa breakwater in Italy, Luigi Luiggi (Minikin, 1963) mounted dynamometers on a remaining breakwater and measured wave forces. He also piled quarry waste into cones on top of the remains of the destroyed breakwater. Each pile was made of rocks of uniform densith while the rock size varied from pile to pile. After a storm with 23 ft. waves, the rock piles had been leveled off at different depths and Luiggi was able to devise a diagram to represent the vertical distribution of forces against a vertical wall based on the monomum depth for which rock of a certain weight had not been moved. For a 23 ft. wave incident on an 82 ft. breakwater, he showed a maximum pressure of 3.0 tons/ft^2 at the still water level with the wave pressure dropping both above and below. He claimed his pressure profile diagram could be applied to any height wave by simple scaling. Thus, a 10 ft. wave would have a peak pressure of slightly less than 20 lb/in^2. This result was used to set the specification at 25 lb/in^2 for the pressure sensors used in this study.

Gaillard (Office of Division Engineer, 1938) used spring and diaphragm dynamometers on piers in Lake Superior to measure wave forces during his exhaustive studies of Great Lakes waves. These data are somewhat limited as each dynamometer recorded only the maximum reading for each storm. However, Gaillard was able to conclude that the impact of a wave on a vertical wall did not resemble that due to a solid body but apparently followed the law of dynamic pressure due to flowing water.

From their full scale measurements of the Prince Umberta mole at Genoa and from model experiments, Cagli and Stuckey (Minikin, 1963) concluded that the pressure distribution of a 5 m high wave, 110 m long would be as shown in Figure 1. Note that the height of the wave at the wall is 8.5 m or more than 2 1/2 times the amplitude of the wave in the open sea.

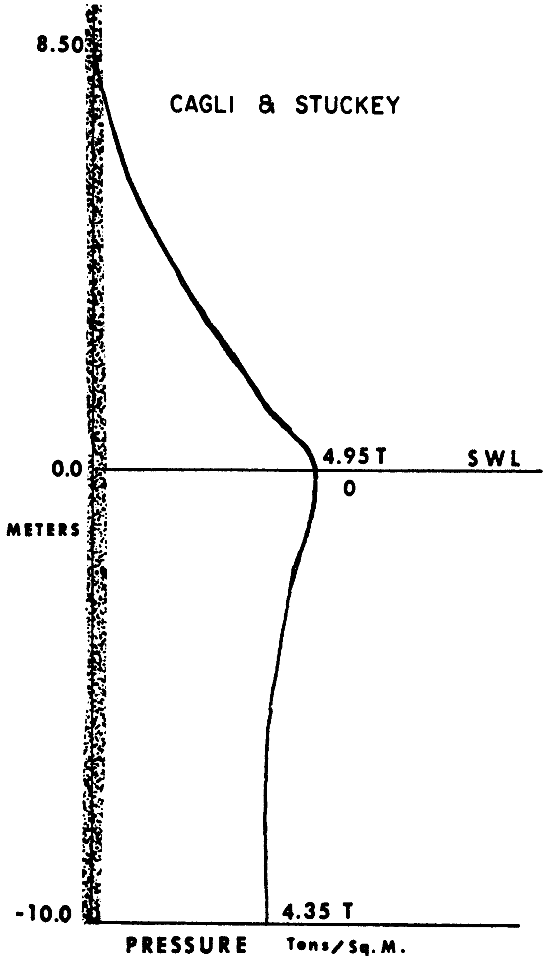


Figure 1. Pressure profile on a vertical wall due to an undisturbed wave 5 m high, 100 m long as determined by Cagli and Stuckey.

In a study at Dieppe, France during 1933-35, Rouville and Petry (Minikin, 1963) showed that the wave pressure against a wall is hydrostatic when the wave does not break but rises and falls, as a standing wave, in contact with the wall (clapotis). They found that this type of wave rises somewhat greater than twice the height it had before reaching the wall. Some 3% of the measured waves exhibited pressures greater than hydrostatic and of these 3% some exceptional pressures were measured. The duration of exceptionally high pressure cases was short, with the highest pressures occurring for waves with the shortest durations. Peak values of 6 tons/ft^2 were observed. These unusually high pressures probably were manifestations of the shock pressures due to breaking waves.

THEORETICAL FORMULATIONS

In 1923, Bénézit (Office of Division Engineer, 1938) applied the hydrostatic pressure concept to non-breaking waves with the assumption that the clapotis will have twice the amplitude of an approaching wave. With the additional assumption of the trochoidal theory of wave motion in deep water he was able to develop formulas for the wave pressures on the vertical wall.

Sainflou (Minikin, 1963) asserted in 1928 that particle motion near a breakwater should follow shallow water elliptical orbits rather than deep water circular paths. He modified Bénézit's formulation of wave pressures to obtain the following formulation for the pressures produced on a vertical wlll subject to clapotis: a) The pressure is zero at a height of $H + h_o$; i.e., the wave height in the open sea, H, plus an increase, h_o, in mean water level at the wall due to the clapotis. b) The maximum pressure due to the wave reflection occurs at the still water level. c) Below still water level, the wave pressure diminishes slightly if the water depth is small compared to the wave length. The wave pressure at the base of the breakwater is:

where density of water, H = height of wave before reaching wall, L = length of wave, crest to crest and D = depth of water at base of breakwater. The maximum intensity of wave pressure (at the still water level) is:

Figure 2 shows a pressure diagram, according to Sainflou, on a vertical wall at the time the water has reached its highest point during a clapotis. P_1, P_2, h_o, H and D are illustrated in this figure.

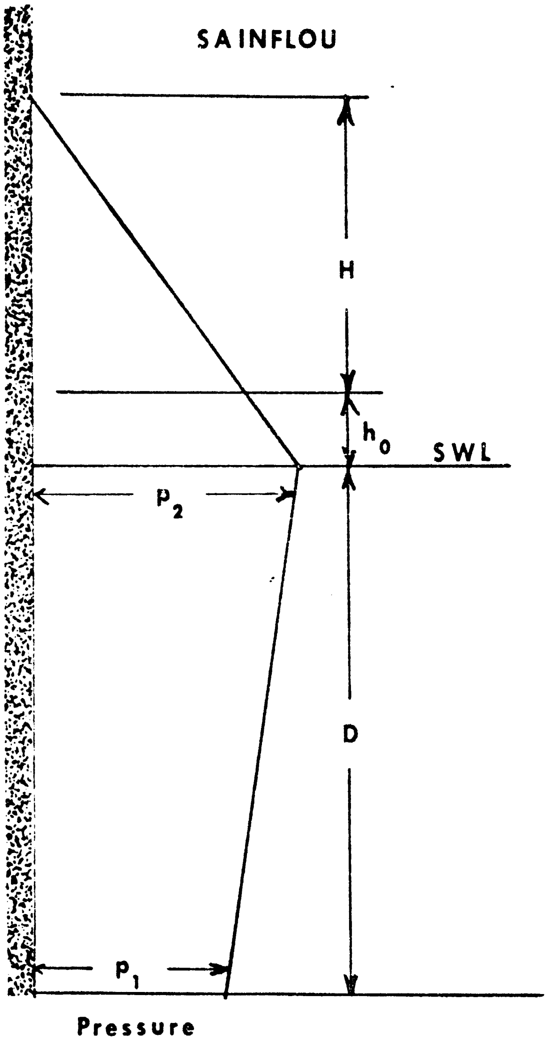


Figure 2. Maximum pressure conditions on a vertical wall due to an undisturbed wave of height H, according to Sainflou.

Minikin proposed a simplified solution to the pressures produced on a vertical wall by a wave undergoing clapotis. His proposed solution is: a) The zero point of the pressure diagram is at a height 1.66 H above still water level. b) The maximum pressure is at SWL and is: $P_2 =$ H, the hydrostatic pressure due to a wave of height H in the open sea. c) The pressure increases linearly between the zero point at the top of the clapotis and the maximum pressure at SWL. d) Below SWL the wave pressure is uniform and is equal to the maximum pressure p_2. Figure 3 illustrates a pressure-diagram according to Minikin.

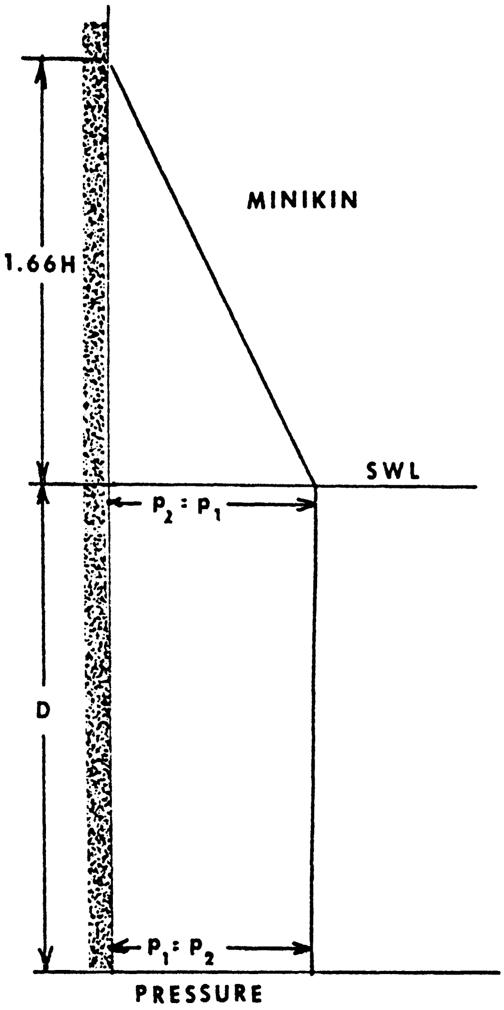


Figure 3. Wave pressure diagram as formulated by Minikin for an open ocean wave of height H as it reflects on a vertical wall.

BREAKING WAVES

Bagnold and White (Minikin, 1963) studied breaking waves in a wave tank with a sloping beach and a vertical wall. They found that with wave-making conditions set very precisely, breaking waves could be made that produced high shock-pressures on the vertical wall. The physical mechanism whereby these high pressures could be produced were described as: a) An advancing wave front must curl over at the crest so that a pocket of air is trapped between the water and the vertical wall. b) If the horizontal length of the air pocket exceeds its thickness by two times or more, high shock-pressures will be developed. c) The water of the wave acts as a shock-wave driver on the entrapped air to produce the high shock-pressures. d) The amplitudes of the shock pressures are dependent on irregulatities of the wall and on disturbances in the water from preceeding waves. Bagnold estimated from similarity considerations that full-scale pressures as great as 60 tons/ft^2 could exist.

Investigations of breakwater failures due to breaking waves have led to estimates of mean pressures of 2 tons/ft^2 over the face of the breakwater, while peak pressures must have been at least twice as large. Minikin states that if the water depth is at least 1 1/4 times the height of the wave, breaking waves will probably not occur. Instead the wave crest will move up the wall to a height above still water level greater than the height of the undisturbed wave and will then descend into the trough to a depth less than the height of the undistrubed wave. As Lake Erie is 15 to 25 ft. deep off the Lorain breakwater and as wave heights were not expected to exceed 12-15 ft., breaking waves were expected to occur very rarely. Coupling the scarcity of breaking waves with the small probability that an air pocket would be entrapped at just the right location so that a shock wave could be produced and measured by pressure sensors, it seemed that an entire season could pass with very few or no data if the measurement program was established for breaking waves. On the other hand, clapotis will occur most of the time and pressure measurements anywhere on the breakwater within the wave reflection region will be meaningful. Therefore, pressures on the breakwater due to clapotis were chosen to be measured and breaking-wave shock-pressures were left to be studied at another time. Thus, the field measurement program at Lorain, Ohio, was conceived and executed to obtain full-scale experimental data for an evaluation of the applicability of the previously discussed clapotis relations to Great Lakes conditions.

THE FIELD MEASUREMENT PROGRAM

Location. The East Breakwater Shorearm in Lake Erie at Lorain, Ohio, was chosen as the site for field measurements for the following reasons: a) It has vertical walls. b) It has no rubble toe at the base of the breakwater to complicate the flow patterns. c) It is oriented in a NW-SE direction (N 54° - 46' - 38.2" w) so that NE winds on Lake Erie have a long fetch and can produce large waves having a direction of propagation normal to the breakwater. d) The breakwater is constructed of steel piles in the form of circular caissons of 35 ft. diameter filled with rubble and capped with concrete. e) The breakwater connects to shore for easy access and is owned by the Corps of Engineers and thus readily available for use. Figure 4 shows the breakwater at the test site.

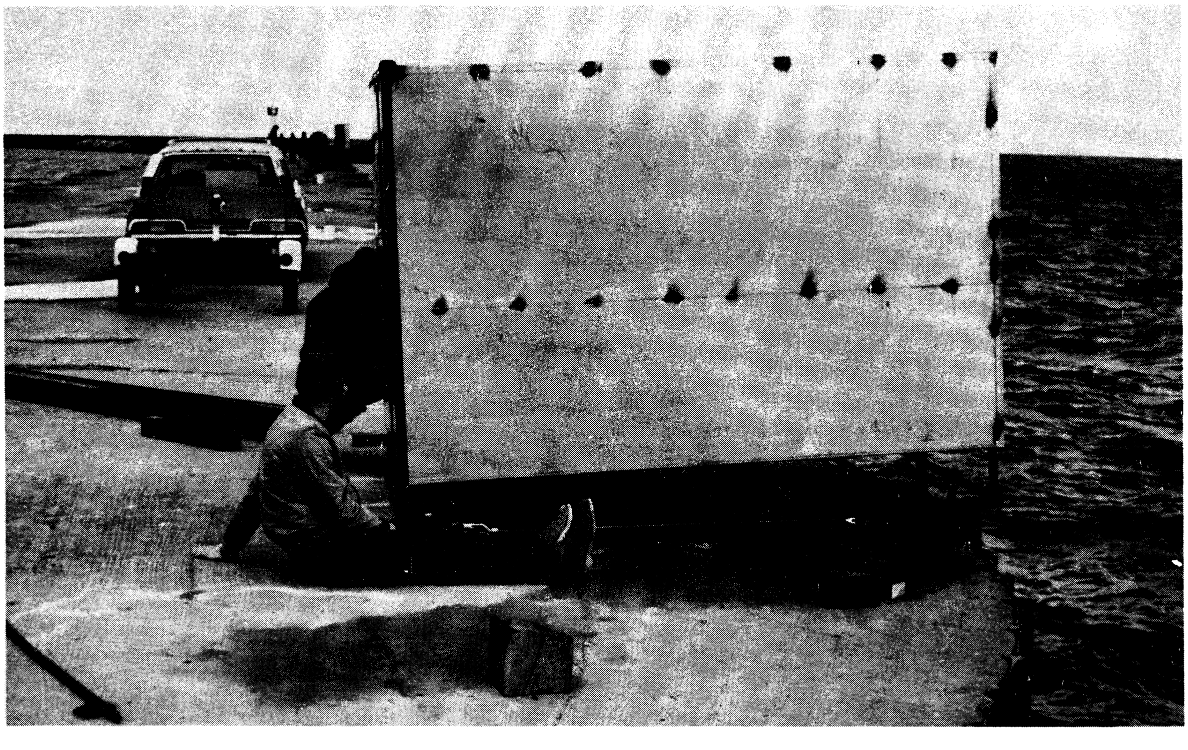


Figure 4. The test site on the East Breakwater Shorearm at Lorain, Ohio, showing the diving stage used by workmen both above and below the water.

Variables measured at the breakwater.

a. Wave Pressures: Strain-gage pressure transducers (Consolidated Electrodynamics Corporation Model #4-313-0002) with an active range of 0-25 lbs/in^2 absolute pressure were selected as the wave pressure sensors. These sensors are of sealed construction and when connected with the appropriate bridge circuit produce an analog voltage proportional to the total pressure on the face of the gage. A risk of possible damage to the sensor due to over-pressure by a breaking wave or mechanical damage due to impact by solid debris in the water existed; however, only one sensor was damaged during two months exposure so the risk was minimal. These sensors were flush mounted in ¼ in. steel plates which were bolted to Z frames attached to the breakwater as shown in Figure 5. (SEE FIGURE 5) The Z frames were fastened to the steel cassion of the breakwater by 3/8" studs driven into the steel breakwater wall with a .38 caliber stud gun. (Mine Safety Appliance Co. Model NUD 38). Cables from these sensors as well as the other power and signal cables were brought to the top of the breakwater behind the steel plates and thus were well protected from damage.

The wave pressure sensors were to be mounted in an array as shown in Figure 6. (SEE FIGURE 6) The vertical array of seven sensors was designed to measure the pressure profile both above and below the still water level in order to evaluate the models discussed above. They were mounted with respect to the expected still water level according to the lake level forecasts of the U. S. Lake Survey. As these forecasts do not consider the lake set-up nor the change of mean lake level with wave reflection, there was no assurance that #4 sensor would be at either still water level or mean water level at the breakwater. Sensors #8 and #9 were planned to

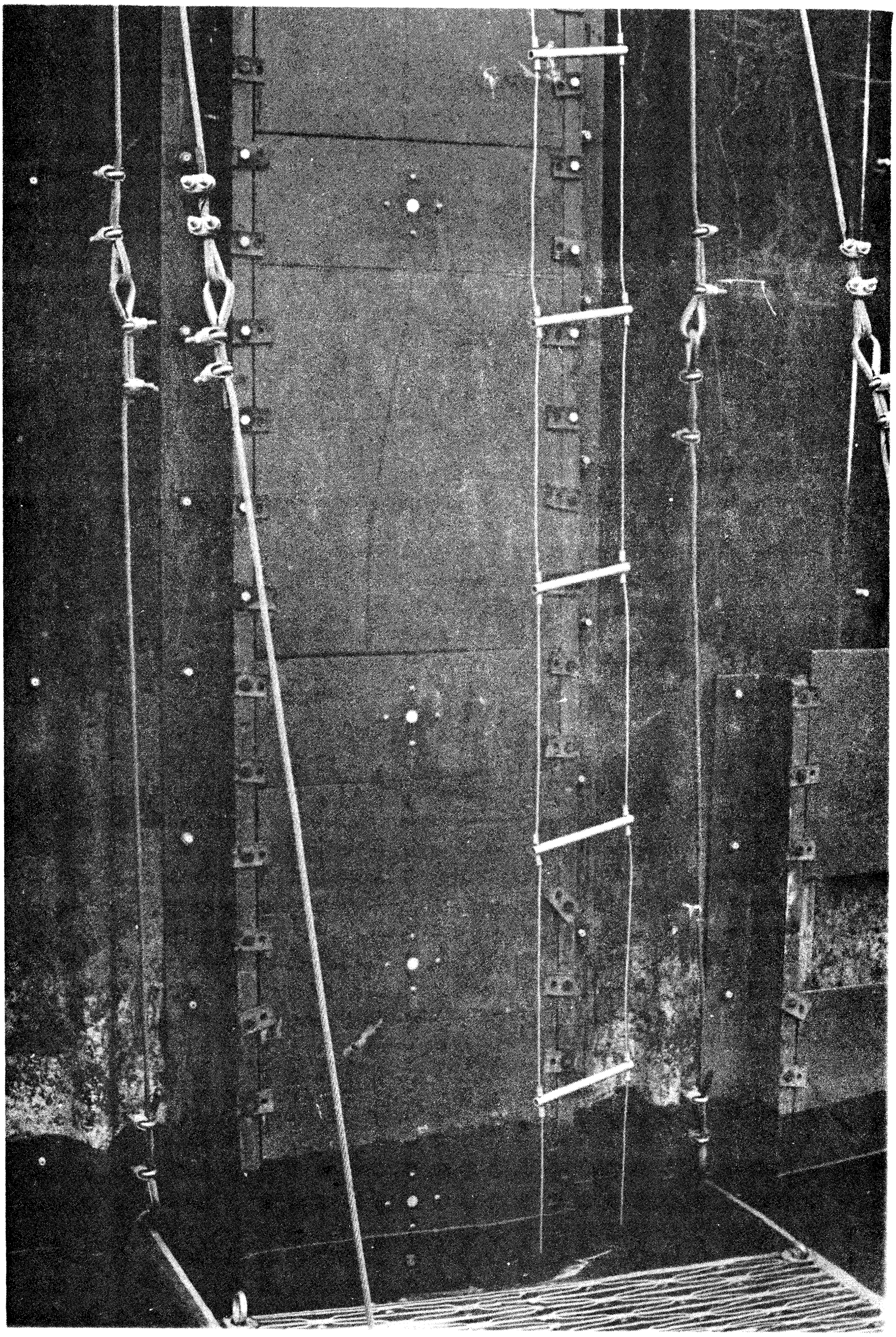


Figure 5. Mounting of pressure sensors on the Loraine Breakwater. The ladder and diving stage were used for installation and maintenance only and were removed during operation.

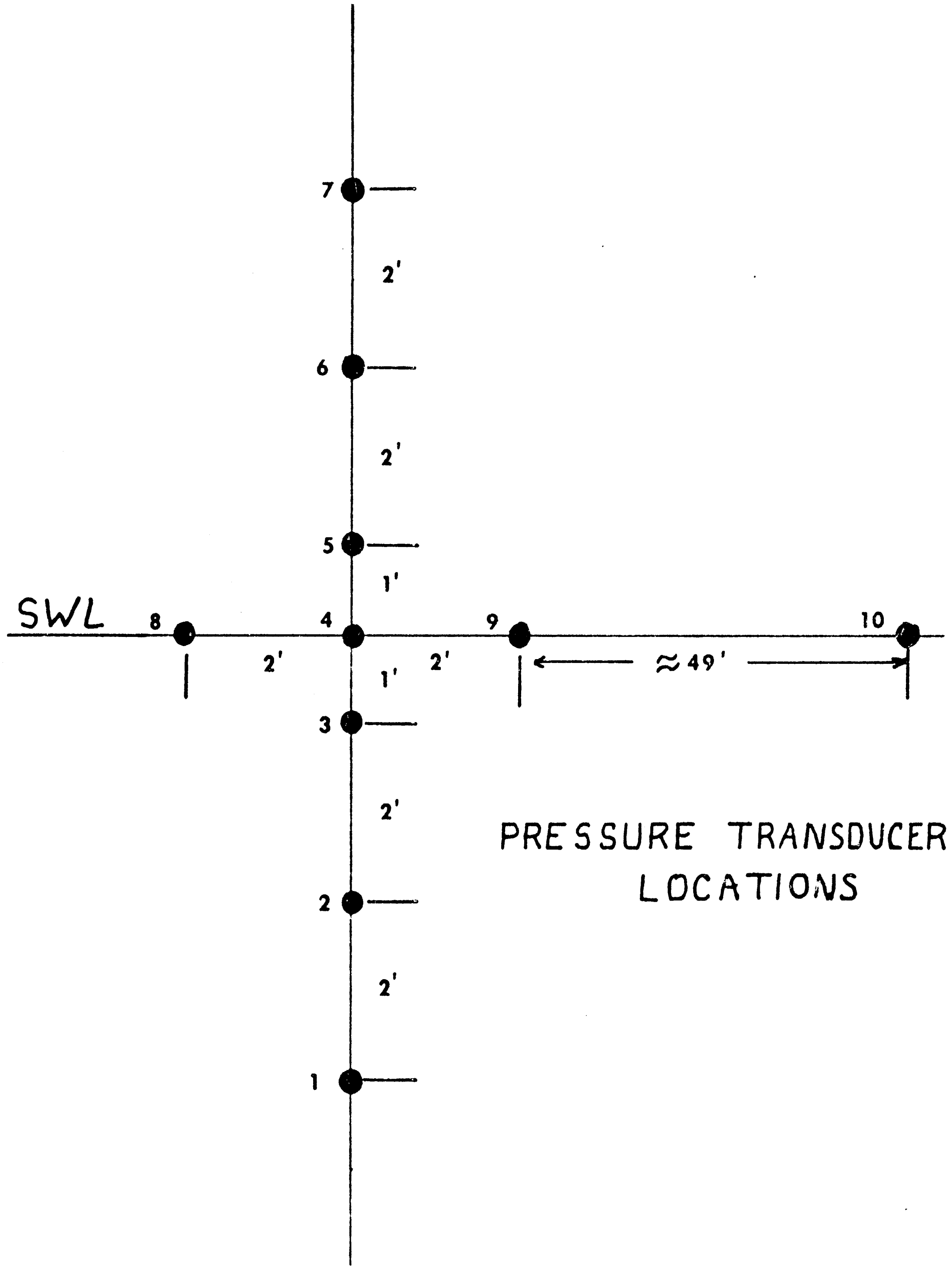


Figure 6. Location of wave pressure sensors on the Lorain breakwater.

measure horizontal variations in the wave pressures, however #8 had to be removed so that the staff wave-height gage could be mounted in close proximity to the pressure sensors. Gage #10 was to be mounted far enough away from the primary sensor array so that any time differences in the occurrences of peak pressure between it and sensor #4 could be related to the direction of the incoming wave. Due to the requirements of more urgent work, neither #9 or #10 were made operational during the investigation and wave direction was not determined.

b. Breakwater Wave Height: The heights of the waves on the breakwater were measured by a staff wave-gage mounted on the breakwater near the pressure measuring array. This gage resolved water surface elevation to .2 ft. It is visible to the left of the pressure sensors in Figure 7. (SEE FIGURE 7) From these data, values of $(H + h_o)$ in Sainflou's theory can be determined.

c. Breakwater Lake Level: A 16 in. diameter steel pipe 18 ft. long with a small bottom hole was mounted on the breakwater to act as a stilling basin for lake level measurements as shown in Figure 8. A lake level gage was mounted on top of the pipe with its float and counterweight inside. By comparing data from this gage with those from an identical lake level gage on the tower located 1800 ft. NE of the breakwater, values of h_o were calculated. (SEE FIGURE 8)

d. Harbor Water Level: Another stilling basin and a lake level gage of the same design were mounted on the harbor side of the breakwater. While the data from this gage are of no direct concern to the wave pressure problem they can be compared to the other water level data to determine effects of winds from various directions, etc., on harbor water levels.

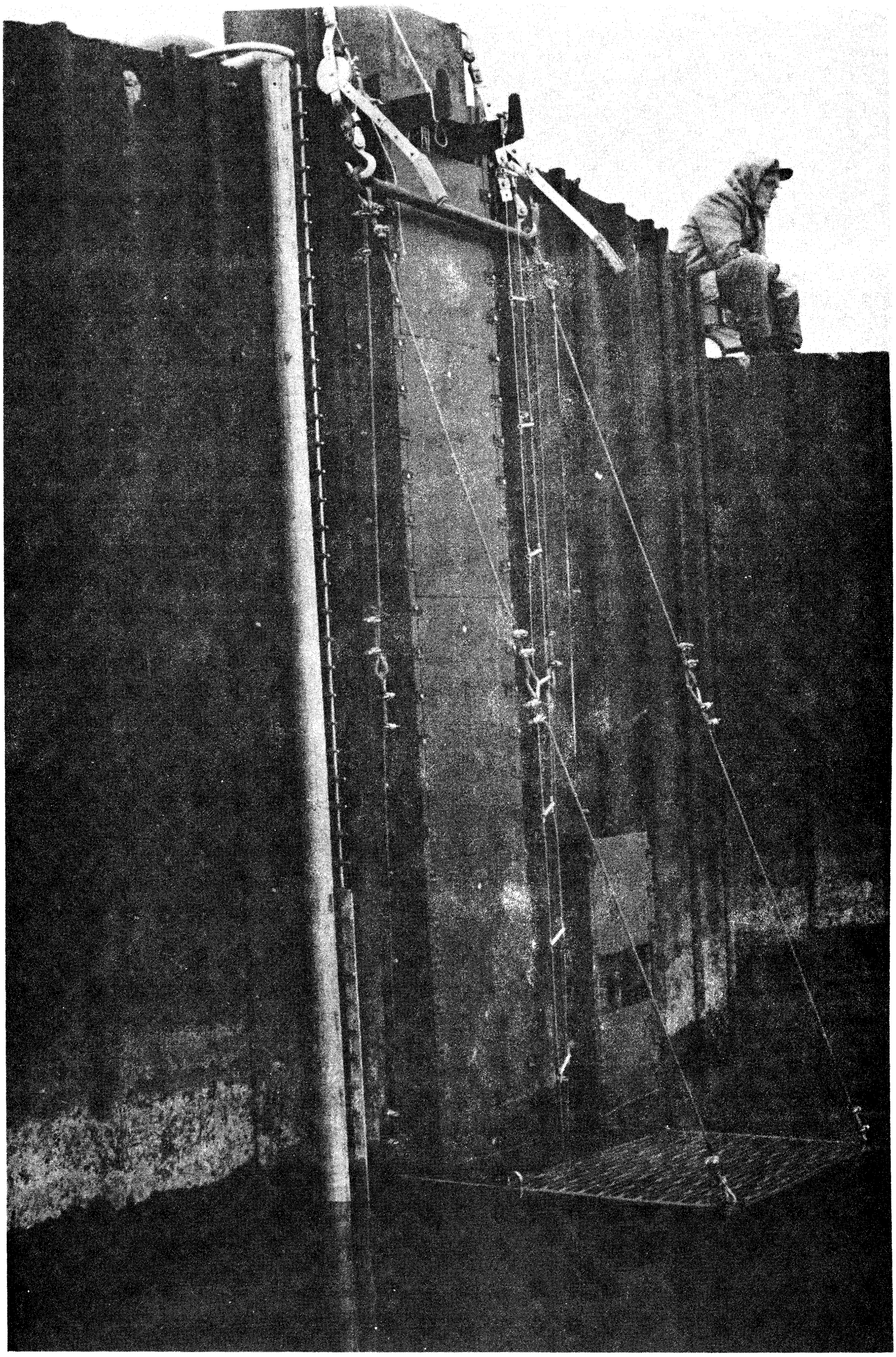
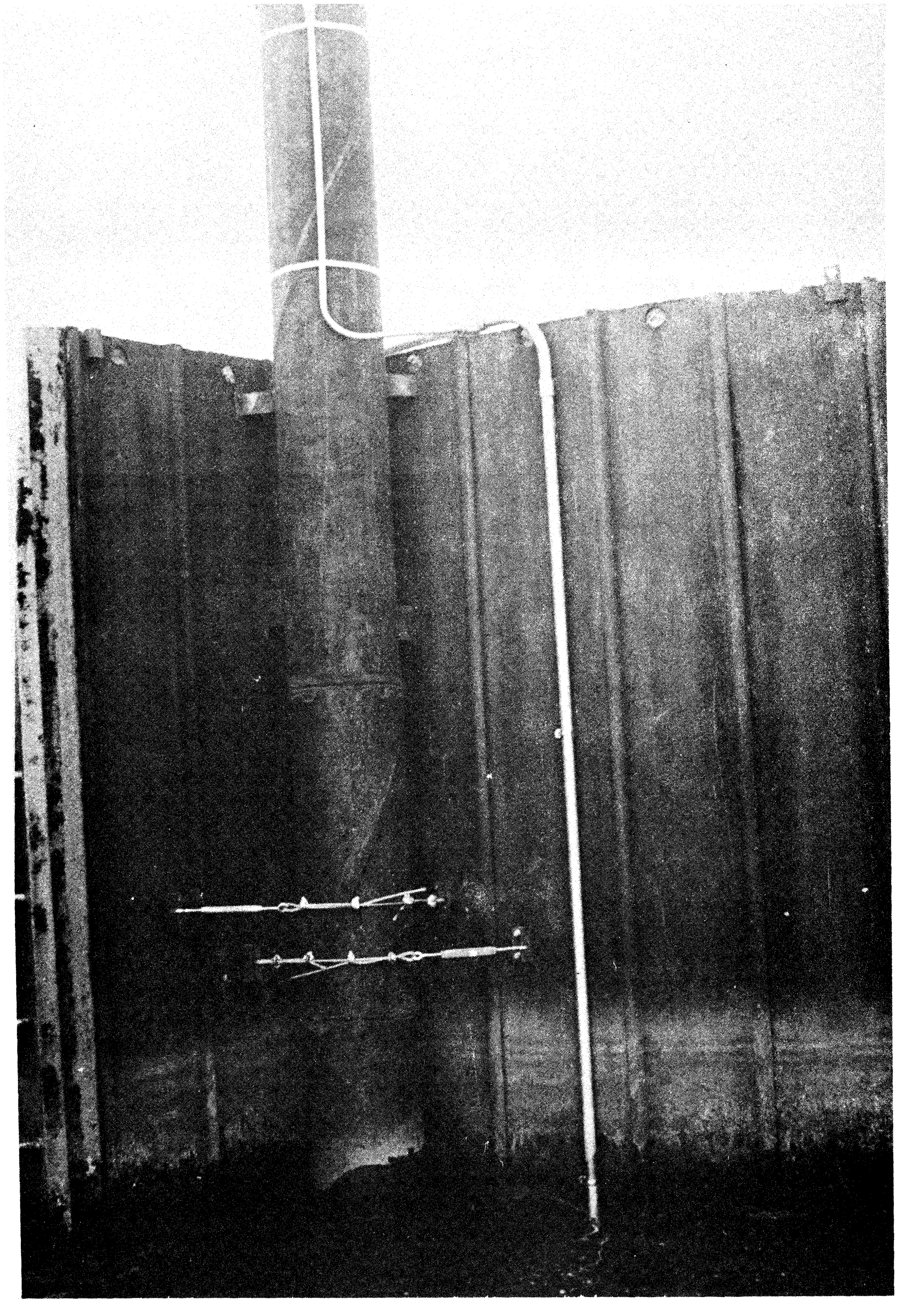


Figure 7. Location of staff wave gage.

Figure 8. Stilling basin used for lake level measurements.



e. Water Temperature: A thermograph modified to produce an analog voltage proportional to the temperature of the sensor bulb was used to measure water temperature. The sensor bulb was located behind the pressure sensor plates at a water depth of about 6 ft. This location protected the bulb from damage due to wave action but allowed water to move about it in order to obtain a representative water temperature.

f. Air Temperature: Air temperature was measured with an identical thermograph in the instrument shelter with its bulb mounted in an aspirated system that pulled air in from the north side of the shelter.

The instrumented tower. A 50 ft. triangular steel tower, set on the lake bottom in 25 ft. of water and guyed to three large ship anchors was used to support the equipment installed for the measurement of open-water wave conditions (Figure 9). The tower was located on a line normal to the breakwater at the instrumented site and 1800 ft. from the breakwater. Electrical power was transmitted to the tower and signals returned to the instrument shelter on the breakwater by submerged cables. (SEE FIGURE 9)

Variables measured at the tower.

a. Wave Height: The wave height was measured using a staff wavegage (Figure 10) identical to the one on the breakwater. These data constitute the open water wave height or H values required by Minikin's and Sainflou's formulations.

b. Lake Level: A water level gage identical to the two used on the breakwater was mounted on a 6 in. diameter stilling basin attached to the tower as shown in Figure 10. (SEE FIGURE 10)

c. Wind: A three cup anemometer and a wind vane were installed at the top of the tower to measure wind speed and direction.

Figure 9. The 50 ft. guyed tower mounted on the bottom of Lake Erie. The think dark line in the background is the East Breakwater Shorearm.

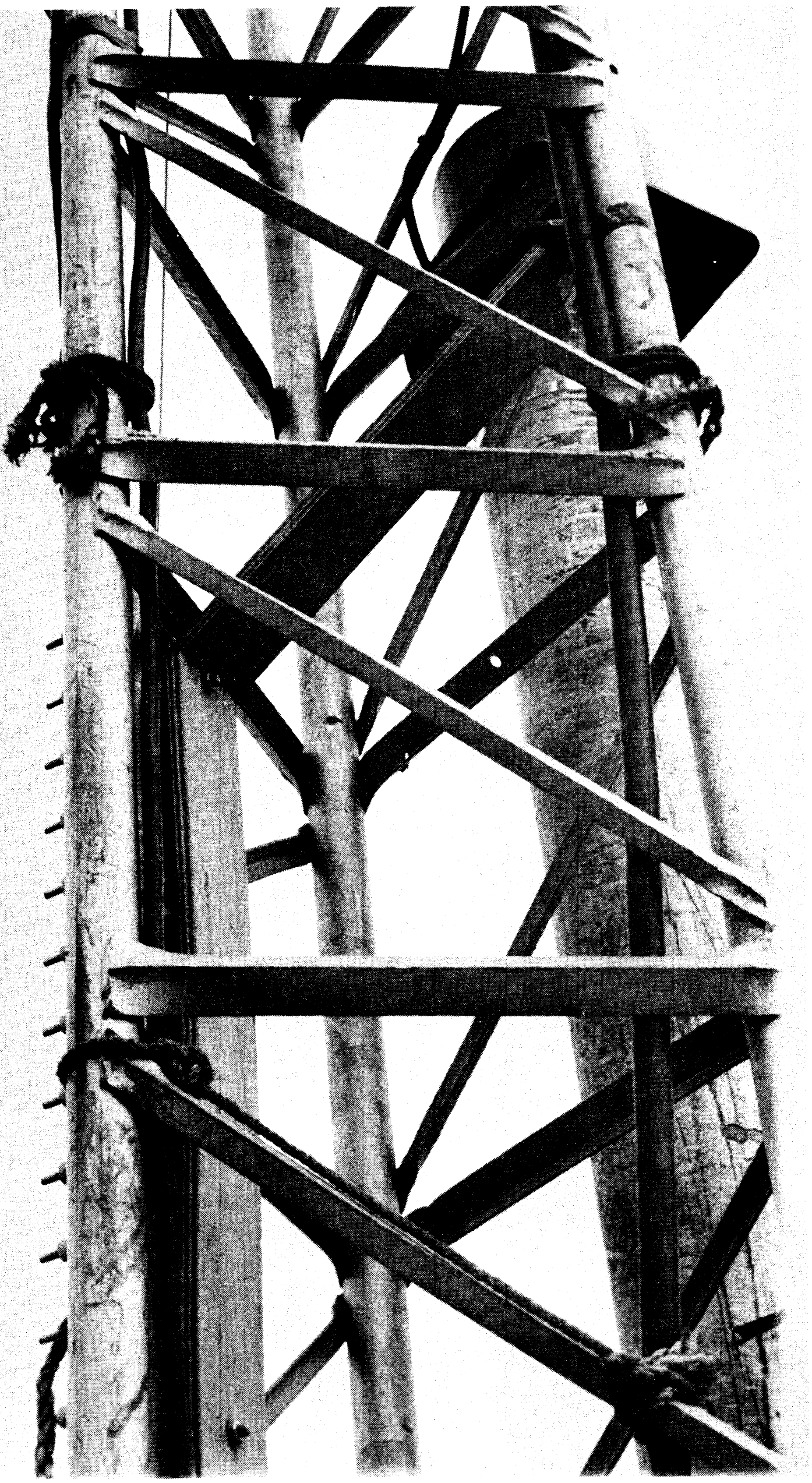


Figure 10. The lake level gage and staff wave gage installed on the research tower in Lake Erie.

Recorders used in the field study.

a. Wave Pressure Data: The wave pressure signals were recorded simultaneously on an 18 channel optical-beam recording oscillograph. In addition to the pressure records, one channel recorded the data from the staff wave-gage mounted on the breakwater. Thus, simultaneous records were made of the height of the wave at the breakwater and the pressure exerted at the pressure sensor locations.

A modification was made to the recorder so that the chart speed could be changed automatically between .25 in/min and 16 in/min by an electrical signal from a timer. With the slow speed, used for monitoring wave pressures, each wave appears as a spike that is just discernable; while with the fast chart speed, each wave is displayed in detail.

b. Wave Height Data: Wave heights were recorded on slow speed magnetic tape recorders. The signals from the breakwater staff gage also were recorded on the optical-beam oscillograph as described above. A strip chart recorder was used occasionally to provide a visual record of the wave gage signal from the tower.

c. All Other Data: A punched paper tape recorder was modified to cycle through 10 channels every 5 minutes. This recorder was used to record wind speed and direction, water and air temperatures, harbor water level, breakwater lake level and tower lake level, against time. The equipment described above was operated when in good repair during November and December, 1968.

FIELD OPERATIONS

Installation of field equipment commenced in mid September when the U.S. Coast Guard Cutter TUPELO placed three ship anchors on the bottom of Lake Erie to act as supports for the research tower. A 40 foot lightweight television tower was erected on the lake bottom with guy wires to the anchors. This tower proved inadequate as it buckled when the power cable was being pulled to the breakwater. It was replaced with a much stronger, 50 foot tower provided by the U.S. Lake Survey which proved adequate for the entire operation.

The 50 foot tower was of the type described by Duane and Saylor (1966). The bottom of Lake Erie at the tower site is a mixture of sand, gravel and silt with many boulders. Due to the large rock content, screw anchors could not be used as tower supports and large ship anchors of 4000 and 6000 pounds were substituted. All guy wires on any one side of the triangular tower were fastened to one anchor. The tower was assembled on a spare marine railway at the Lorain Coast Guard station. Four 55 gallon drums were installed for floatation just below the final water line with another at each end. Figure 11 shows the tower as it was ready for launching. It was towed to the site, the middle (SEE FIGURE 11) guys connected to the anchors and the 55 gallon drums released from the top and bottom to allow the tower to tilt into an erect position. With the other guy wires connected the tower was easily pulled to the bottom and made vertical. The conclusions of Duane and Saylor (1966) that these inexpensive, easy-to-erect towers provide stable, well exposed structures to support instrumentation was verified. The tower and its instrumentation suffered no ill effects from storms that put the breakwater installation out of operation.

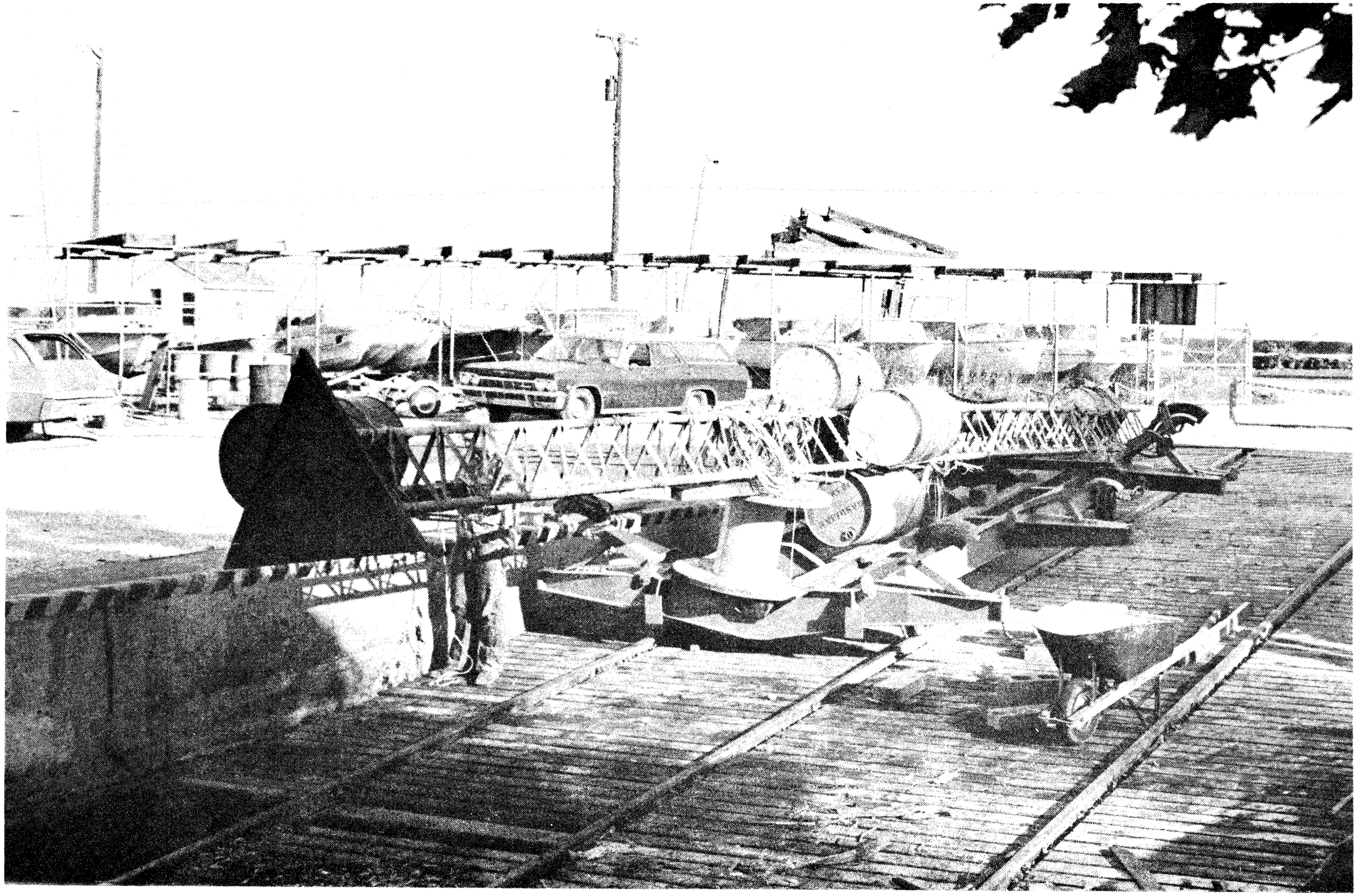


Figure 11. Research tower prior to launching and installation.

An instrument shelter constructed of a welded angle-iron frame and 3/4 inch plywood covered with 16 guage galvanized iron was constructed and mounted on the lake side of the breakwater immediately over the wave force sensor array. The shelter overhung the breakwater wall by approximately 8 inches to allow signal and power cables a direct access to the recorders in the shelter. Figure 12 shows the instrument shelter in late October.

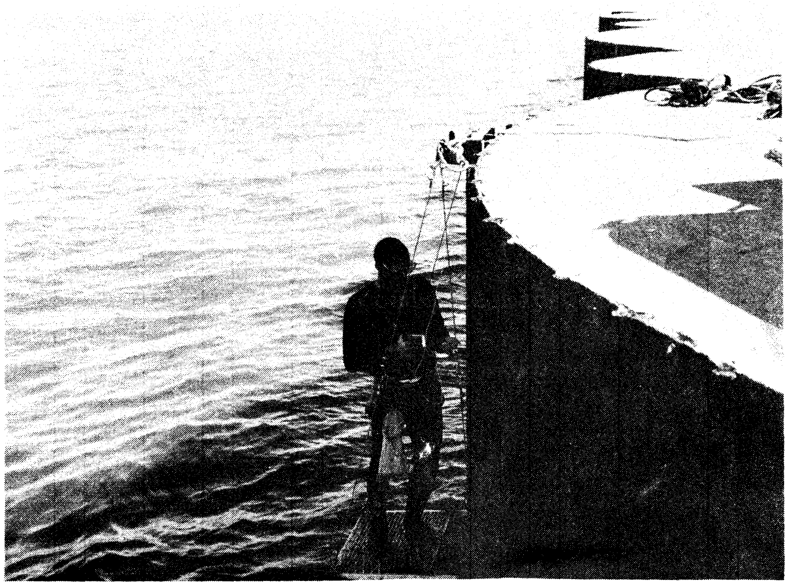


Figure 12. Instrument shelter mounted on lake side of breakwater.

The staff wave gages were installed on the breakwater in mid-October and data collection commenced. By the first of November all ancilliary data were being recorded and the wave pressure sensors and recorder were being installed. During September and October the lake was relatively smooth with no winds and waves from the northeast. On 5-7 November, northeast winds of 12 to 20 m.p.h. developed due to a low pressure system over West Virginia. These winds developed waves of the type desired for study but they proved to be more than the instrument shelter could stand. The overhanging floor of the shelter was pounded loose by the upward thrust of the clapotis and water sprayed inside the shelter causing an electrical short that curtailed data collection. Before all equipment could be made operational again, a second storm with northeast waves of greater intensity struck on 10-12 November and completely stopped data collection. To prevent future occurrences of equipment failure due to water damage from high waves, the instrument shelter was moved to the harbor side of the breakwater and a small junction box constructed of 1/4 inch steel replaced it at the top of the wave force sensor array. Steel conduit was installed between the junction box and the instrument shelter to protect the power cable and the signal cables.

Through the remainder of November, sensors were reinstalled and connected to recorders. Data collection was initiated whenever a system became operational. Table 1 shows how the data collection increased during this time. However, it (SEE TABLE 1) wasn't until the first week of December that the wave pressure sensors were functional. On 4 December five pressure sensors and all ancilliary sensors were operational but the wind was not northeasterly when the sensors became operational. On 9 December 1968 northeasterly winds occurred for a short time and wave pressure measurements were made with five sensors. These data were the only wave pressure data obtained with waves normal to the breakwater. The winds that produced the northeasterly waves later backed into the north and icing conditions developed. During the later phases of this storm the conduit pipes between the instrument shelter and the junction box were damaged and cables were broken. This damage brought an effective end to the collection of field data. Retrieval of the tower on and breakwater sensors 23 December by University of Michigan divers and the lifting of the anchors by the U.S. Coast Guard Cutter TUPELO in late December completed the field studies of 1968. A spring storm in late April, 1969, removed both the instrument shelter and the junction box from the breakwater.

TABLE 1

Tabulation of usable data collected on the Lorain breakwater during November and December, 1968

	BREAKWATER													TOWER			
Date	temperature		water level		wave	wave pressure sensors							wind		wave	lake
	air	water	harbor	lake	height	1	2	3	4	5	6	7	speed	direction	height	level
								NOVEMBER								
1	X	X	X	X	X								X	X	X	X
2	X	X	X	X	X								X	X	X	X
3	X	X	X	X	X								X	X	X	X
4	X	X	X	X	X								X	X	X	X
5	X	X	X	X	X								X	X	X	X
6	X	X	X	X	X								X	X	X	X
7	X	X	X	X	X								X	X	X	X
8					X										X	
9					X										X	
10					X										X	
11					X										X	
12																
13																
14																
15	X		X										X	X		X
16	X		X		X								X	X		X
17	X				X	X							X	X		X
18	X				X								X	X		X
19	X				X	X							X	X		X
20	X				X								X	X		X
21					X											X
22					X											
23	X	X	X	X	X								X	X		X
24	X	X	X	X	X								X	X		X
25	X	X	X	X	X								X	X		X
26	X	X	X	X	X								X	X		X

TABLE 1 (Concluded)

	BREAKWATER												TOWER			
Date	temperature		water level		wave	wave pressure sensors							wind		wave	lake
	air	water	harbor	lake	height	1	2	3	4	5	6	7	speed	direction	height	level
NOVEMBER (Concluded)																
27	X	X	X	X									X	X		X
28	X	X	X	X									X	X		X
29	X	X	X	X									X	X		X
30	X	X	X	X									X	X		X
DECEMBER																
1	X	X	X	X									X	X		X
2	X	X	X	X									X	X		X
3	X	X	X	X	X								X	X	X	X
4	X	X	X	X	X	X	X	X	X				X	X	X	X
5	X				X	X	X	X	X	X			X		X	
6		X	X	X									X			X
7		X	X	X									X			X
8		X	X	X									X			X
9		X	X	X	X	X		X	X	X						
10																
11																
12	X	X	X	X												
13	X	X	X													
14	X		X													
15	X		X													
16	X		X													
17	X		X													

As logs large enough to act as battering rams are often found on the breakwater after a large storm, it is assumed that such a log was washed onto the breakwater and was the agent that removed the shelter and junction box.

DATA ANALYSIS

Evaluation of the empirical and theoretical formulations of Minikin and Sainflou require that, during conditions of waves incident normally on the breakwater, simultaneous data be acquired for the following parameters: a) Wave pressure profiles on the breakwater. b) Maximum heights of the clapotis on the face of the breakwater. c) Wave heights before their interaction with the breakwater. d) Wave length of the undisturbed wave. e) Depth of the water at the base of the breakwater. Figure 13 shows 12 hourly (SEE FIGURE 13) wind directions as measured at the Lorain Water Treatment Plant which is located approximately 1/2 mile from the breakwater test site. These data were used rather than the tower winds because of their continuity throughout the entire period and because of a wind vane failure known to have occurred around midnight of 1 December 1968. This failure was subsequently traced to a broken shaft between the wind vane and the variable resistor used to sense the vane's position. Even in its broken condition enough friction remained that some movement was transmitted but the wind direction readings were meaningless thereafter.

From Figure 13 it is seen that meaningful data would have had to be obtained on November 7, or on November 10, 11 and 12. Brief periods of northeasterly quadrant winds occurred on November 27, December 4 and December 9, but these were transitory and occurred for only a few hours as the wind shifted from a northerly to a southerly or from a southerly to a northerly orientation.

As discussed earlier, the two occurrences of northeasterly wind in November caused waves of the type required for the study but they disrupted the operation of the recorders so that limited or no data were

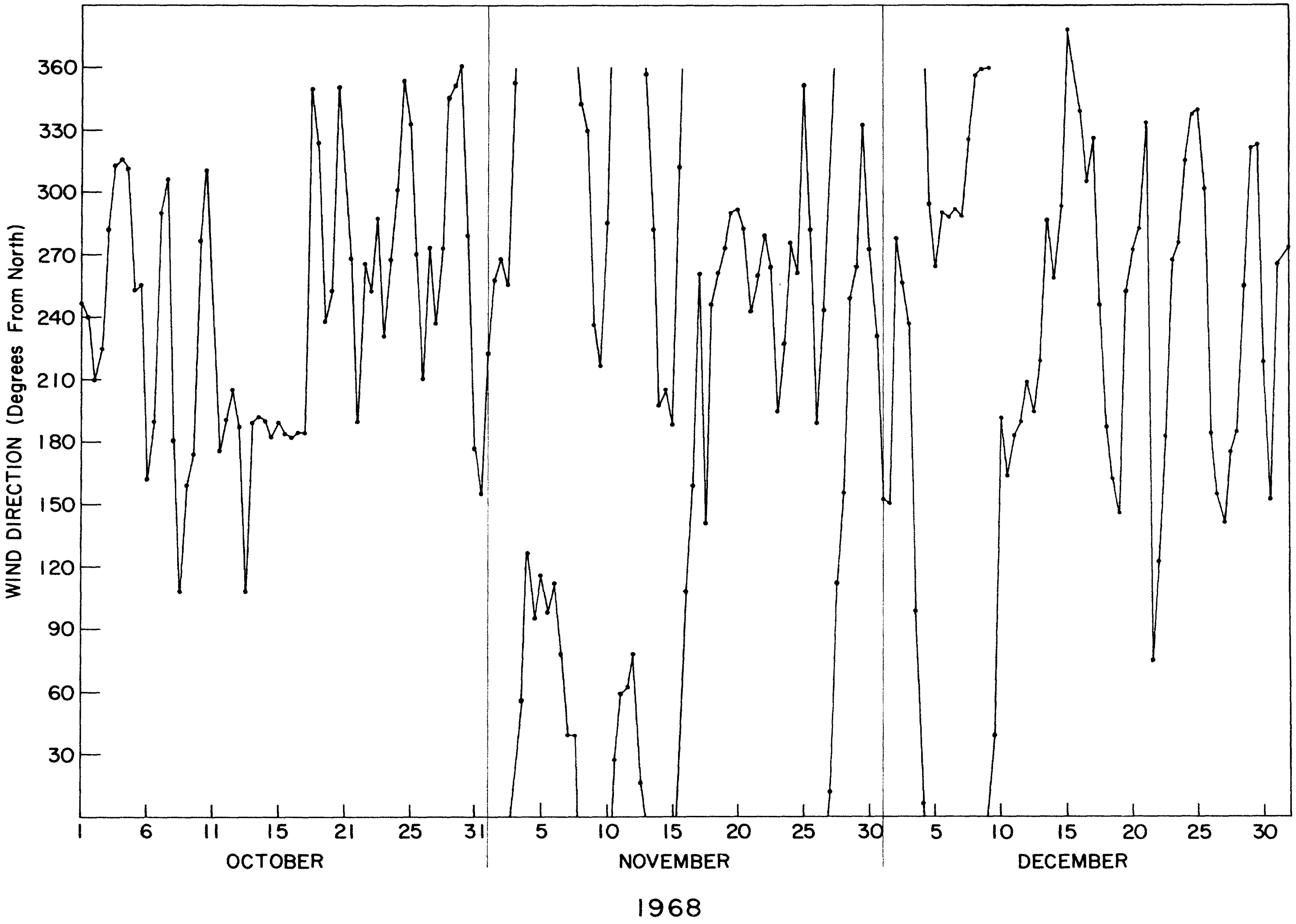


Figure 13. Twelve hourly wind directions at the Lorain Water Treatment Plant for October, November, and December, 1968.

obtained. By December 9, useable data was limited to water temperature, harbor and lake level temperature, breakwater wave height and wave pressures at 4 locations. Data for the height of the undisturbed waves were completely missing due to signal cable failure. Without the undisturbed wave height, estimates of the wave length became unreliable and calculations of pressure on the breakwater were impossible.

Wave Pressure Studies on 9 December 1968. Despite the lack of data required for a quantitative evaluation of the various theoretical wave-pressure profiles, the observed pressure profiles can contribute in a meaningful manner to a qualitative evaluation. In particular, the Sainflou formulation predicts the following:

a) A decrease in pressure increment due to clapotis with depth below the still water level.

b) An increase in mean water level when waves are incident normally on the breakwater.

Inspection of the other observed and theoretical wave profiles shows that Minikin's proposed formulation shows neither of the above while Cagli and Stuckey show a peak at the still water level and a non-linear decrease below.

Wave pressure profiles were drawn from 9 December data and invariably they showed a maximum increment of pressure due to clapotis at the sensor that was just below the still water level. These pressure profiles also showed that pressure decreased between the SWL pressure cell and the lower one. This is a qualitative verification of Sainflou and a refutation of Minikin. Figure 14 shows three wave pressure profiles typical of many measured on 9 December, 1968. (SEE FIGURE 14)

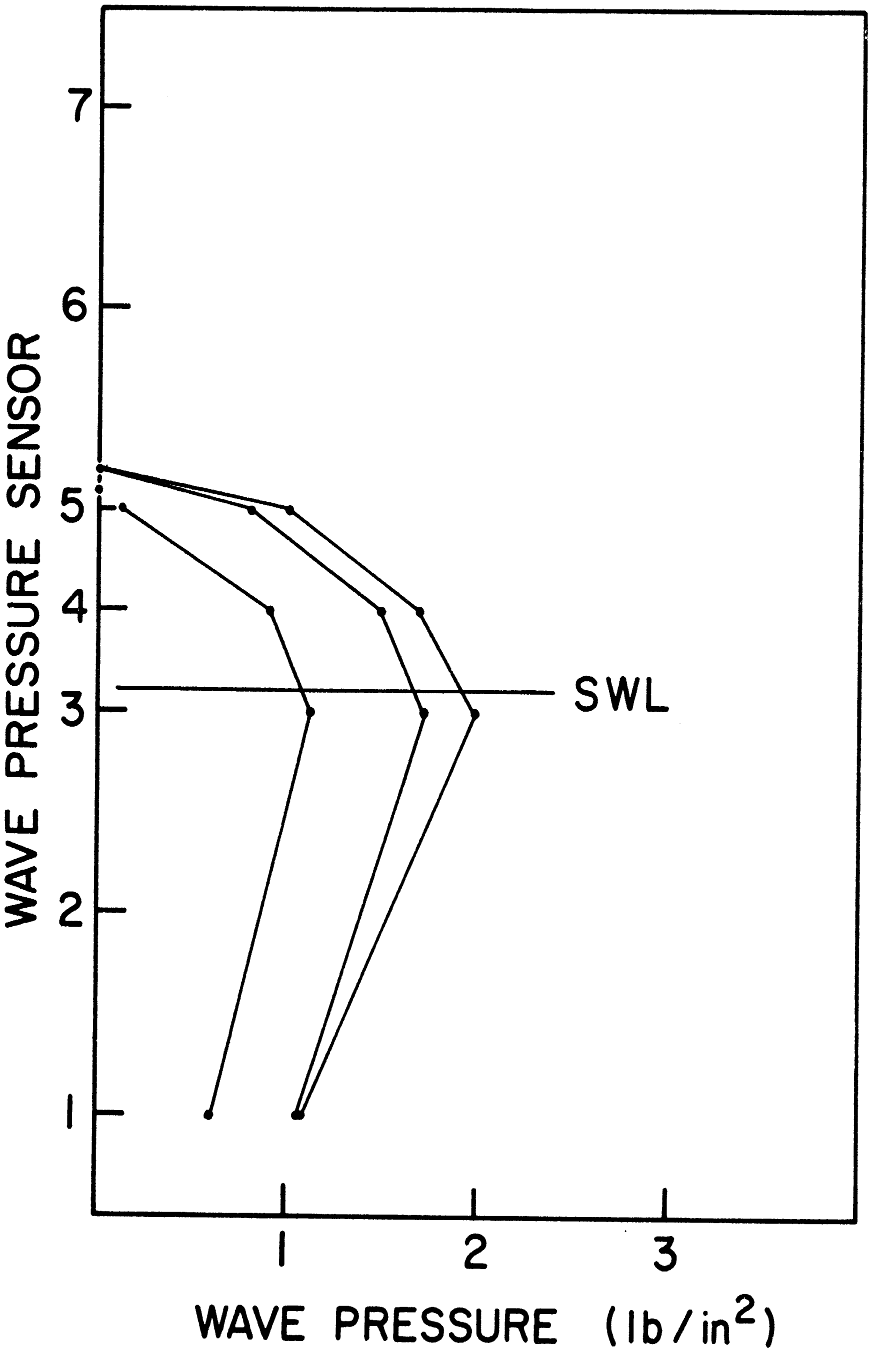


Figure 14. Wave pressure profiles for three waves, typical of those recorded on 9 December 1968.

Ratios of the peak pressure at location #3 to those at location #1, #4, and #5 were calculated for 90 waves. All but one showed a ratio greater than 1, thus verifying that peak pressure occurs at SWL. The average pressure ratios for each case are: a) 2.3 for wave pressure at location 3 divided by wave pressure at location 1. b) 2.3 for wave pressure at location 3 divided by wave pressure at location 4. c) 4.7 for wave pressure at location 3 divided by wave pressure at location 5.

The increased height of mean water level at the breakwater. Sainflou's theory requires an increase in the mean water level at a vertical wall when it is subjected to clapotis. Such an increase in mean lake level did occur on 9 December, 1968. As the tower lake-level gage measured mean lake level, any difference between it and the lake-level gage at the breakwater is a measure of the effect of wave reflection. Table 2 shows the results of an investigation of lake level differences for time periods when the wind blew steadily from some arbitrary direction.

The case of the positive rise of mean lake level occurred on 9 December, 1968, with a wind blowing nearly normal to the breakwater. These data indicate a verification of Sainflou's prediction of increased mean water level under clapotis.

TABLE 2. **Mean differences** between breakwater and tower lake levels as a function of **wind** direction and speed.

Mean wind speed mph	Mean wind direction	Breakwater-level minus tower water-level feet
17	270°	-0.1
12	350°	-0.1
14	100°	-0.1
19	240°	-0.18
16	310°	-0.15
15	210°	-0.15
28	260°	-0.14
12	50°	+0.1
6	190°	0.0

CONCLUSIONS

The wave pressure data obtained on 9 December 1968 qualitatively verify the reduction of pressure increment due to clapotis for locations below the still water level. As only one pressure measurement was taken below the still water level for each pressure profile, the shape of the pressure profile was not determined and qualitative verification can be claimed for either the Sainflou or the Cagli and Stuckey formulations. However, the Minikin concept of equal pressure increment appears to be disproved. All pressure sensors were calibrated in situ and again after removal from the breakwater so the possibility of the lower pressure value being in error is very small.

The apparent verification of Sainflou's prediction of increased mean water level under clapotis as shown in Table 2 is based on less positive evidence than is the pressure decrease below SWL. The reference value for each of the three water level gages was determined by taking the mean value of all observations during the fall of 1968. It was assumed that the mean value over three months at each measuring site would represent the same mean lake and harbor level and the mean values at each site could be used as relative reference values for their respective gages. Thus, differences between instantaneous values and mean values for each gage represent changes of the harbor or lake level from the mean values. Variations between these values for the tower site and the breakwater site were the data used to produced Table 2. Any changes in the response of either of these instruments could cause biased results and wrong conclusions. There is no way to verify the accuracy of the water level measurements, now that the equipment has been removed.

The field study conducted during the fall of 1968 showed that the equipment selected was able to measure the parameters required for an evaluation of existing wave pressure formulations. The unforseen experimental problems that often occur with a new field study were severe enough to prevent the necessary simultaneous collection of data. Correction of these experimental difficulties was accomplished in the field in most cases so that data collection could be resumed. However, the season ran out before all equipment could be made operational at the same time that northeasterly waves occurred.

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