University of Washington
Department of Civil and Environmental Engineering

REFLECTED WAVES IN LAKE WASHINGTON

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Water Resources Series
Technical Report No. 19
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Seattle, Washington

Mrs. Kay Jones
2328-43rd Avenue East
Seattle, Washington

Mr. William Reed
1500-42nd Avenue East
Seattle, Washington

Mr. Douglas Robinson
2225 Evergreen Point Road
Bellevue, Washington

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ABSTRACT

Some phenomena on the shoreline of Lake Washington have been reported to be caused by waves reflected from the Evergreen Point (Floating) Bridge. An exploratory or "Phase 1" study was undertaken to ascertain the limits of reflected waves and their frequency as related to wind speed and direction. Wind data from three official recording stations were utilized to determine probable wind-wave conditions. Four sets of aerial photographs were taken under different wind conditions for the purposes of obtaining wave lengths and general patterns. A portable sensing unit was used to measure wave height and frequency from piers extending into the lake from selected shore locations. These measurements were found to agree favorably with predictions from standard techniques. A 16-mm. motion picture film was taken under a moderate wind condition to show some of the typical phenomena adjacent to the bridge and the shoreline.

An analysis was developed to describe the advance of a wave train against a wind. Predictions of the decay with distance of such a wave based on this analysis fit field observations quite realistically. Generalized interpretations were made for the interaction of the reflected waves with the shoreline and shoreline structures.

The possibilities of applying a pneumatic or hydraulic breakwater to dissipate the waves at the bridge were investigated in considerable detail. The scarcity of known experimental data for the deep-water waves encountered, precluded a positive conclusion on required dimensions without test data.

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CHAPTER 1

INTRODUCTION

1.1 Background

Lake Washington lies partly within the city limits of Seattle, Washington, (see Figure 1). It is oriented in a north-south direction and is about 23 miles long and a mile and a half wide. The lake is very deep especially through its midsection, (see Figure 2), where a depth of 200 feet is reached within a thousand feet of either shore and maintained approximately throughout the center portion of the lake. The outlet for the lake is through Lake Union at the Chittenden Locks where the lake level is controlled within a range of about one and one-half feet, with the minimum level around December and the maximum level in the spring.

The first bridge crossing of the lake, a floating, pontoon structure about 6,400 feet long, was completed in 1940. A second crossing was completed in 1963 at a location about three miles to the north of the first bridge. This second bridge, referred to as the "Evergreen Point Bridge," has a floating section 7,578 feet long. It is basically rectangular in cross-section with a width of 60 feet and a draft of about 8 feet. Winds from the southerly quadrant are predominant both in frequency and magnitude, followed by those from the north. Winds from the west or the east are infrequent and of short duration.

1.2 Purpose and Scope of Investigation

Soon after the completion of the Evergreen Point Bridge, waves generated by the wind were reported to be reflecting from the bridge, advancing to the shoreline, and causing changes in normal equilibrium. The broad problem is a very complex one involving wind and wave characteristics, a reflecting surface, and the interaction of the two wave systems with the shoreline and specific structures thereon. Each one of these topics is an area of study in itself with its own current research to refine existing theories and data; the combination of them into a single problem adds additional complexities. It was decided, therefore, to embark first upon an initial exploratory, or "Phase 1" study using established techniques and simple field measurements, to assessthe probable limits of any reflected waves and problems they might create. The results of this Phase 1 study would then provide a firmer basis for a more detailed investigation of those facets of the problem, if any, not defined adequately in the first phase. The specific objectives proposed for the Phase 1 study were to:

1. Delineate the nature, intensity and effect of incident and reflected waves.
2. Review existing literature pertinent to the subject.
3. Obtain measurements of actual wave heights for a reporting condition.
4. Interpret the information from 1, 2, and 3 above in order to determine the types of problems that arise and their significance.
5. Explore the utility of a ripple tank analogy of the wave problem.
6. Prepare a report containing all conclusions and recommendations significant in Phase 1.

1.3 General Approach

To meet the objectives of the study, the investigation was divided into the following main components:

1. Compilation of wind data on speed, direction and frequency from the reporting stations near the lake. These stations are the Seattle-Tacoma Airport, Boeing Field and the Sand Point Naval Air Station.

2. A portable wave-height sensor was designed and used to obtain nine sets of wave height-frequency data from four selected shoreline sites.

3. Four sets of aerial photographs were taken along the shoreline for exploring this method of identifying reflected wave patterns and recording shoreline configurations. Some still photographs were taken of site conditions. The still photography has a definite, but restricted, use in illustrating wave phenomena where motion is the main aspect. Therefore, a 16-mm moving picture film was taken of the bridge and adjacent shorelines from a helicopter and stationary vantage points.

4. Forecasts of significant wave heights at the bridge were made for wind directions from S30E to S30W and a speed of 20 miles per hour, and for S20E and S20W for 30 miles per hour. A procedure was developed for predicting the decay of the reflected waves as they move outward from the bridge against the causative wind fields. This procedure yielded results that agree satisfactorily with observations on the lake, even though some simplifying assumptions had to be made in its development.

5. The possible interaction between the waves and some generalized shoreline situations were summarized.

6. A survey was made of possible methods of reducing or eliminating the reflected waves by some device located at or near the bridge. Attention was focused on the method of generating a countercurrent to induce wave breaking and energy dissipation. Calculations were made to determine approximate dimensions and power requirements, and some intermediate laboratory and field steps were considered.

7. The results from a simple ripple tank used for exploratory purposes indicated that meaningful results could be obtained only from a rather elaborate model which would have consumed

an inordinate amount of the gross project effort at the sacrifice of the main objectives, so no further work was done on the ripple tank approach to the problem.

CHAPTER 2

WIND DATA

2.1 Site Description

The 23-mile long major axis of Lake Washington lies in a north-south direction. Hills from one to two hundred feet high ring most of the lake on the east and west shores and exert a considerable steering influence on the prevalent wind systems. Mercer Island, rising about 400 feet above the lake, divides the southern third into two channels. The cyclonic weather systems typical of the Pacific Northwest from late fall to early spring generally impart to the area winds from the southwest to southeast. Northerly winds accompany the cold frontal systems that pass occasionally during the winter months. Northerly winds also occur during the summer season during those periods when the Pacific anticylone is favorably situated. The general meteorological conditions and site topography are not conducive to the formation of winds from either the due westerly or easterly directions.

2.2 Stations

The four reporting stations in the Seattle area are: (1) the Seattle-Tacoma Airport, (2) Boeing Field, (3) downtown Seattle, (Federal Building), and (4) the Sand Point Naval Air Station, located on Figure 1. An anemometer (non-recording) was installed, (November 1964), on the control tower of the Evergreen Point Bridge from which wind direction and speed can be obtained during the time that a bridge operator is on duty.

The Seattle-Tacoma Airport is on a flat ridge or plateau and its exposure should provide the wind data most representative of the prevailing pressure systems. Boeing Field lies in a valley having a NNW-SSE orientation and is sheltered on the east side by a 300-400 foot ridge which separates it from Lake Washington. Fewer compiled data were readily available for the downtown Seattle site, so it has not been used as a reference station. The Sand Point Naval Air Station is located on the west shore of Lake Washington about three miles north of the Evergreen Point Bridge. A high ridge just west of the station blocks winds from that direction.

The Seattle-Tacoma station has the best exposure for responding to the wind fields, but is farthest, (6 miles), from the south end of the lake; the Boeing Airport station is closer, but its wind recordings show the influence of the station location; the wind gage at the Sand Point Naval Air Station is close to the runways and appears to be shielded from the southerly direction. The site on the bridge tower is very good, but the gage there has been in operation only a short time and readings can be obtained only when an operator is on duty, so that no statistical data can be compiled from the sporadic observations recorded. However, this gage is invaluable, for it is the best index available on the lake and by comparing readings concurrently at the official stations, some correlation can be obtained with their long-term records.

2.3 Wind Records

The surface observations reported by official weather stations are taken within five minutes of the hour, so that wind frequency-direction-speed data are based upon "Number of occurrences" of hourly observations. There is, therefore, one sample per hour. Winds characteristically are unsteady in direction and magnitude, so that the hourly reading only infrequently samples the peak value. The regular hourly observations include characteristics of wind gusts and special observations may be taken when warranted, but these are not included in the standard summaries.

To show the annual wind statistics for the Lake Washington area, the wind roses for the Seattle-Tacoma Airport, Boeing Field, and Sand Point are given as Figures 3, 4, and 5. The annual percentage frequencies of direction and speed are presented in Tables 1, 2, and 3. Monthly wind roses for Boeing Field and Sand Point are given in Figures 6 through 10. The monthly percentage frequencies for the three stations appear in Tables 4 through 10.

Four sets of aerial photographs were taken on February 16, October 18, November 4 and December 3, 1965. The wind data from the Seattle-Tacoma Airport, the Evergreen Point Bridge and Sand Point for these dates are presented in Tables 11 and 12. Some miscellaneous wind data which coincide with wave measurements and/ or photographs from shoreline sites are given in Table 13. The speeds from the Naval Air Station are reported in knots; values from the other stations are in miles per hour, unless otherwise noted.

2.4 Discussion of Wind Records

The parameters governing conditions conducive to the generation of waves which may reflect from the bridge are: direction, speed, duration, fetch (effective over-water distance upwind from any point), and frequency. The bridge is so oriented that only winds from the sector from southeast to southwest have an exposure favorable for reflected waves which might reach a shoreline. The orientation of the bridge and the low frequency of northerly winds preclude any important waves reflected from the bridge from reaching a shoreline.

The annual summaries of wind data group speeds into the ranges shown in the pertinent figures and tables. Observations of waves on the lake and of the wind speeds from the gage at the bridge tower, concurrent with those from the reporting stations (Tables 11, 12, and 13), show that the minimum important wind group is that from 8-12 miles per hour (or knots).

Wind speeds increase in elevation from the surface up to the top of the friction layer where the "gradient" wind is reached, so that winds measured at different heights as well as at different horizontal locations are difficult to relate quantitatively without special instrumentation, yet some conclusions can be reached by comparing data from the available stations.

It is doubtful that waves of a significant height would be generated by a wind of only 8-12 knots as measured fifty feet or more above a water surface, but it appears that when winds are recorded in hourly observations at nearby land stations in this speed range, the winds affecting the lake are considerably higher. For example, for October 18 in Table 12, between the hours of 0900 and 1600 the highest speed at Sand Point was 14 knots, while the recorded speeds at the bridge tower, (Table 11), ranged between 22 and 25 mph, then dropped to 18 mph at 1600. The 3-hourly reports from the Seattle-Tacoma Airport for this period show a maximum value of 13 knots at 1000.

The directions reported at the three sites are generally within 10^{o} of each other when the wind is above 10 knots and from the south at the Seattle-Tacoma Airport. An evidence of the steering effect caused by the valley containing Lake Washington appears in the data of February 16th when the directions at the Seattle-Tacoma Airport were 20^{o} to 30^{o} west of south at the time that Sand Point was registering winds from the south.

A motion picture was taken of waves on the lake during the hours of 1200-1500, June 28th, 1966. The wind record from Sand Point, (Table 13), for the hourly observations shows speeds not exceeding 12 knots, although gusts of "20+" were recorded. Some additional discussion of duration and fetch and the importance of gustiness is presented in Chapter 4.

The table below has been prepared from the annual summaries to show the comparison of wind frequencies from the different sectors at the three major reporting stations.

ANNUAL PERCENTAGE OF SURFACE WINDS
ABOVE 8 MPH (8 KNOTS AT SAND POINT)

Direction		Seattle-Tacoma Airport	Boeing Field	Sand Point Naval Air Station
SE		4	1.1	0.6
SSE		3	5.8	1.7
S		7	8.2	10.5
SSW		10	8.4	5.6
SW		12	6.4	1.2
	Sector Total	36	29.7	19.6
WSW		3	2.3	0
W		2	0.5	0
WNW		1	0.6	0
	Sector Total	6	3.4	0
W		1	3	1.1
NNW		3	4.1	3.2
N		7	1.9	2.7
NNE		6	1.4	0.3
NE		5	1.1	0.2
	Sector Total	22	11.5	7.5
ENE		1	0.5	0.2
E		2	0.2	0.2
ESE		5	0.4	0.2
	Sector Total	8	1.1	0.6

2.5 Significant Winds

It is concluded that winds from the SE to SW sector reported at Seattle-Tacoma Airport, the site best exposed to the prevailing weather systems, are steered by the valley of Lake Washington about one compass point toward the south, i.e., SW at the airport becomes SSW over the lake. The wind roses and tabulations show this trend. Winds from this sector are the ones most likely to generate waves which might reflect from the Evergreen Point Bridge. The speed group of 8-12 miles per hour (or knots), as appearing on hourly weather reports, is considered to be the best index of minimum speed needed for the generation of waves important to this study. The percentage of observations showing winds from the southern sector and above 8 mph varies from 20 per cent at the Sand Point Naval Air Station to 36 per cent at the Seattle-Tacoma Airport.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Scope

In order to stay within the bounds of the exploratory nature of the Phase 1 study, it was necessary to confine field measurements of wave patterns to a few wind conditions and sites. The installation of several wave height, (and desirable, directionally sensitive), sensors and supporting wind instruments for a more detailed study was considered to be beyond the intent of the initial investigation. The objective of the field measurements was to establish a link between the waves on the lake under various wind conditions with the climatological wind records and the established techniques for predicting wave characteristics from given wind fields. With this objective established, (1) photographs of four conditions were obtained, (2) a portable wave sensor was used to sample wave conditions at four shore sites, (3) visual observations were made under many wind conditions, and (4) a motion picture was obtained for one particular wind-wave condition.

3.2 Wave Characteristics

Wind waves are very complex in nature. Early approaches to relate wind speed and fetch length to wave heights were quite empirical. The demands for forecasting wave conditions on landing beaches in World War II stimulated extensive research in the phenomena. Stemming from this initial impetus have come two prominent methods of analysis, the "significant wave method" and the "wave-spectrum" method. Recent books by Kinsman (1965), and Wiegel (1964) contain extensive discussions references and data on these methods as well as on other aspects of wave mechanics, so only the terminology as used in this report shall be defined here.

It is generally considered that the wave-spectrum method has a firmer conceptual basis than the significant wave method since it is based on the distribution of energy among simple-harmonic components. However, there are more data available on the significant wave method and it is easier to apply to the problem on Lake Washington in view of the limited field measurements obtained. Similar conclusions regarding the choice of method for characterizing wave parameters were reached in a study by the Beach Erosion Board, (1962), and by McLaughlin and Anton (1964).

The wave characteristics of length, height (crest to trough), period and celerity are readily defined for a uniform wave train. The waves in a wind-generated system are very irregular. A statistical parameter introduced by Sverdrup and Munk (1947) to describe such a system is the "significant wave height, $H_{1/3}$" which is defined as the mean of the highest one-third of the waves present. The choice of this height is based upon the premise that a practiced observer will report such a height from visual observations. With this height defined, it is possible to extend the statistical likelihood of waves of other wave heights. In the classical wave theory there is the relationship that

$$L = CT \qquad \ldots\ldots (3.1)$$

that is the wave length is equal to the product of its celerity (wave-phase speed), and period, so the use of the "period of the significant wave," $T_{1/3}$, has come into use. Thus, the irregular waves are thought of as if they were replaced by a single sine wave with a height equal to $H_{1/3}$ and having a period of $T_{1/3}$, even though the two terms are only statistical parameters.

The small-amplitude, or linear, theory used to describe wave characteristics yields

$$C^2 = gL/2\pi \tanh 2\pi h/L \qquad \ldots\ldots (3.2)$$

in which L is the wave length and h is the water depth. The term "h/L" is the relative depth. When h/L is small, Eq (2) reduces to

$$C = \sqrt{gh} \qquad \ldots\ldots (3.3)$$

the familiar relationship for the speed of a gravity wave in relatively shallow water, i.e., when $h/L \leq 1/20$. For values of $h/L \geq 1/2$, Eq (3.2) becomes

$$C = \sqrt{gL/2\pi} \qquad \ldots\ldots (3.4)$$

and by substitution into Eq (2.1)

$$C = 5.12\ T \text{ (ft per sec)} \qquad \ldots\ldots (2.5)$$

$$L = 5.12\ T^2 \qquad \ldots\ldots (2.6)$$

The large depths (up to 200 feet), in Lake Washington between the two floating bridges and the wave periods of about two seconds insure that h/L is very large so that the waves generated are "deep-water" waves. A wave with a length of 20 feet would begin to sense the bottom effects in a depth of 10 feet, which is generally obtained within about 75 feet of the shoreline.

The average total energy per unit surface area is the sum of the potential and kinetic components and is

$$E = \gamma H^2/8 \qquad \ldots\ldots (2.7)$$

where γ is the specific weight of water and H is the wave height. The rate at which this energy is propagated is called the "group velocity," C_G, where

$$C_G = C/2\ [1+2(2\pi h/L)/\sinh 2(2\pi h/L)] \qquad \ldots\ldots (2.8)$$

for deep-water waves, $C_G = 1/2\ C$; for shallow-water, $C_G = C$.

3.3 Wind-Generated Waves

As a wind of a given speed and direction blows over a body of water, there is an energy exchange on the interface which results in the formation of waves which grow as the time and distance progress. For a given wind, there is some maximum wave height at which the net energy exchange is zero. This height may be limited by either the time or the distance to the equilibrium state, i.e., the wave may be duration- or fetch-limited. Many measurements at sea and some in more confined water bodies have been obtained in the attempt to relate the complex phenomena involved. An excellent compilation of work from many sources has been prepared by Wiegel (1964, pages 209-229), from which Figure 12 has been reproduced. The parameters are dimensionless so that any consistent system of units may be employed. The fetch length is F, and U is the wind speed at the gradient level, usually taken as being at 10 meters above the water, but many data have been recorded at other heights. The speed U should be regarded as that at a height above the layer of strong surface frictional effects.

A different arrangement of wind-wave characteristics is revised by Bretschneider (1958), in Figure 13 where the fetch, speed, significant height and period may be obtained graphically. From this figure, it is seen directly that all winds over 15 knots are limited by the fetch length of 3 miles between the two bridges rather than by the duration of the wind.

Figures 12 and 13 consider the case of a constant wind acting on an initially undisturbed water surface. It is reasonable to expect that if a wind increased from, for example, 10 knots to 20, a new equilibrium wave height would be reached in less time (or distance) than if the 20-knot wind started to blow over a calm surface. A technique devised by Bretschneider (1958), can be applied to Figure 13 using the lines of constant H^2T^2 to account for changes in the wind field. However, this refinement has not been applied to the current problem in a quantitative way.

3.4 Aerial Photographs

The aerial photographs were planned to provide an over-all picture of the wave patterns and a method of obtaining some measures of wave lengths. Any one flight required the infrequent combination of adequate ceilings and visibility, favorable timing and lighting, persistent wind conditions and aircraft availability. During 1965, photographs were taken on February 16, October 18, November 4 and December 3. The flights were run at an altitude of 1500 feet; the resulting map scale was 1 inch to 250 feet. Each one of these sets of photographs contributed to the background information for describing the wind-wave patterns on Lake Washington.

The wind direction and speeds reported at the Seattle-Tacoma Airport, the Evergreen Point Bridge and the Sand Point Naval Air Station are given in Tables 11 and 12 for the dates of the photographs, with the observations nearest to the time of the flights marked "x." The winds were predominantly from the southerly direction, with a directional agreement within about 20° among the three stations. Typically, the speeds from the bridge site were higher than those at the other stations. The magnitude of the gusts reported at Sand Point are close to the speeds, (20-25 mph), taken from the gage at the bridge.

The photographs presented as Figures 14-20 have been selected to show site locations, some shoreline features and wave patterns to be discussed in the sequence of the numbers inset on the figures. The photographic scale of 1 inch to 250 feet was preserved in the reproductions.

Figure 14

February 16, 1965

Inset Number	Item
1	Madison pier measuring site, 2000 feet from the Evergreen Point Bridge, (labelled "Madison" on Figure 2).
2	The Park Shore Apartment Building.
3	The lighting or exposure did not show wave detail except for the waves breaking on the shore. The lake level was at Elevation 20.4 feet. Note the
4	reflected wave breaking on shore between 1 and 3 and at 4. Two cusps are visible along the shoreline.

Figure 15

December 3, 1965

Inset Number	Item
5	Reflected wave sequence between 5 and the end of the pier, with lengths of 20-25 feet.
6	The cusps which were present on Figure 14 near point 3 do not appear. Some concrete blocks which probably caused the cusps to form are no longer present. The material around them has been moved southward along the beach between 6 and 7. The lake level on this date was at Elevation 19.6 feet. The shielding of the incident waves by the buildings near 7 allow the reflected waves to be identified within the embayment of Madison Beach.
7	Some realignment of the shoreline has taken place at this point, (4 on Fig 14), between February and December.
8	The overlapping pattern of the incident and reflected waves is visible in the vicinity of this point. Wave lengths 25-20 feet.

Figure 16

October 18, 1965

Inset Number	Item
9	The Robinson site, (see Figure 2), 2600 feet from the bridge, shows rather weak intersection patterns caused by the incident and reflected waves which appear just to the north and the south of 9. Wave lengths are about 15 feet.

Figure 17

December 3, 1965

Inset Number	Item
10	The diffraction pattern around the west end of the floating section of the bridge highlights the absence of any waves on the north side in the lee of the incident wave advance. Practically no energy is transmitted beneath the floating section of the bridge.
11	The crests of the reflected waves are shown between 10 and 11. To the left of 11 the pattern is exclusively incident.

Figure 18

December 3, 1965

Inset Number	Item
12	No energy is transmitted beneath the floating section of the bridge. The shoaling effects and the diffraction pattern tend to merge between 12 at the east end of the bridge and the shoreline.
13	Whitecaps and short-crested waves are in evidence south of the bridge.

Figure 19

December 3, 1965

Inset Number	Item
14	Reflected waves with wave length of 25 feet are present.
15	Reed measuring site, (see Figure 2), 4100 feet from the bridge. Cross-hatched pattern from intersections of incident and reflected waves between 15 and the shore, with wave lengths 20-25 feet.

Figure 20

December 3, 1965

Inset Number	Item
16	Jones measuring site, (see Figure 2), 750 feet from the bridge.
17	From 16 toward 17, the dominant wave shifts from the incident form to the reflected form in the shelter of the building near 17.

Figure 21

November 4, 1965

Inset Number	Item
18	Only some weak reflected waves are discernible in the Madison Beach area. For reasons that are not apparent from the wind records antecedent to flight time, the waves did not develop as they did on the days of the other flights when the speeds were only slightly higher. The wind direction at Sand Point was predominately at 170° (S10E), prior to flight time, whereas it had a westerly component on the other days. There were strong shadows obscuring much of the shoreline on the east side of the lake

The aerial photographs show the wave patterns that develop under winds from the southerly quadrant in the speed range of 10-17 knots as appearing in hourly weather data. There is further evidence on the wind records from the three stations that there is a strong tendency for the winds to be steered to the south by the valley of Lake Washington. Reflected waves persisted as far south as the Reed site under the conditions prevailing on December 3. None of the flights covered an example of the waves from a strong wind from the SSW-SW, which should provide the conditions for reflected waves on the east shore of the lake. Usually the weather and ceiling heights associated with such winds preclude any aerial photography.

3.5 Wave Measurements

Four sites for wave height measurements were selected as shown on Figure 2 as "Jones," "Madison," "Reed," and "Robinson," where piers extended from 50 to 100 feet from shore where the water depth exceeded 15 feet and increased very rapidly as shown by the depth contours on Figure 2. The wave sensor was of the parallel-wire resistance type with its output amplified and registered on an oscillograph as shown in Figure 22. The unit was portable so it could be taken to the sites under suitable wind conditions. The gage was calibrated before each measurement in a static reservoir filled with lake water. For the usual amplifier magnification, the calibration consistently yielded a one-inch height per millimeter of chart record. The gage was not directionally sensitive so that the reflected waves, when present, were distinguished visually from the incident waves by their direction of travel and orientation. Their traces were checked on the oscillograph record as the waves passed the gage.

Two observers were needed for this operation. Frequently the superposition of the two systems at the gage nullified the height changes, although the separate waves could be seen approaching the gage. When two crests arrived at the gage at approximately the same time, an effort was made to mark such peaks "D".

Samples cut from the wave records at the four sites are shown in Figure 32. The companion wind reports are contained in Table 13. At the time of the observation recorded in Figure 32a, the wind at Sand Point was S 10°-30° W with speeds of 13-16 knots, and with a gust of 19 knots reported at 1330. The highest reflected wave was 21 inches.

On March 14, an effort was made to sample in close succession the three sites on the west shore. The winds were S at Sand Point and SSW at the bridge. Although the speed at Sand Point was 10-14 knots with gusts to 23, the gage at the bridge was registering in the 25-40 mph range. The heights of the incident and reflected waves at the Jones site, (Figure 32b), were 10-18 inches; at the Madison site, the heights were up to 23 inches. At both these sites, the reflected wave patterns were very distinct even though the Jones site is sheltered from SSW wind. Figure 32 shows a common characteristic that first a reflected pattern may be dominant, and then give way to the incident pattern. The incident waves at the Reed site, (Figure 32d), showed heights up to 18 inches; the reflected waves could be seen about 50 feet beyond the pier, but were less frequent than at the other stations, and reached a height of only about 12 inches. The wind had slackened somewhat at the time of this observation.

A summary of the wave measurements is given in Table 14. The significant wave height, $H_{1/3}$ was computed as the average of the one-third highest waves. The wave periods range between 1.4 and 2.5 seconds. From the data of March 14, it appears that the height of the reflected wave has decreased by one-third from the Madison site to the Reed site. The ratio of the number of reflected waves identified to number of incident waves is 0.30 or 0.33 at the Jones and Madison sites, but drops to 0.06 at the Reed site.

The method used to measure the waves in the lake under a variety of wind conditions was quite adequate for an initial study, but was primarily restricted to periods of normal working hours. Many strong winds occurred during the night or on weekends. A system of recording and directionally sensitive wave gages and recording wind gages would be needed to provide the volume of data that could be used to add significant refinements to the method used.

3.6 General Observations

A series of still photographs taken on June 13, 1966 is presented as Figures 23-30. The hourly wind reports at Sand Point between 1200 and 1400 gave the direction between 160° and 170° and speeds from 4 to 7 knots; the instantaneous readings at the bridge were S 20 mph, but variable.

Figure	Inset Number	Item
23	19	Northeasterly view from top of Park Shore Apartments. Number 19 identifies the Evergreen Point Bridge Control Tower.
24	20	Southerly view from top of Park Shore Apartments. Number 20 is the Reed site.
25	21	Northerly view from top of Park Shore Apartments. Number 21 is the Madison site. The crests of some reflected waves can be seen between 21 and the beach.
	22	A close-up view of this area appears in Figure 26.
26	23	The barrels on the right lie in the trough between the crests of reflected waves. These barrels appear just inshore of 1 on Figure 14.
27	24	The shoreline in this location has receded about 10-15 feet since February 16, 1965, the date of Figure 14. The erosion is believed to be the combination of wave systems in which the material loosened by one wave is transported by the other.

Figure	Inset Number	Item
28		Westerly view from the control tower of the Evergreen Point Bridge.
29	25	Easterly view from the control tower. The flanking pontoon is 100 feet long. Both incident and reflected wave forms are outlined against the pontoon.
	26	The Robinson site.
30		View toward the bridge from the hill overlooking the Robinson site.
31		The Robinson property taken under the calm conditions of June 9, 1966.

The wave patterns on Lake Washington, particularly between the two bridges, have been observed under a variety of winds for over a year and a half. Visual observations as well as various measurements have led to the following conclusions:

1. The measured wave heights agree quite closely with those computed from published sources of wave height versus fetch, wind speed and duration.
2. Reflected waves can be identified, (by direction of motion and crest orientation), more frequently and for greater distances south of the Evergreen Point Bridge on the west shore than on the east shore. An explanation is offered in Chapter 4.
3. There is evidence of littoral drift attributable to reflected waves in the vicinity of Madison Beach.
4. The topography surrounding the lake exerts a strong steering influence on wind direction and speed.
5. The wave patterns generated are more sensitive to wind speed than to direction.

6. The bridges form perfect reflecting barriers. No energy is transmitted to the lee of either bridge.

7. Some breaking of waves begins on the Evergreen Point Bridge when the wind speed has been in the 25+ mph range for about two hours.

8. Reflected waves reaching a shoreline from the north side of the Evergreen Point Bridge are very unlikely due to the alignment of the bridge and the infrequent north winds. This bridge has reduced the fetch length over which any north winds can generate waves between the two bridges.

CHAPTER 4

REFLECTED WAVE ANALYSIS

4.1 Introduction

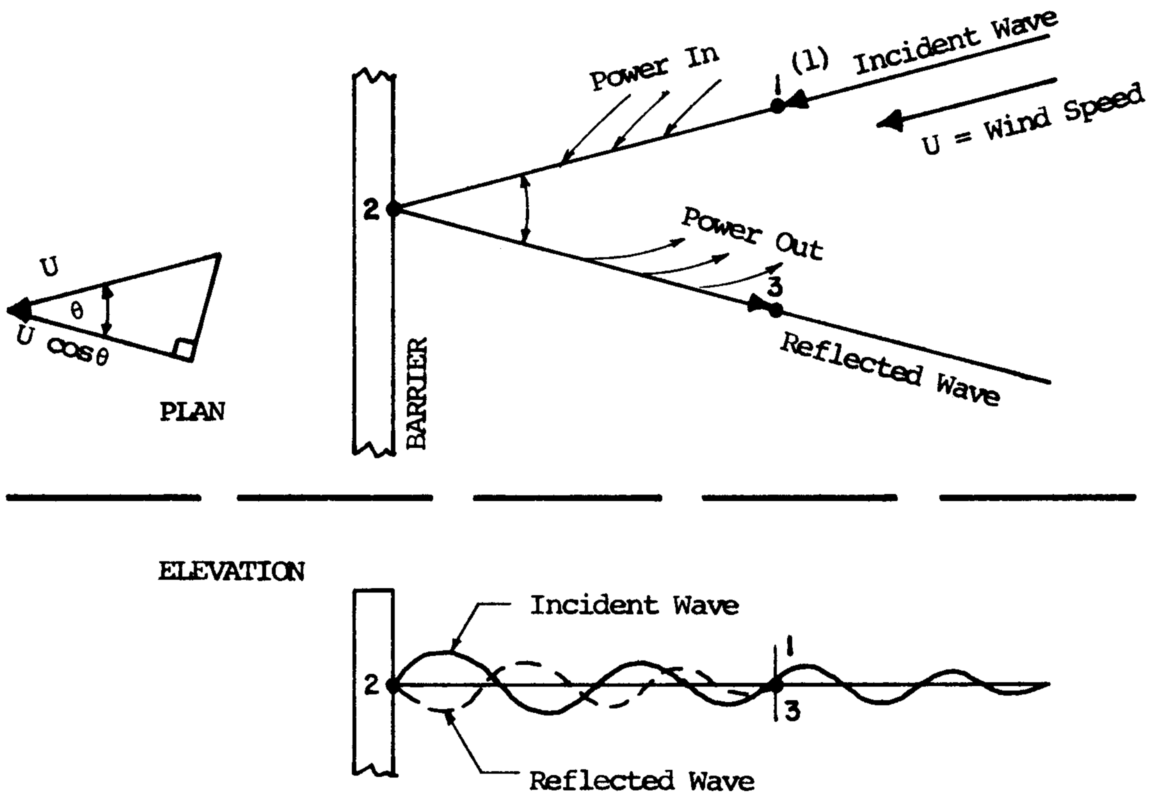
As the wind-generated waves strike the Evergreen Point Bridge, they are reflected and begin to move against an opposing wind field. Many theories and much data have been accumulated for the growth of waves in the direction of the wind; some procedures have been developed to cope with the movement of waves as they leave a generating zone at sea, but the problem of waves moving against a wind field in a constricted space apparently has escaped previous attention. Only under an unusual set of circumstances would the upwind travel of deep-water waves be on any interest or concern. Some of the general conclusions made from observations of such wave travel on Lake Washington as summarized in Chapter 3 can be explained and given approximate quantitative values from the following analysis.

4.2 Method Development

Jeffreys, (1925, 1926), formulated that the power, P, per unit area transmitted from the wind to the water waves could be expressed as

$$P = B\ (U-C)^2 HC \qquad \text{. . . . . (4.1)}$$

in which B includes a numerical constant, the mass density of air, the wave number and a "sheltering" coefficient. The wind speed is expressed as U, C is the phase speed and H is the wave height. Wiegel (1964), summarizes the extensive work that has been done on Jeffreys' initial concept. Equation (4.1) is basically an adaptation of the standard drag equation to a moving, deformable boundary, so it has a firm physical basis and is not just an empirical relationship. Suppose, as shown in the definition sketch, that a wave system having a characteristic height, H, enters a boundary at (1). Its energy flux across (1) plus the power added to it by the wind is equal to the



DEFINITION SKETCH

energy flux at the downwind position (2), that is,

$$\frac{\gamma H_1^2}{8} C_{G_1} + C_d \rho \frac{AV^2}{2} C_{1,2} = \frac{\gamma H_2^2}{8} C_{G_2} \qquad \ldots . \ (4.2)$$

In this equation, γ is the specific weight of water, C_G is the group velocity, (the rate of energy propagation), ρ is the mass density of air, C_d is the drag coefficient, $A = 1/2\ (H_1 + H_2)$, V is the velocity of the wind relative to the wave, and $C_{1,2}$ is the average phase speed. If the points (1) and (2) were not afar apart, it would be reasonable to assume that the speeds C and C_G would have the same respective values at the two locations. However, one objective sought in the analysis was a prediction of the distance from the bridge to where the reflected waves would be completely degenerated, so some method was needed to obtain the average speed $C_{1,2}$. The height $H_{1/3}$ and celerity, C, are functionally related through the parameter gF/U^2 as shown on Figure 33. As a first approximation to this relationship it was assumed that the linear functions

$$C_{G_1} = H_1/H_2\ C_{G_2}$$
$$C_1 = H_1/H_2\ C_2 \qquad \ldots . (4.3)$$

could apply over a limited range of gF/U^2. To check this assumption the speeds and heights were computed from Fig. 33 for the extremes of speed and fetch likely on Lake Washington as tabulated below.

U (fps)	F (ft)	gF/U^2	C/U	C (fps)	$gH_{1/3}/U^2$	$H_{1/3}$ (ft)	$C/H_{1/3}$	$\frac{C_1/H_1}{C_2/H_2}$
14.7	10,000	1490	0.6	8.82	0.07	0.47	18.8	
	20,000	2980	0.7	10.3	0.095	0.637	16.2	1.16
44.0	10,000	166	0.33	14.5	0.028	1.69	8.6	
	20,000	332	0.40	17.6	0.043	2.59	6.8	1.26

The linear correction is valid within 25% for the extreme condition. It is an oversimplification of the functional relationship among the parameters, but any more intricate assumptions led to equations that were difficult to solve.

For the wave moving with the wind, the relative velocity is

$$V = U - C_{1,2} \qquad \text{. . . . (4.4)}$$

Equation (4.2) now may be reduced to the following form:

$$C_d \rho (H_1 + H_2)^2 (U - C_{1,2})^2 C_2 = \gamma C_{G_2} (H_2^3 - H_1^3) \qquad \text{. . . (4.5)}$$

For the upwind migration of the reflected wave it is assumed that incident wave is reflected undiminished, that the power leaves the system in the same manner as it entered and the relative velocity is now

$$V = U \cos\theta + C_{2,3} \qquad \text{. . . . (4.6)}$$

so that energy flux-power equation similar to Equation (4.5) becomes

$$C_d \rho (H_2 + H_3)^2 (U \cos\theta + C_{2,3})^2 C_2 = \gamma C_{G_2} (H_2^3 - H_3^3) \qquad \text{. . (4.7)}$$

The simultaneous solution of Equations (4.5) and (4.7) yields:

$$H_1^3 = H_2^3 - (H_2^3 - H_3^3) \left(\frac{H_1 + H_2}{H_2 + H_3}\right)^2 \left(\frac{U - C_{1,2}}{U \cos\theta + C_{2,3}}\right)^2 \qquad \text{. . . (4.8)}$$

Thus, H_2 is the characteristic wave height taken to be that of the "significant" wave at the bridge, and may be found from the Sverdrup-Munk-Bretschneider, (S-M-B) curves shown on Figure 33 for a given fetch, F, and wind speed, U. The angle θ between the incident and reflected waves is fixed for each wind direction. The value H_3 is selected and then Eq. (4.8) may be solved by trial-and-error for H_1. The fetch, F_1, is then determined from the S-M-B curves. The distance from the bridge to the position of the H_1 and H_3 waves is then found from

$$x = F_2 - F_1 \qquad \text{. . . . . (4.9)}$$

since the points (1) and (3) are the same distance from the bridge.

4.3 Critique of Method

A critique of the method summarized in Eqs (4.8) and (4.9) for predicting the advance of a reflected wave is in order before proceding with the results of computations.

It was assumed that the waves were generated with their crests normal to the wind velocity vector, likewise assumed to be steady. The crest lengths of wind-waves are relatively short, being only two to three times the wave length. Wiegel (1964, p 230), refers to an unpublished article by Arthur who found that waves within a wind field will grow even though they are moving at angles of as much as plus or minus 45 degrees with the mean wind direction, and that the height of these waves will be at least 50% of the height of the waves moving in the mean wind direction. A similar conclusion, based on studies in the Fort Peck and Dennison reservoirs, appears in the Beach Erosion Board Technical Memorandum No. 132, (1962, p 37). As pointed out earlier, wind fields are inherently unsteady and turbulent, and often have gusts up to twice the mean wind speed. The waves these fields produce are bound to exhibit the energy characteristics of the winds themselves.

Wiegel, (1964, p 220), points out that "Since the gust moves over the water surface for a finite length of time and since wave energy is transmitted with the group velocity . . . a group of waves are formed that trail the gust area, and are close to being uniform in height and period. This group may consist of as many as five to ten waves." This phenomenon has been observed on Lake Washington and is mentioned in paragraph 3.5. It seems very likely that the growth of the waves in a sector within 45° of the mean wind direction is due partly to the variation of the wind speed and direction from the mean values. However, the well-defined valley containing Lake Washington seems to limit the short-term variations in wind direction to about 20° to either side of the mean direction rather than the 45° range. A refinement on effective fetch length like that applied in the reservoirs reported in Tecnical Memorandum 132 could be developed for Lake Washington with more definitive wind records and more wave measurements, but was not attempted for this report.

The assumption of perfect reflection was used to relate the heights of the incident and reflected waves (H_2 in Eq 4.8). This assumption is very good until the waves start to break at the bridge, which begins when the wind speed is 25+ mph. For those waves which break, Eq (4.8) should be modified to account for the corrected height of the reflected wave.

In spite of the several assumptions made in deriving Eq (4.8), the predictions of travel distances of the reflected waves agree quite well with observations and focus attention to features which might escape notice if no attempt were made to develop a quantitative prediction.

4.4 Computational Results

A speed of 20 mph at the height of 10 meters above the water was chosen as representative of the hourly reports with speeds of more than 12 mph. Twenty-one percent of the hourly observations at the Seattle-Tacoma Airport, 13% of those at Boeing Field and 6% of those at Sand Point fall into the sector from SE to SW and exceed the 12 mph speed. For the speed of 20 mph, the significant wave height at the Evergreen Point Bridge and the distance to the reflected wave heights of one foot, one-half foot and zero were computed from Eq (4.8) for 10° intervals from S 30 E to S 30 W and presented on Figures 34-40.

The fetch lengths were taken as the over-water distances, not corrected for topographic effects. However, the fetch of 25,000 feet used for the S 30 E winds yielded a height of 1.65 feet; the length of 19,000 feet used for the other directions decreased the height only to 1.47 feet. Figures 41 and 42 display similar information for the speed of 30 mph from the S 20 E and S 20 W.

The calculated waves from the S 30 E strike only a part of the bridge as shown on Figure 34. No allowance has been made on any of the figures for the lateral spreading of the waves from the mean wind direction. The idealized reflected wave from the SE winds has its crest nearly parallel to the prevailing wind, so it is retarded very little by the wind. As the wind direction progresses clockwise around the compass, more of the bridge is opened to the incident waves, and more of the shoreline on the west side is exposed to the reflected waves. However, the reflected wave must now advance more strongly into the wind, (see the cosine term in Eq (4.8)), so that the heights decrease more rapidly with distance from the bridge. The wave measurements for March 14 discussed in paragraph 3.5 correspond quite closely to the predictions on Figure 37.

The reflection diagrams show why the reflected wave patterns are more frequent and discernible for greater distances on the west shore than on the east side. Winds from most any direction from S 30 E to S 30 W can generate waves which may be reflected toward the west shore; winds with a westerly component are needed to create patterns which may be reflected toward the east shore. The diagrams have been prepared for mean wind directions; important wave groups may be generated in directions ranging within about 20° of the mean direction.

Reflected waves have been observed on the east shore as far as 4000 feet south of the bridge, but appeared only in occasional groups, possibly those generated by the wind gusts. None have been observed as far south as Medina , even under very favorable wind conditions. The measurements at the Robinson site, some 2000 feet south of the bridge, were discussed in Chapter 3. The relatively rapid decay with distance, as observed, is borne out by the reflection analysis.

On the west shore, most any wind with a speed of 20 mph at the bridge tower from the southern sector produced waves which could be observed reflecting into the Madison Beach area. Their decay with distance is less rapid than on the east shore. Intermittent low-amplitude patterns have been observed occasionally at Denny Blaine, some 8000 feet south of the bridge, but even these were not discernible at

Madrona. These observations agree quite well with the reflection analysis if some allowances are made for the variations of generated waves from the mean wind direction.

4.5 Near-Shore Effects

The frequency, the magnitude, and the decay-distance of reflected waves on both shorelines between the two bridges on Lake Washington have been enumerated in the preceding sections. Although their consequences on and near a shoreline are very complex and have not been assessed quantitatively, there are properties of waves in general which may be drawn upon to explain some of the phenomena involved in the current problem. These properties are:

1. A wave whose crest is at an angle to a shore in deep water is bent towards a parallel to the beach through the shoaling effects as the wave responds to the bottom on its approach to the beach. The beaches in the areas of concern in Lake Washington shelve off very quickly to deep water, so the waves are bent very little before they run out on the shore. As a consequence, there is a strong littoral, (along-shore), component.

2. Deep-water waves moving in different directions may pass through each other with little mutual interference, but as these waves reach shallow water, ($h/L<1/2$), the significant velocities extend over the full water depth. Sediment agitated and set in motion by one wave may be transported in the opposite direction by the littoral component of the other wave. Waves with heights of about one foot in deep water are capable of moving small gravel in the beach zone. The waves observed in Lake Washington have periods of about two seconds, so a large number of impulses occur during a few hours of wave action.

3. A beach or shoreline equilibrium established by waves from one direction may be disturbed by similar waves from another

direction. The stability of erodible materials is reduced when subjected to alternating forces from different directions. How much disturbance takes place will depend, of course, upon the beach material.

4. The effectiveness of structures such as groins, bulkheads, boat slips, etc., designed to offset some effect of waves predominantly from one direction, will be impaired by waves from other directions.

5. The superposition of wave systems can produce wave heights approaching the sum of the heights of the individual waves which happen to coincide in space and time. If the waves from more than one system impinge against a structure, the resulting reflection patterns become more complex than if only one system were present.

The significance of problems which may be encountered at a particular site must be interpreted in each case, for different combinations of the general wave properties may become important. The character of the shoreline materials, the type of structure present, and the exposure of the site with respect to the wave directions need to be considered. The peculiarities of each site become especially important when the objective is to sort out the differential effects of one wave system superimposed upon another.

One of the best ways to measure the net annual changes in shoreline configurations is to obtain measurements at the same season for a succession of years. The comparison along the Madison Beach area, (Figures 14 and 15), between February and December 1965 shows that there has been a transport of material, largely coarse sand, toward the south. This instance is cited merely as evidence of the existence of waves moving toward the beach from the north or northeasterly direction, which are those reflected from the bridge.

CHAPTER 5

METHODS OF WAVE ATTENUATION

5.1 Introduction

This chapter considers possible remedial measures which might eliminate, or at least reduce, the problem caused by waves reflecting from the Evergreen Point Bridge. No shoreline works of any sort are proposed. These are considered impracticable from a number of standpoints and, in themselves, would not form a solution to the problem. Attention has been focused upon remedial works located at, or attached to, the bridge. No cost estimates have been made, but the calculations included here provide a basis for first estimates of installation and operating costs of some types of works. Then, recommendations for some particular laboratory studies are presented; these are indicated as logical steps before an installation of any kind is proposed on the bridge. Pertinent references in the literature are cited as support for evaluation and calculations concerning possible wave attenuators.

Since the bridge acts as a nearly perfect reflector for the 'deep water' waves, ($h/L>0.5$, or $L/h<2$), developed on Lake Washington, it then seems logical to consider some form of wave attenuator which will eliminate or at least markedly reduce the incident waves striking the bridge. Two general classifications of such attenuators may be given:

1) A structure appended to the bridge as some form of outrigger which might either attenuate the waves by causing them to pass through some physical baffle or skimmer device or cause the waves to shoal and break on a beach-like surface.

2) Creation of a surface current moving outward from the bridge and opposed to the direction of the incident waves, causing the latter to steepen and finally break due to the action of the opposing current.

Perhaps one of the simpler solutions would be an open-work 'beach' attached to the bridge. As indicated by Eagleson (1956), plane beaches with slopes of the order of 1:15 to 1:20 are known to be very effective in causing waves to shoal and break with essentially zero reflection. Such a device, if attached to the bridge, could result in a structure which might well extend 30-50 feet outboard from the bridge. Even if constructed primarily of timber, such a structure would be expensive to install and perhaps to maintain.

Another type of breakwater structure which has been suggested recently by Ippen and Bourodimos (1964), is a so-called "open-tube" breakwater. It is basically a "de-tuning" device for periodically transmitted wave energy, consisting of arrays of open tubes aligned with the direction of wave motion. Wave energy is dissipated by currents induced in the tubes and generating turbulence at the ends; in preliminary tests, no wave breaking occurred. The tubes would be confined to a relatively thin layer of water near the surface (perhaps a few feet for the Lake Washington waves); the tube length should be about L/2, or about 10 feet for typical Lake Washington waves. The result would again be a structure of quite large size; in addition, it has not yet been tested for deep-water waves.

For reasons indicated structural appendages have not been considered to any extent in this report, and attention has been concentrated on the feasibility of attenuating incident waves by the generation of opposing water currents at the lake surface. One advantage of such a scheme is that almost all of the installation required is not readily visible from either the bridge itself or from the shore. In addition, since the need to attenuate waves is sporadic, the device could be operated only when actually needed during times of wave existence on the lake; such scheduling could result in reduced operating costs.

The following sections constitute a brief review of theoretical and experimental studies treating horizontal surface currents as the agents causing waves to break. Two types of such breakwaters have been investigated and are discussed here, the "pneumatic breakwater" and the "hydraulic breakwater." The different names stem from the fact that the surface currents necessary to cause the incident waves to steepen and to eventually break, and hence transmit reduced energy and height past the breakwater, are initiated through either the release of air bubbles or water jets from some manifold-type structure. The resultant surface currents and wave-breaking mechanism are the same in both cases. For this reason the existing theory is discussed first, followed by a partial review of the literature reporting studies of the two types of breakwaters.

5.2 Theory of Breaking of Waves by Opposing Currents

The only theory treating the breaking of deep water waves under the action of an outward-flowing current of finite depth of which the authors are aware was presented by Taylor (1955). Taylor derived relationships for which such currents can be made to prevent the passage of waves; his mathematical formulation of the problem, based upon linear wave theory, in general does not consider the mechanism of how the surface currents are created. Two types of current were considered: a current of uniform velocity distribution over a finite depth, and a current with a velocity decreasing uniformly and vanishing at a finite depth. Taylor's solution results in calculated surface velocity magnitudes and current depths required to stop waves of shorter than specified wave length. It is of note that the wave height is not a factor in the calculation.

Yu (1952) has shown both theoretically and experimentally that for deep water waves which move from still water upstream against a flowing current, complete breaking of the waves occurs when the velocity of the opposing current is 1/4 of the wave velocity. The current in this case however, is uniform over the entire depth of water, and hence for the Lake Washington case, Yu's results cannot be applied.

Perhaps the most concise summary of theoretical findings has been presented by Schijf (1961), who summarized requirements of stopping velocities for different types of waves (shallow water through deep water) for full-depth currents and who also compared results for finite-depth currents from Taylor's theory with some pneumatic breakwater results.

The essentials of the theory may be summarized. Waves can be stopped by an opposing current $V = \alpha C$. For full-depth currents the ratio α depends upon both the initial L/h and steepness of the wave. For deep water waves, where the wave energy is concentrated near the surface, the surface currents may be restricted to depths of 15-25 percent of the wave length. The amount of wave energy passing beneath the current is small. If the surface waves may not be caused to break completely they will still be attenuated by the current.

5.3 Pneumatic Breakwaters

The customary pneumatic breakwater consists of a submerged perforated pipe, located on the bottom or suspended in the water, through which compressed air is forced. The "curtain" of air bubbles rising from the pipe (or manifold) produces an upward air-water mixture current. At the water surface the air escapes and the water flow branches into two horizontal surface currents, one in the direction of wave propagation and one opposing the wave travel. The reduction or attenuation of wave height is caused by this opposing current.

A fairly thorough survey of field and laboratory results from pneumatic breakwaters was given by Green (1961). Model tests and some full-scale tests have indicated that pneumatic breakwaters caused considerable wave attenuation for L/h ratios up to about 4 when adequate air supplies were available. The smallest L/h ratios listed in Green's historical summary range from 0.6 to 1.1, still well above the 0.1 = 20/200 value common on Lake Washington. Wave height reductions in these model tank studies ranged from 75 to 90 percent; air quantities were large. The conclusion was made that pneumatic breakwaters are not suitable for attenuating shallow water waves but would be feasible for deep water where adequate air supplies are available.

Experimental correlations linking the velocity distribution, thickness, power of currents, and air supply rates required for horizontal currents produced by air curtains in water were reported by Bulson (1961). The experiments were performed in still water in a graving dock; water depths ranged to a 34-foot maximum, so that the tests could be considered to be full-scale; the manifold was located on the bottom for all tests. Bulson's equations are based on velocity data obtained at a horizontal distance from the manifold that was equal to its depth of submergence. At this station the velocity distribution in the surface current of finite depth is essentially triangular; this is one of the cases studied by Taylor, (1955). Considering the power available in one of the two surface currents as useful power which could be used to cause breaking of waves, representative efficiencies were in the range of 6-10 percent decreasing with increased water depth. Bulson further concluded that manifold arrangements and perforation (orifice) size and spacing were not influential; surface current thickness was determined to depend only upon the depth of manifold submergence.

Surface currents resulting from air curtains were also investigated by Abraham and v. d. Burge, (1962). The results of Bulson were essentially paralleled in prototype tests in navigation locks with depths ranging from 5 to 10 meters.

Evans (1955), made tests of pneumatic (and also hydraulic) breakwaters in a wave tank containing a 3-foot water depth. He obtained equivalent currents from the two types of devices, and thus was able to conclude that the effect of the air curtain in stopping waves is due almost entirely to the horizontal surface currents established. His test results, with lowest L/h values of about 0.7, indicated that the mean velocity of surface currents of thickness 0.1 L required to stop waves was proportional to $(L)^{\frac{1}{2}}$, as predicted by Taylor, but in addition was dependent to some extent on wave height, a factor which does not appear in Taylor's theory. Evans' results for pneumatic breakwaters came closest to the Lake Washington wave characteristics of any that have been noted in the literature; however, at smaller L/h values of 0.1 the effect of wave steepness as indicated by Evans would be hard to predict.

5.4 Hydraulic Breakwaters

The hydraulic breakwater is a device which uses a series of horizontal water jets to generate the surface current. The jets usually issue from a manifold placed at or close to the water surface.

As with pneumatic breakwaters, most experimental work with hydraulic breakwaters has been confined to L/h ratios of greater than 1.0.

Straub et al, (1958), reported on wave tank tests for waves in the range $1<L/h<6$. They deduced that hydraulic breakwaters are quite effective for deep water waves ($L/h<2$), but are less effective for increasing L/h values. They noted that horsepower and water discharge requirements depend upon wave length and height; more power is required to attenuate steep waves when large attenuation is affected, although the efficiency of the wave breaking process is improved for the steeper waves. These results are somewhat contradictory to the Taylor theory, as the wave height has been noted to have some effect. Tests in the range of $1.2<L/h<1.8$ were run in wave tanks of different sizes, and little scale effect was observed; therefore, it should be possible to extrapolate results to prototype size. In the absence of confirming data, extrapolation of empirical expressions presented relating power and discharge requirements with wave characteristics to the Lake Washington wave characteristics is not possible.

The effect of a single manifold, surface located hydraulic breakwater, on waves generated in a tank by air blowing over the water surface was studied by Williams and Wiegel (1963). Attention was focused upon the energy spectra of the waves in front of and behind (downstream) the breakwater. It was found that shorter, steeper wave components were attenuated to a greater degree than were the longer wave components.

These results are in line with earlier field "observations," since waves in the lee of a breakwater would appear considerably lower while a large portion of the wave energy associated with the longer waves could get past the breakwater.

Dilley (1958), conducted tests of a shipboard hydraulic breakwater mounted on a moored 1:86.5 scale model Liberty Ship. These "three-dimensional" tests were conducted within the range $3<L/h<7$. Within the range of wave heights tested and within the range of experimental error, the wave height for a given L/h did not affect manifold discharge rates required to cause a given wave attenuation. These results thus followed the Taylor theory in that wave amplitude was not an apparent variable.

5.5 Application of Past Studies to the Evergreen Point Bridge

The foregoing literature review indicates there are no experimental data relating to either pneumatic or hydraulic breakwaters that can be applied directly to design or calculation estimates for such devices if used at the Evergreen Point Bridge. This is really not surprising because most wave experiments are made for conditions simulating prototype conditions, and most harbor or coastal structures are located in regions characteristic of shallow-water or transition region waves; the deep-water waves at the bridge are thus not typical for breakwater installations.

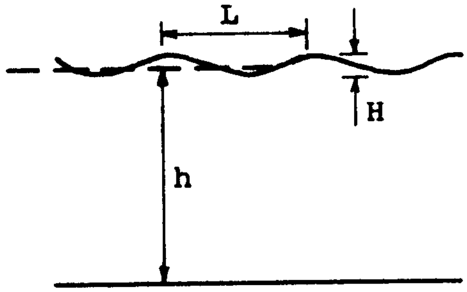
There is a definite information gap concerning breakwaters for wave ranges characteristic to Lake Washington. In addition, as noted, there appears to be conflicting evidence concerning the effect of wave height. There is almost general agreement that the opposing surface currents created by either pneumatic or hydraulic devices act upon waves in the same fashion. Also missing, however, for the L/h ranges on Lake Washington, are experimental indications of the power required to produce the surface currents by the various methods.

Not mentioned so far has been the power loss associated with the supply flow through the manifold. Economic comparison of pneumatic and hydraulic breakwaters might well boil down to a comparison of manifold power losses; surely, manifolds must be designed to minimize these losses.

The points noted have been taken up in the preliminary calculations summarized in this section. It should be observed that the calculations are based upon idealized two-dimensional flows, in which wave crests are parallel to the axis of the attenuating device. The sequence is as follows:

1. The 'design wave' is described.
2. The thickness of a surface current which would be developed by a pneumatic breakwater is calculated.
3. From the theory of Taylor (1955), the maximum (surface) velocity required for the current thickness in step 2 is found.
4. Power and air flow requirements for the pneumatic breakwater are found for these conditions.
5. Comparable terms are found for a hydraulic breakwater flow issuing from a two-dimensional slot and producing the same current. Use is made here of the behavior of diffusing submerged jets as determined by Albertson _et al_, (1950), with simplification to expedite calculations.
6. The hydraulic breakwater is investigated for a surface current of L/15 thickness, again after Taylor (1955), as suggested by Schijf (1961). This is done for slot jets.
7. A hydraulic breakwater having the current characteristics of steps 4 and 5 above is considered. The current is formed from individual circular jets; recent data from Jen _et al_, (1966), are applied.
8. Power requirements of different hydraulic breakwater jet combinations are compared.
9. Rough limit estimates are made concerning power losses in the supply manifolds.

1. Design Wave



L = 20 ft

h = 200 ft

$\frac{L}{h} = \frac{20}{200} = 0.1$, "deep water"

$C = C_o$ = phase velocity $= \sqrt{\frac{gL}{2\pi}}$ = 10.1 fps

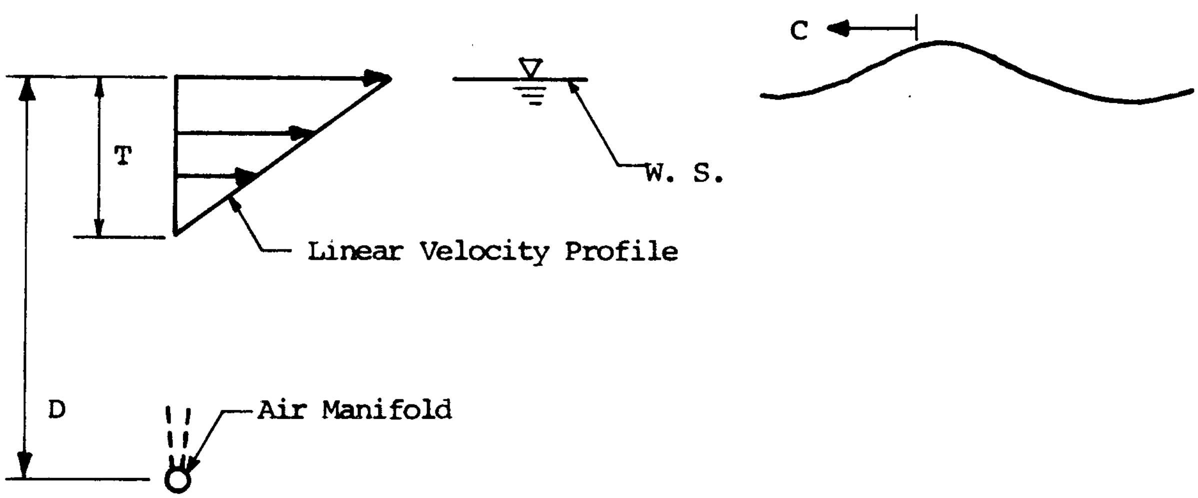
C_G = group velocity = 5.1 fps

$P_w = C_g\, E = C_G\, \frac{1}{8}\, \gamma H^2$, power/unit length of crest

if H = 1 ft, P_W = 0.072 HP/ft (H/L = .05)

if H = 2 ft, P_W = 0.286 HP/ft (H/L = .10)

2. Surface Current Thickness



$T = 0.32\, H_o \ln [1 + \frac{Ho}{D}]$ {Bulson (1961)}

H_o = atmos. pres. head = 34 ft H_2O

D = 10 ft (near max. draft of bridge pontoons)

T = 2.8 ft.

3. Maximum Current Velocity (at surface)

$$\frac{\alpha_{2_m}^2}{Z} = \frac{L}{2\pi T} = 1.14 \qquad \text{\{Taylor (1955)\}}$$

From Taylor's Fig. 5, $\alpha_{2_m} = \frac{C}{V_m} = 3.3$

$$V_m = \frac{10.1}{3.3} = \underline{\underline{3.06 \text{ fps}}}$$

4. Pneumatic breakwater power, air supply requirements

$$P_c = \text{power in surface current} = \frac{\gamma}{2g} TV^3; \; (V^3 = \frac{V_m^3}{4})$$

$$P_c = 19.4 \text{ ft-lb/sec/ft} = .0354 \text{ HP/ft}$$

$$\eta = \text{Efficiency} = \frac{\text{Power in stopping current}}{\text{Power req'd. at air manifold}} = \frac{P_c}{P_m}$$

$$= 0.025 \, [1 + \frac{D}{H_o}]^{-1}$$

{Bulson (1961)}

$$= 0.097$$

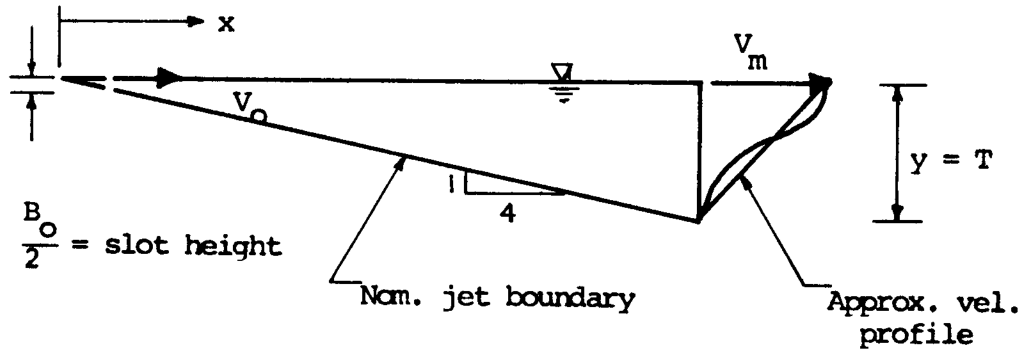
$$P_m = \underline{\underline{0.365 \text{ HP/ft}}}$$

$$P_m = \gamma H_o \, Q_o \ln [1 + \frac{D}{H_o}] \qquad \text{\{Bulson (1961)\}}$$

Q_o = $\underline{\underline{0.366 \text{ cfs/ft}}}$ (air at std. atmos. pres.)

5. Hydraulic breakwater for T = 2.8 ft, V_m = 3.06 fps

Assume manifold is a 2-dimensional slot. Use Albertson et al, (1950), for jet growth, variation of jet discharge with distance. Here, simplify by replacing Gaussian jet velocity profile of Albertson et al, by a linear profile



For T = 2.8 ft, x = 11.2 ft

q at x = 11.2 = $\left(\frac{V_m}{2}\right)$ T = 4.28 cfs/ft

$\frac{q}{q_o} = 0.62\sqrt{\frac{x}{B_o}}$ where q_o = req'd. water jet discharge at slot.
{Albertson et al (1950)}

$(B_o/2)$ ft	q_o cfs/ft	V_o fps	$\frac{V_o^2}{2g}$ ft	$q_o\gamma\frac{V_o^2}{2g}$ ft-lb/sec/ft	P_j HP/ft
.05	.653	13.1	2.66	108	0.197
.025	.460	18.4	5.26	151	0.274
.010	.303	30.3	14.3	270	0.49

6. Hydraulic breakwater for T = L/15

T = 1.33 ft

$\alpha_{2_m} = 2.3$

{Taylor (1955)}

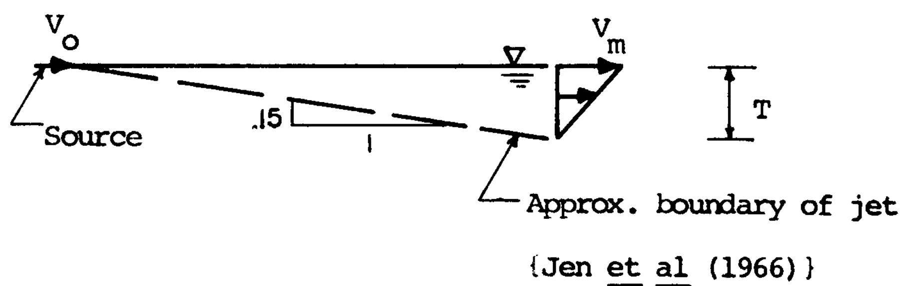
$V_m = \frac{C}{\alpha_{2_m}} = \frac{10.1}{2.3} = 4.40$ fps

For 2-Dimensional Slots:

$(B_o/2)$	q_o	V_o	$\frac{V_o^2}{2g}$	$q_o \gamma \frac{V_o^2}{2g}$	P_j
ft	cfs/ft	fps	ft	ft-lb/sec/ft	HP/ft
.05	.648	13.0	2.62	106	0.19
.025	.460	18.4	5.26	144	0.26
.010	.291	29.1	13.2	240	0.44

7. Hydraulic breakwater, T = 2.8 ft, V_m = 3.06 fps, current formed from individual jets

For combining individual jets, discharged at water surface.



From Albertson et al, (1950), Fig. 17, approximate jet velocity profile with linear variation, and let

$$\frac{V_m}{V_o}\frac{x}{D_o} = 7$$

where D_o = nozzle diameter.

a) Assume jets spaced horizontally at 'T'; at $x_s = \frac{T}{.15}$ a virtually uniform jet having required character is formed.

$$\text{At } x = x_s,\ Q \text{ in width } T = \frac{V_m}{2} T^2 = 12 \text{ cfs}$$

$$\text{At nozzle, } Q_o = A_o V_o = \left(\frac{V_m}{7}\right) \left(\frac{x_s}{D_o}\right) \left(\frac{\pi D_o^2}{4}\right)$$

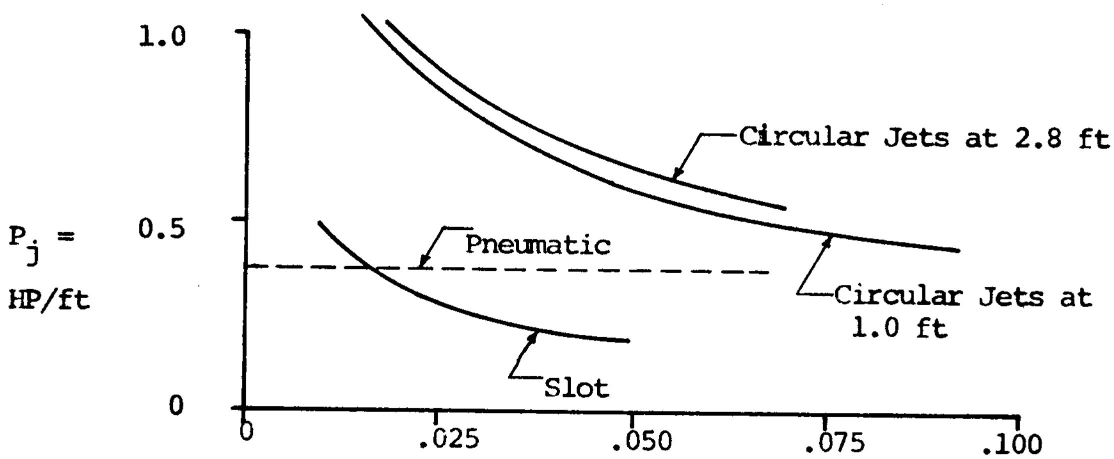
D_o ft	Q_o cfs	V_o fps	$\frac{V_o^2}{2g}$ ft	$q_o = \frac{Q_o}{T}$ cfs/ft	$q_o \gamma \frac{V_o^2}{2g}$ ft-lb/sec/ft	P_j HP/ft
0.10	0.64	81.8	104	0.229	1480	2.7
0.25	1.60	32.7	16.1	0.571	571	1.0
0.33	2.13	24.5	9.35	0.760	442	0.80
0.5	3.20	16.3	4.12	1.14	294	0.54

b) Assume jets spaced horizontally at 1-foot intervals; at x = 1/0.15= 6.67 ft, a 2-dimensional current of thickness = 1 ft is formed. This jet spreads to T = 2.8 ft in (4) (2.8-1.0) = 7.2 ft; at x = 6.67 ft from nozzles, q_1 = 2.54 cfs/ft and V_{m_1} = 5.08 fps. Values tabulated below give jet requirements to produce this current.

D_o ft	$Q_o = q_o$ cfs/ft	V_o fps	$\frac{V_o^2}{2g}$ ft	$q_o \gamma \frac{V_o^2}{2g}$ ft-lb/sec/ft	P_j HP/ft
0.10	0.376	48.2	36.1	846	1.5
0.25	0.949	19.3	5.80	342	0.62
0.33	1.26	14.5	3.26	256	0.47
0.5	1.88	9.6	1.43	168	0.31

8. Comparison of Power Requirements

The different hydraulic breakwaters are compared on the basis of P_j vs nozzle area/ft of manifold length for the T = 2.8 ft, V_m = 3.06 fps current. The results of the slot-type hydraulic breakwater for T = 1.33 ft, V_m = 4.40 fps are not plotted, being almost identical to the slot characteristics for T = 2.8 ft.



$$A_j/\text{ft} = B_o/2, \text{ slot}$$

$$= A_o/T, \text{ circular jet}$$

The 0.365 HP/ft value calculated for the pneumatic breakwater, (at the manifold), in step 4 is also indicated.

9. Consideration of Power Losses in Supply Manifolds

As first estimates of the losses in the "blowing" manifolds, local losses and pressure changes due to jet discharges are neglected. Limits can be placed on the friction losses.

(a) Maximum loss; let Q_o = discharge, assumed constant over full length of constant diameter (D) manifold.

$$h_f = \frac{f}{A^2 D(2g)} (Q_o^2 L)$$

where f = Darcy friction factor, A = conduit area.

(b) Let f and D be constant, and assume linear withdrawal of Q so that $Q = Q_o - Q_o \frac{x}{L}$, with x = distance from upstream end of manifold.

$$h_f = \frac{f}{A^2D(2g)} \left(\frac{Q_o^2 L}{3}\right)$$

The design case of

$$\frac{V^2}{2g} + h_{f_{0-x}} = \text{const.}$$

lies between cases (a) and (b). No detailed manifold calculations are made here; use (a) as an upper limit determination. Note: For either (a) or (b), equal volumetric flow rates of air and water give power losses approximately proportional to their specific weights.

Air Supply - Pneumatic Breakwater

Let L = 100 ft; Q_o = (100) (.366) = 36.6 cfs;

Assume D = 12 in. = 1 ft (could use plastic pipe)

V_o = 46.7 fps; smooth pipe f ≈ .015

Head loss/ft = 0.51 ft/ft

Power loss/ft = $Q_o \gamma_{air} h_f/L$ = 1.42 ft-lb/sec/ft

= 0.0026 HP/ft

Water Supply - Hydraulic Breakwater

For comparison,

Let Q_o = 36.6 cfs

To reduce pipe velocities

Let D = 2 ft

V_o = 11.7 fps; smooth pipe f ≈ .011

Head loss/ft = 0.0117 ft/ft

Power loss/ft - $Q_o \gamma h_f/L$ = 26.6 ft-lb/sec/ft = 0.048 HP/ft

5.6 Comments and Recommendations

Pneumatic and hydraulic breakwaters have been reviewed. They are considered the only practicable methods for attenuating waves and reducing the waves reflected from the Evergreen Point Bridge.

Calculations in the prior section indicate the pneumatic breakwater to be more efficient and hence, for a reasonable size, less costly. Most of the difference between overall efficiencies of the two types of breakwater systems is in the manifold power losses, since the power requirements to create equal surface currents are comparable. The power losses for supply air in the manifold are much smaller than for supply water, further allowing air ducts to be much smaller than water manifolds. The conclusion is that the pneumatic breakwater offers the greatest possibility as a remedial measure.

Another factor is that Bulson's, (1961), power, quantity, and efficiency relations apply to the case of an air curtain creating branching surface water currents. This suggests the possibility that, if the air manifold were installed adjacent to a vertical pontoon face, the efficiency might be nearly doubled and therefore, power requirements halved. This would have to be verified.

The calculations in the preceding section have involved many simplifying assumptions, and should have some experimental confirmation before any field installations would be designed. For that reason, the following program of laboratory tests is proposed.

1. Formation of branching surface currents by an air curtain in still water; measurement of air flow rates and current profiles would indicate how well laboratory results agree with the prototype-size data of Bulson.

2. Formation of a surface current in still water by an air curtain created at a manifold placed adjacent to a surface-piercing vertical wall.

3. Wave attenuation studies for "deep-water" waves for each of the above breakwater configurations; trial positioning of the air manifold could be attempted to determine the optimum location. Wave attenuation, air flow rates, and efficiencies would be determined.

It is proposed that these tests be conducted in a flume capable of having waves generated in water of a 2-foot depth. Deep-water waves, (say, L = 1 ft; L/h = 0.5, maximum), can be generated by a flap-type wave generator formed from a rigid plate attached to the flume bottom by a hinge around which the plate may pivot and driven by an arm linked to a drive unit mounted above the flume.

These laboratory tests, providing data for operation in ranges of wave characteristics not yet studied, would provide information necessary to confirming whether or not such a pneumatic breakwater is feasible for the Lake Washington installation. If feasibility is demonstrated, field tests at the bridge are recommended next.

The extent of the bridge span from which reflected waves of significant height may reach the shoreline has been indicated in Figures 34 through 41. These results may in turn be used for initial estimates of manifold lengths required. At the east end of the span, a 1000-foot length would most likely be adequate; in turn, it might be appropriate to begin at the west end of the span and increase the manifold length incrementally, working toward the draw span, until satisfactory performance is achieved, while holding installation and operating costs to a minimum.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

Most of the objectives set forth at the inception of the Phase I study of the reflected waves on Lake Washington have been met and are summarized in subsequent paragraphs. By the end of the study there had accumulated several individual areas worthy of a general research study in themselves. It was necessary, however, to curtail investigating these areas in depth to stay within the stated objectives and duration of the project. In some cases more work in a special area would have permitted more definitive answers to questions bearing directly upon the project; in some others further study would be of a theoretical rather than an applied nature. For example, the geometric fetch length for wave generation was used in height forecasts; if adequate data could have been obtained, a correction for "effective fetch length" may have led to more refined height predictions. On the other hand, there are some interesting wave-mechanics problems in the vicinity of the bridge, but their solution would not bear directly upon the study objectives.

6.2 Wind Data

The analysis of the wind records from three official reporting stations, supplemented by observations from the anemometer at the control tower at the Evergreen Point Bridge, show that winds from the sector from SE to SW in the speed groups beginning with the 8-12 mph category as appearing in the regular hourly observations, are correlated with the occurrence of waves reflected from the bridge. The important gusty characteristics of the winds do not appear in the climatic summaries of hourly observations, even though they do appear in the hourly weather reports. The percentage of observations reported in the key southern sector varies from about 20% at Sand Point to 36% at the Seattle-Tacoma Airport.

The primary waves generated by the wind develop in a sector lying 20 degrees or so to either side of the mean wind direction. From another viewpoint, the wind direction within limits, is not as important in the generation of waves as the magnitude of the wind speed and its gusty or unsteady characteristics.

Data from a recording wind gage at the bridge tower accumulated over a period of a few years and correlated with concurrent records at the official stations would help to refine the wind analysis. However, the waves resulting from the winds are the main objective, so that additional wind data without the associated wave data would not increase appreciably the predicted correlation between the waves and the winds.

6.3 Reflected Waves

The observations, measurements and analyses have shown that reflected waves occur on the west shore from a point just off the west end of the bridge for about 4000 feet southward. Some intermittent, small-amplitude waves occur farther to the south, but the divergence of the shoreline and the natural decay of the waves moving against the wind cause these to be rather unimportant.

The section of the east shore exposed to the reflected waves is shorter than that on the west side, being mainly confined to the range between 1000 and 3000 feet south of the bridge, as a result of the alignment of the bridge with respect to the common wind directions and the shoreline.

The analysis for the decay of the reflected waves gave results in good agreement as to magnitude and extent with the observed valuess

6.4 Shoreline Effects

The frequency of the reflected waves and their areal extent of characteristic heights has been delineated. Whether or not these reflected waves may have initiated changes in shoreline environment has to be interpreted individually for each site of concern. If merely the presence of reflected waves should be a concern, the on-site observations of a few typical wind-wave situations should establish a basis for evaluating their significance. On the other hand, the assessment of accumulated effects as would arise in an erosional problem, periodic measurements or the analysis of past measurements likely would be necessary to establish a time factor or "rate" in the process.

6.5 Wave Attenuators

The comparative analysis of methods for attenuating waves as based upon available literature showed promise that the incident waves might be absorbed at the bridge, thereby reducing or eliminating reflected waves. To make the analysis, however, it was necessary to extrapolate from data reported in the literature to the unusual case of deep-water waves striking a vertical barrier. Additional laboratory and field work would be necessary to supply quantitative measurements to support the analysis before a prototype installation could be designed and its cost estimated reliably.

6.6 Phase II Considerations

The Phase I study has mapped out the extent of the reflected waves and has set forth generalized conclusions regarding the types of problems that may exist. A Phase II study could proceed in several directions:

1. Instrument the lake with three or four recording wave gages to measure heights and directions, and at least one recording anemometer so that the correlations and predictions of wind-wave relationships could be refined.
2. Delineate for study specific shoreline sites to ascertain more definitively the special problems which may occur at such sites.
3. Pursue the prospect of eliminating or at least reducing the magnitude of the reflected waves by an attenuator or absorber at the bridge.

4. Take advantage of the natural laboratory which Lake Washington offers to investigate, in a basic way, the several areas of wind-wave mechanics and structural interations which have only been touched by the Phase I study.

The authors wish to defer specific recommendations for a Phase II study until there has been an opportunity to discuss thoroughly this report on the Phase I study.

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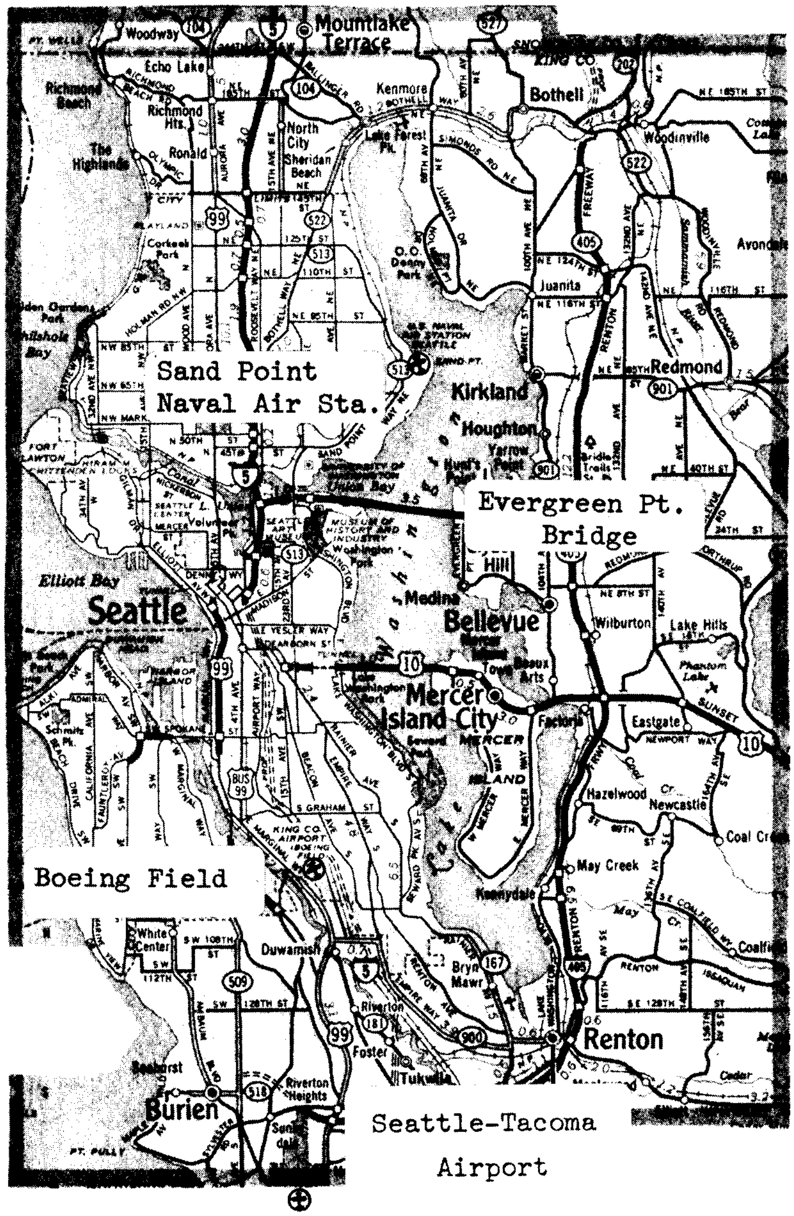

Sand Point
Naval Air Sta.
Evergreen Pt.
Bridge
Boeing Field
Seattle-Tacoma
Airport
Seattle
Bellevue
Kirkland
Redmond
Renton
Burien
Bothell

Figure 1

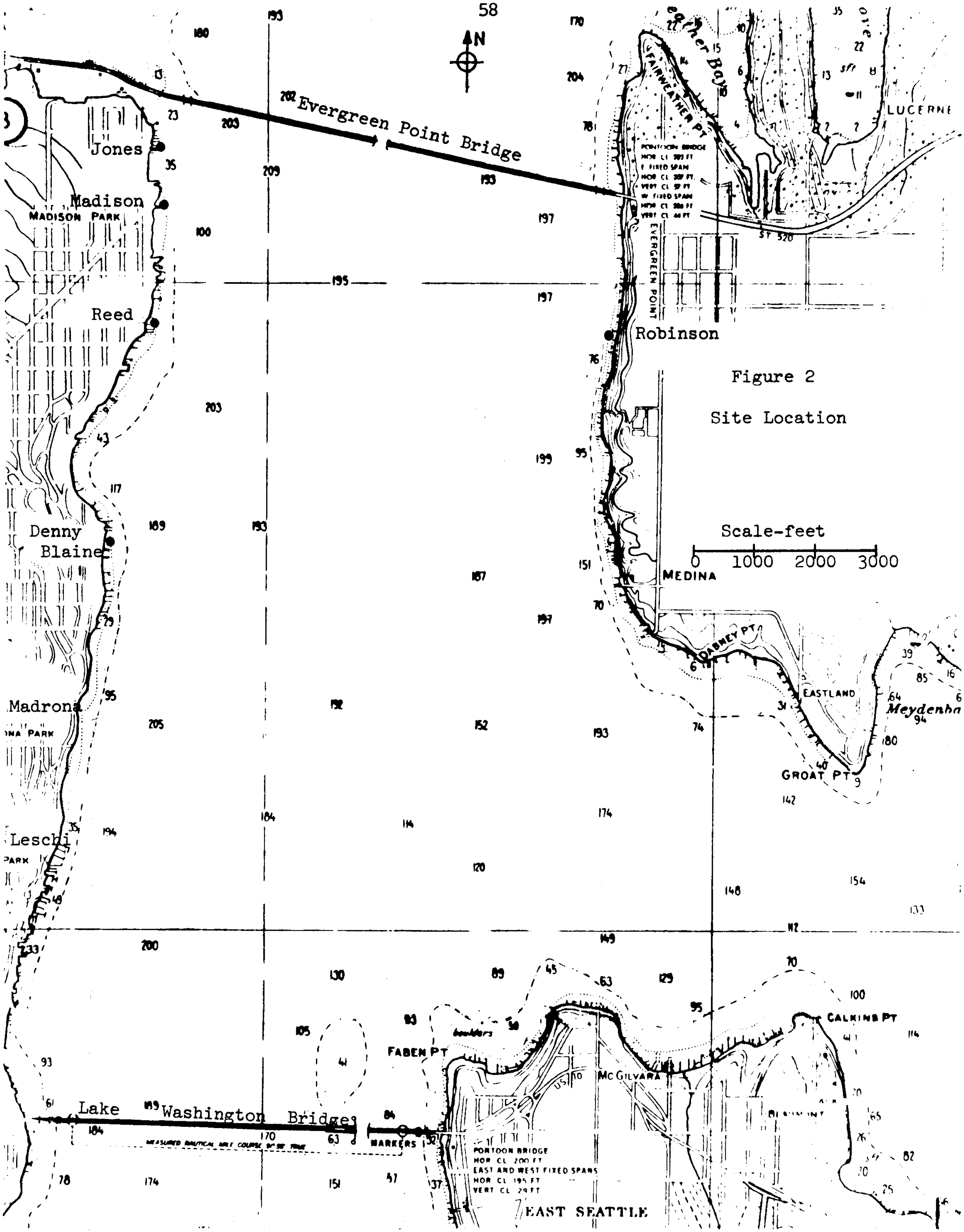


Figure 2

Site Location

ANNUAL SURFACE WIND ROSE

SEATTLE-TACOMA AIRPORT

1951 - 1960

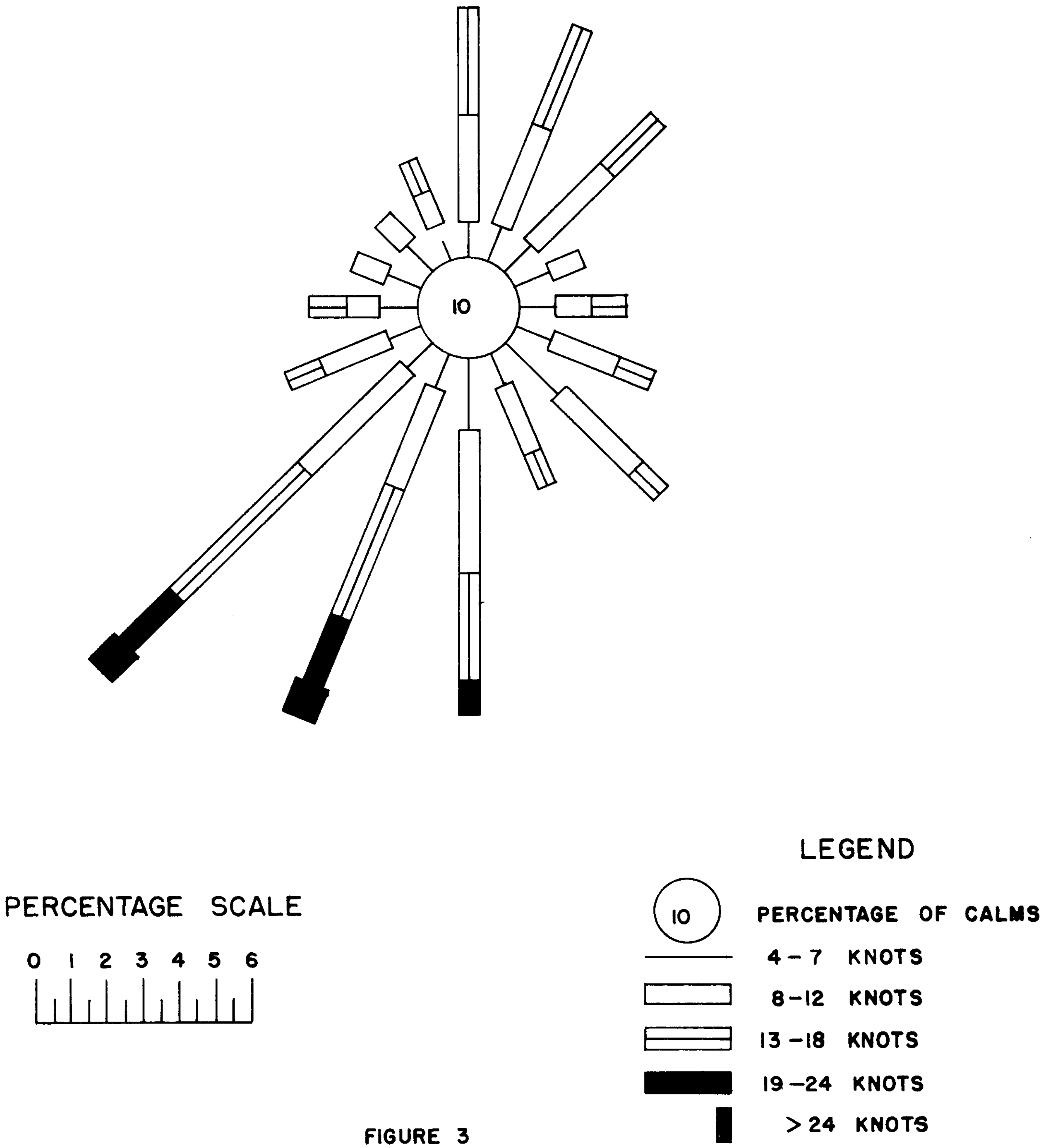


FIGURE 3

ANNUAL SURFACE
WIND ROSE
BOEING FIELD
1950-1959

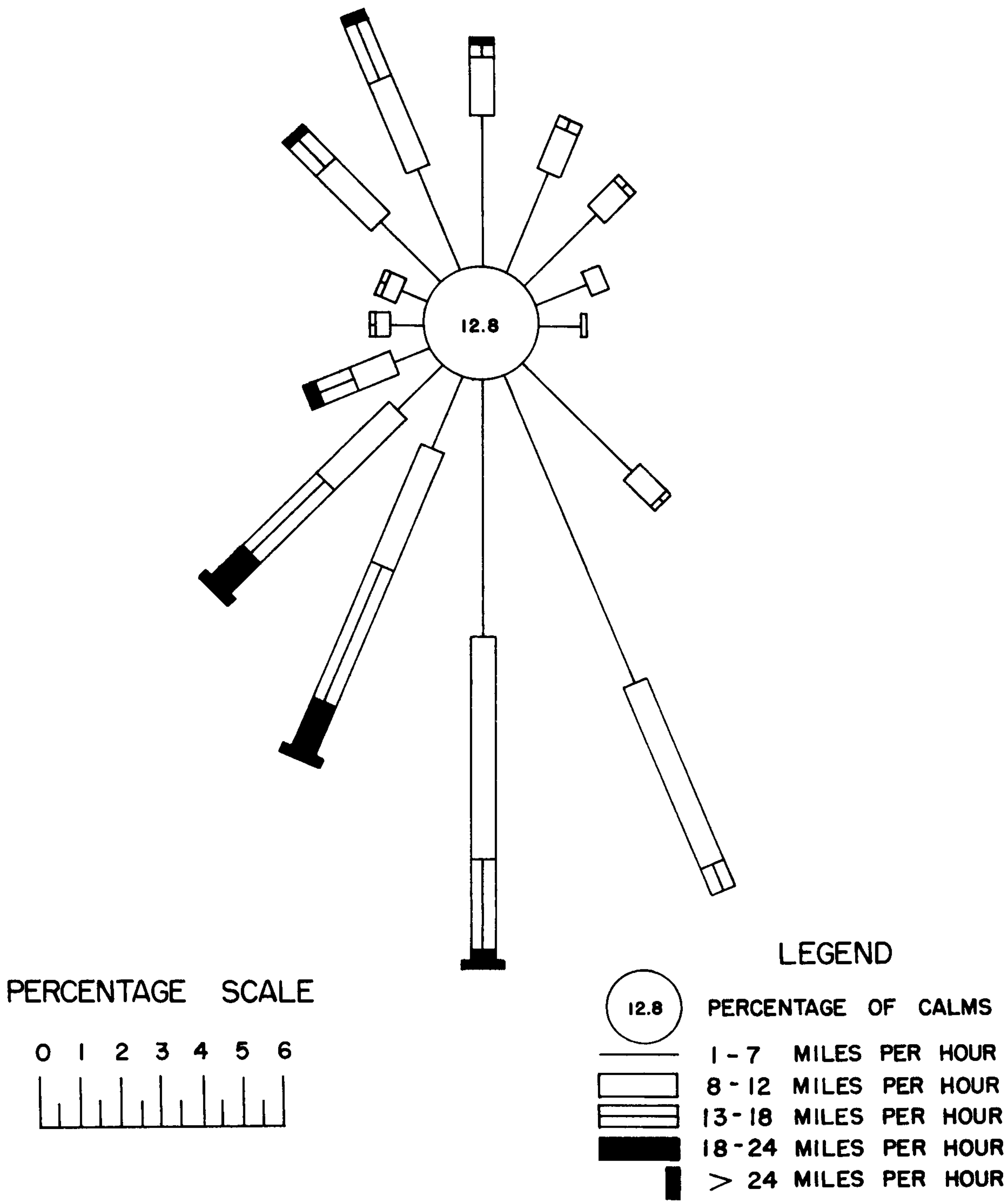


FIGURE 4

ANNUAL SURFACE WIND ROSE
SAND POINT N.A.S.
1949 - 1964

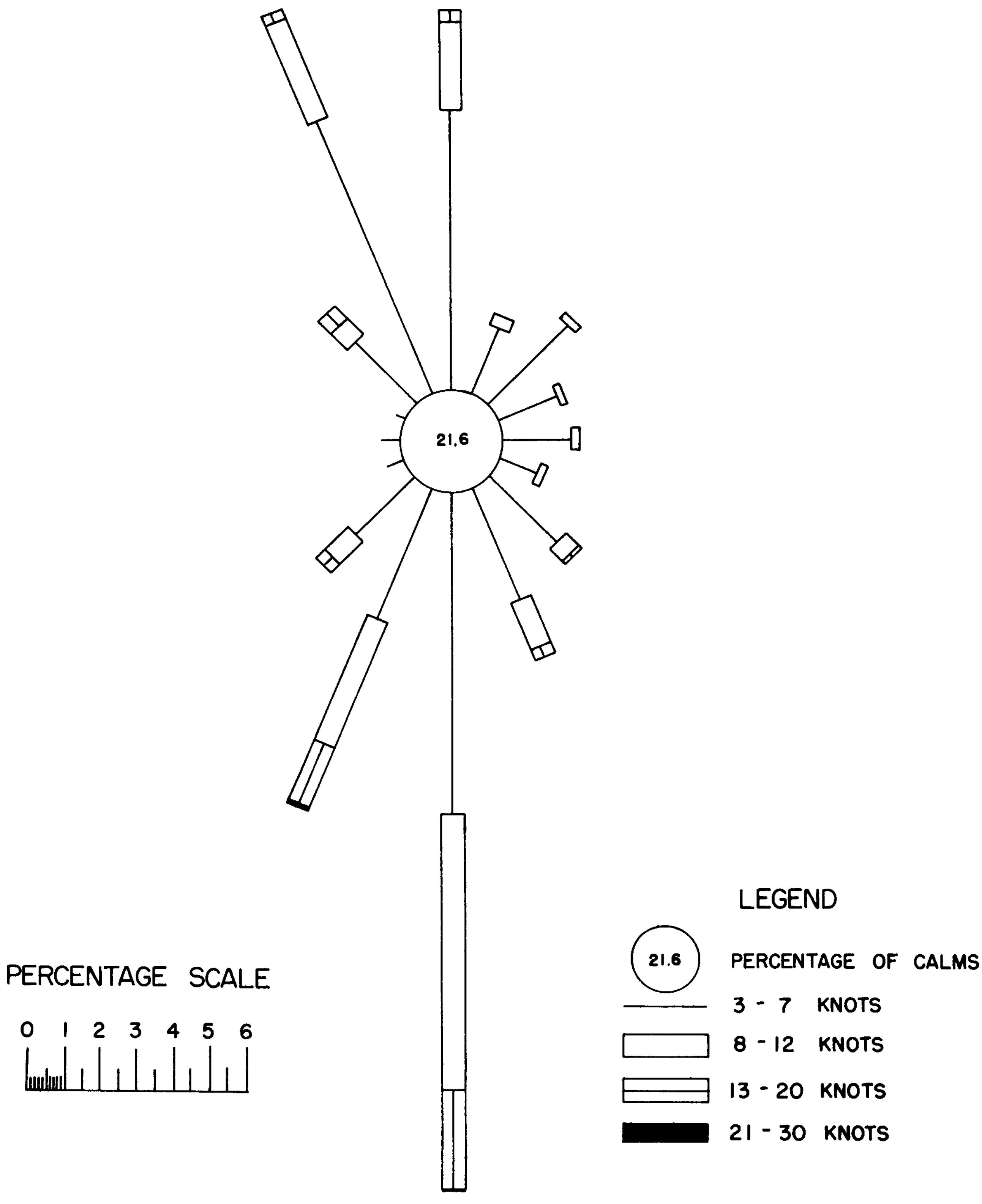


FIGURE 5

MONTHLY SURFACE WIND ROSE

BOEING FIELD

1950 - 1959

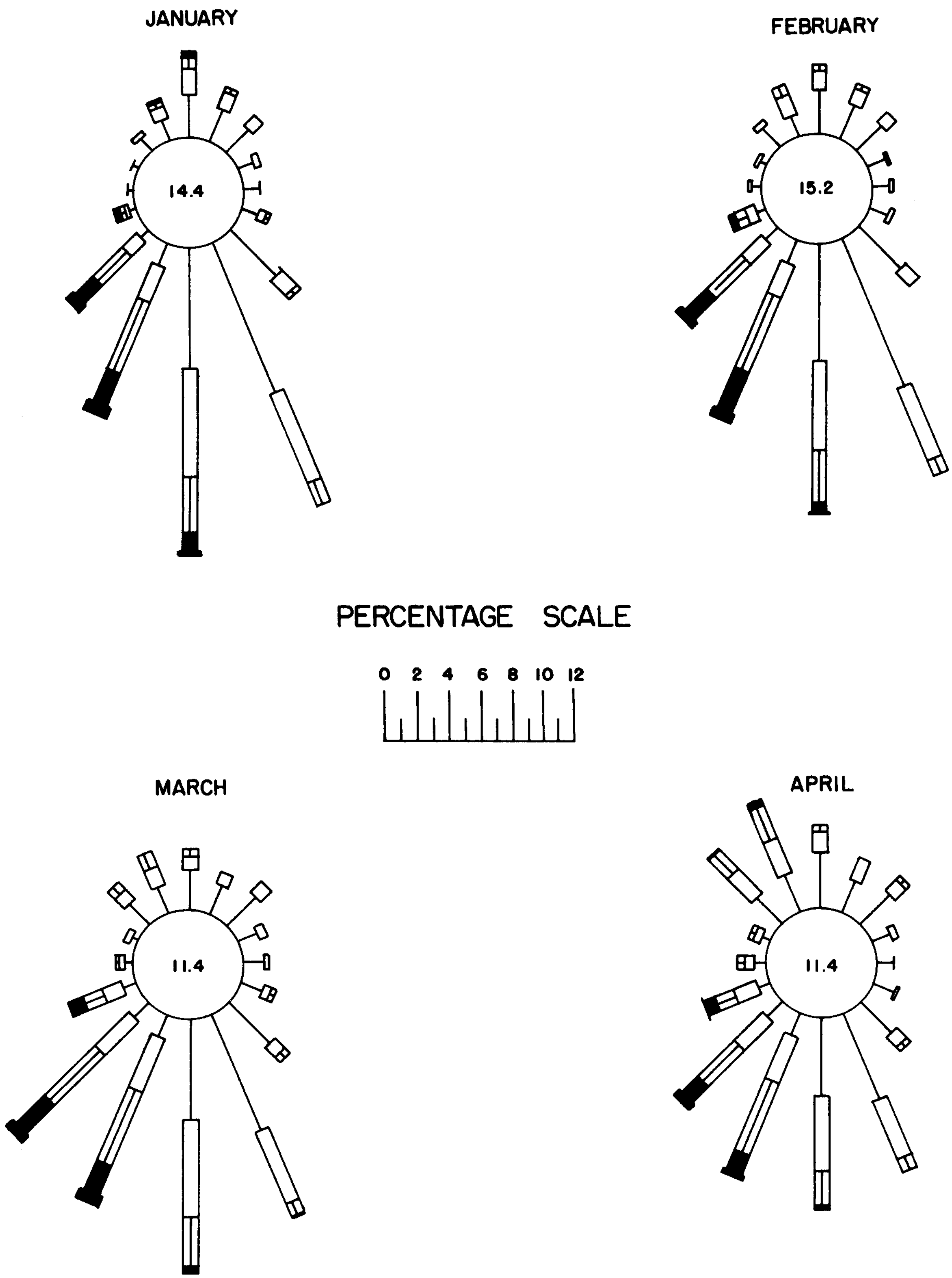


FIGURE 6

MONTHLY SURFACE
WIND ROSE
BOEING FIELD
1950 - 1959

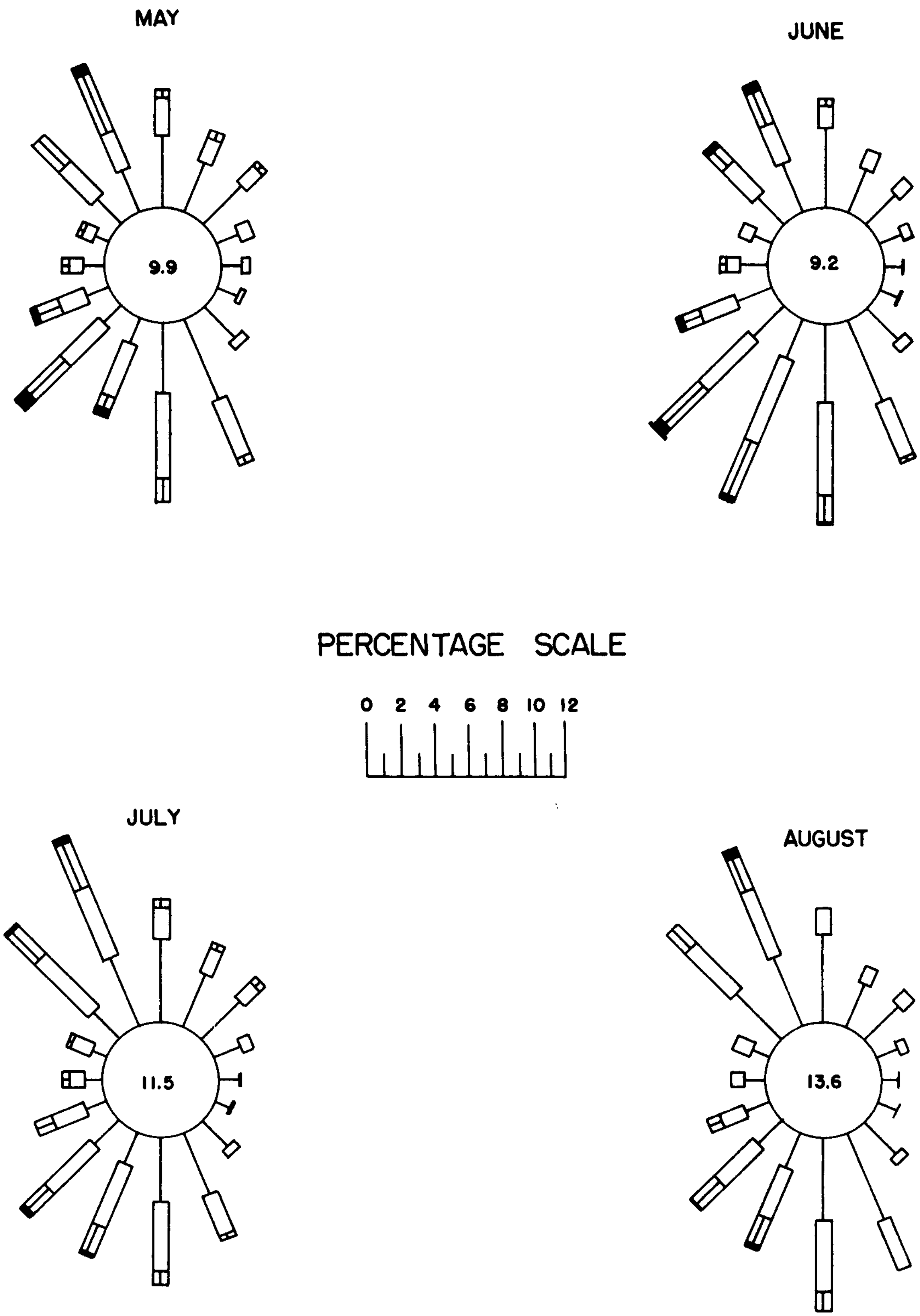


FIGURE 7

MONTHLY SURFACE WIND ROSE

BOEING FIELD

1950 - 1959

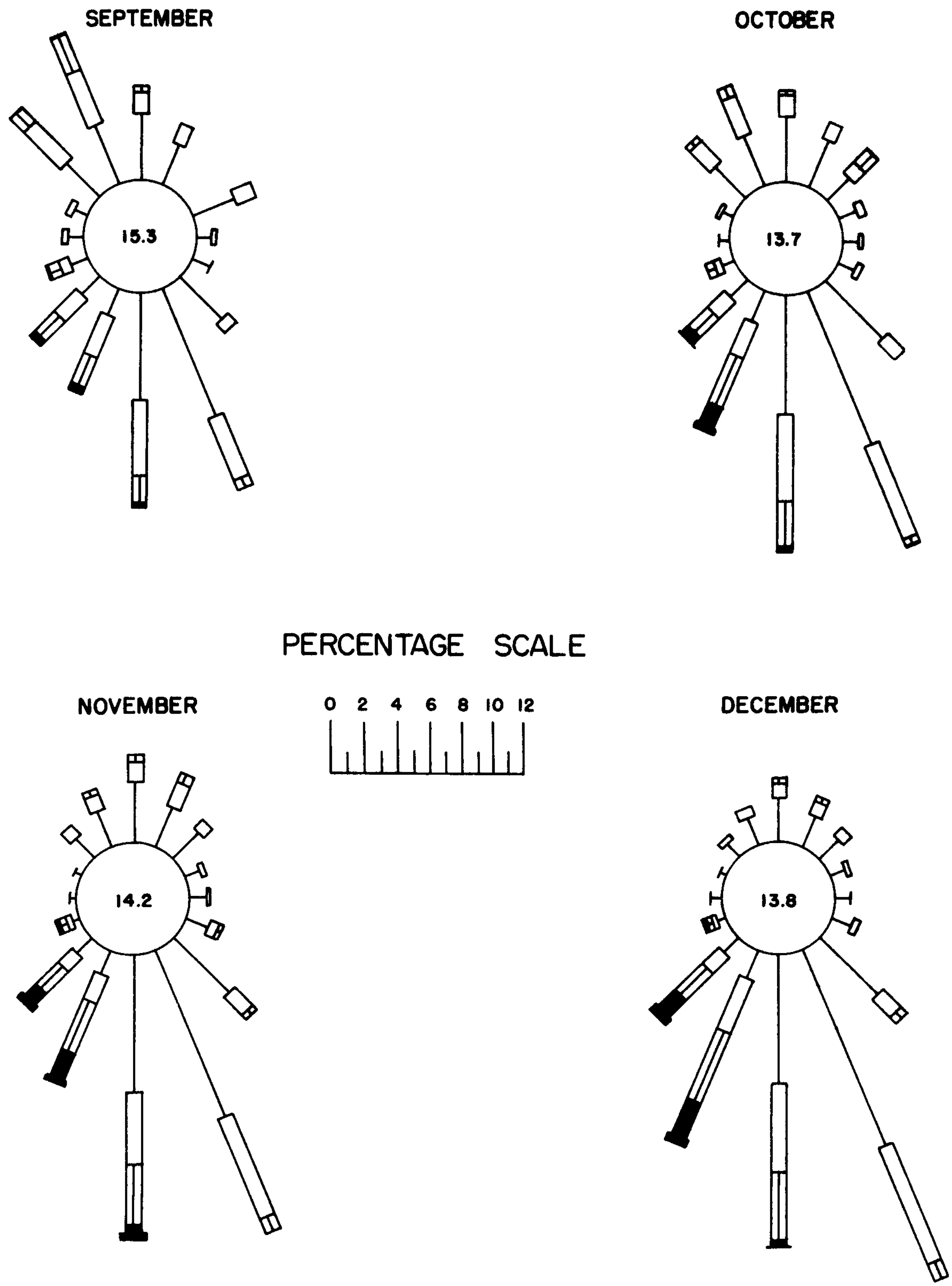


FIGURE 8

MONTHLY SURFACE WIND ROSE

SAND POINT N.A.S.

1949 - 1964

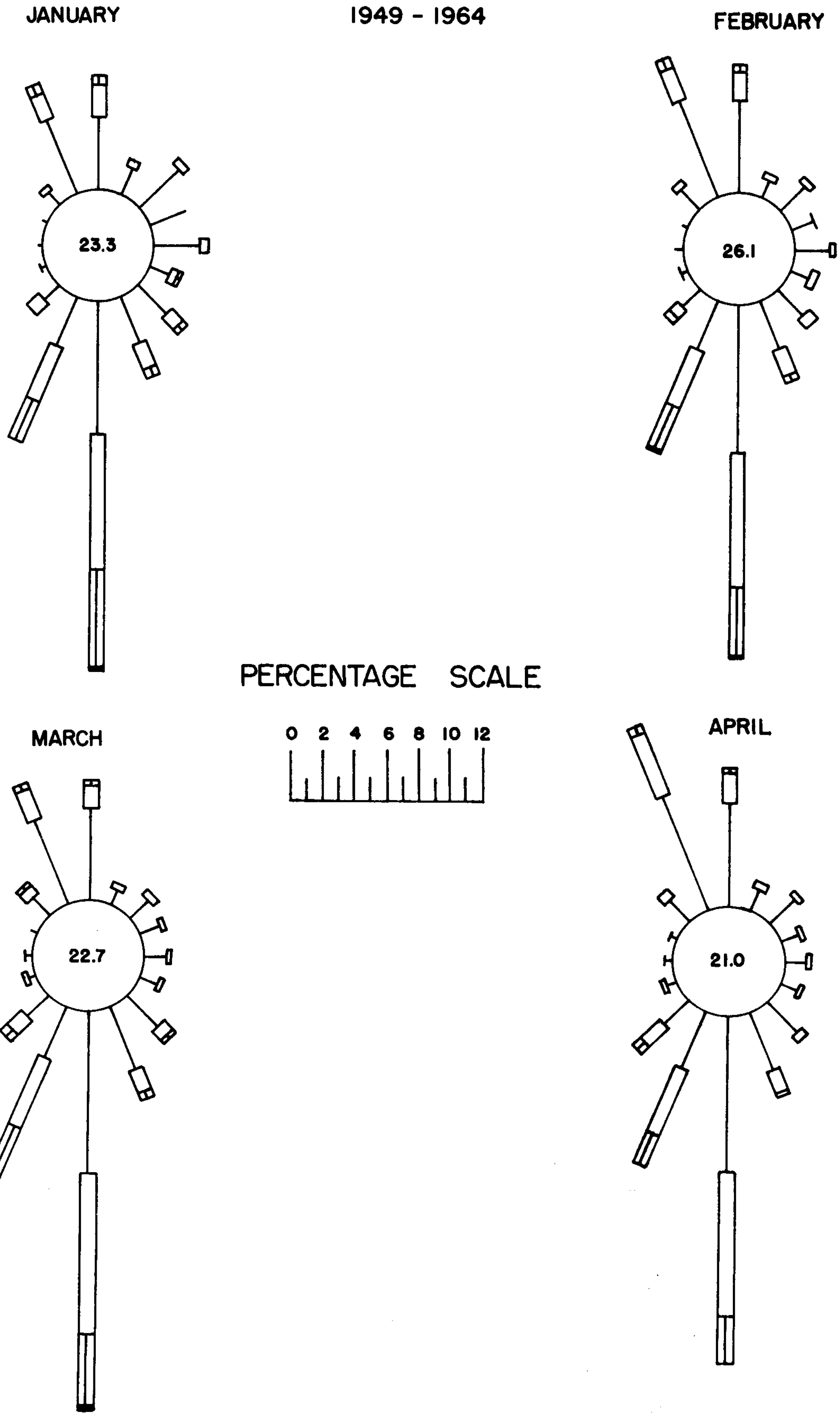


FIGURE 9

MONTHLY SURFACE WIND ROSE

SAND POINT N.A.S.

1949 - 1964

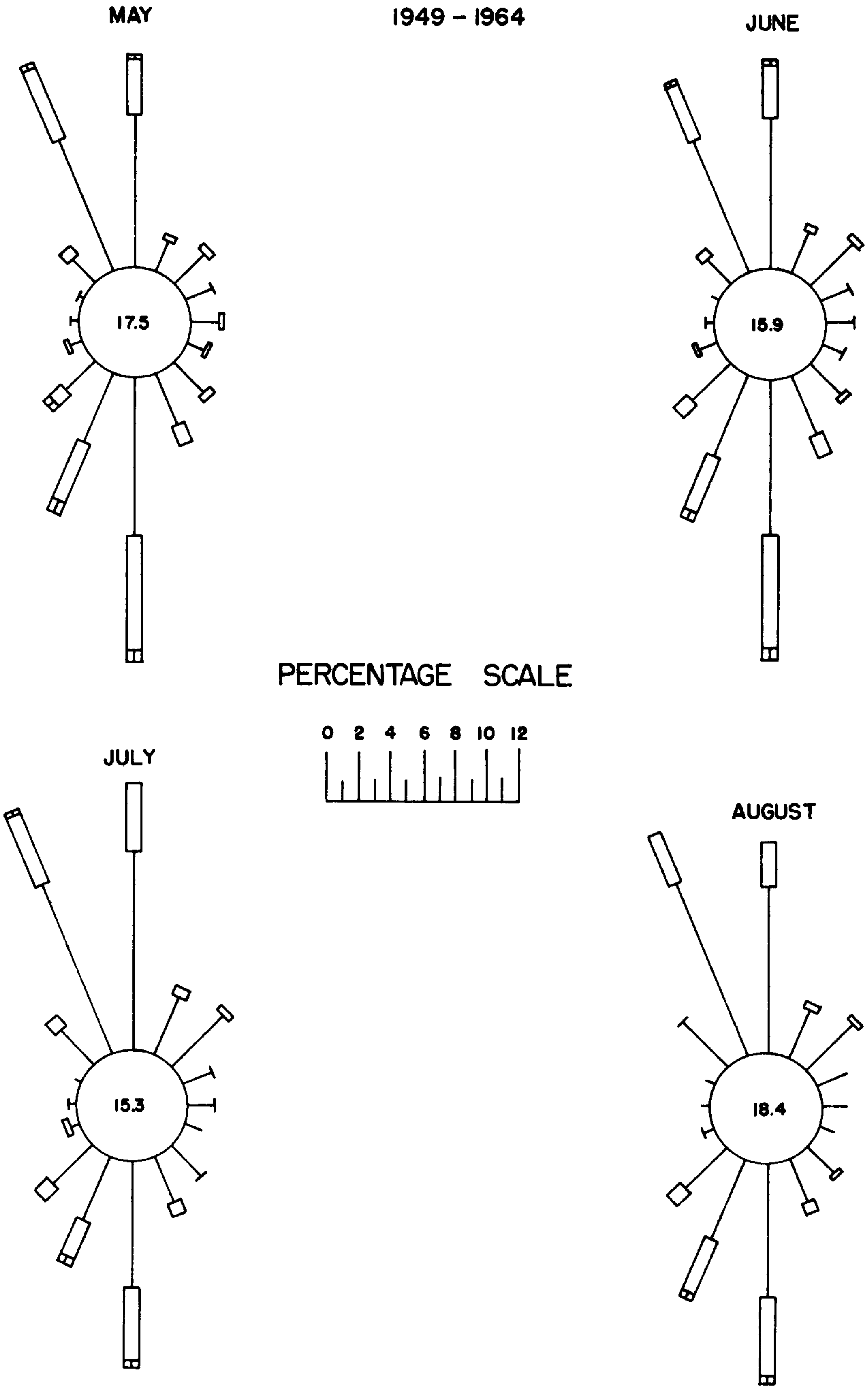


FIGURE 10

MONTHLY SURFACE WIND ROSE

SAND POINT N.A.S.

1949 - 1964

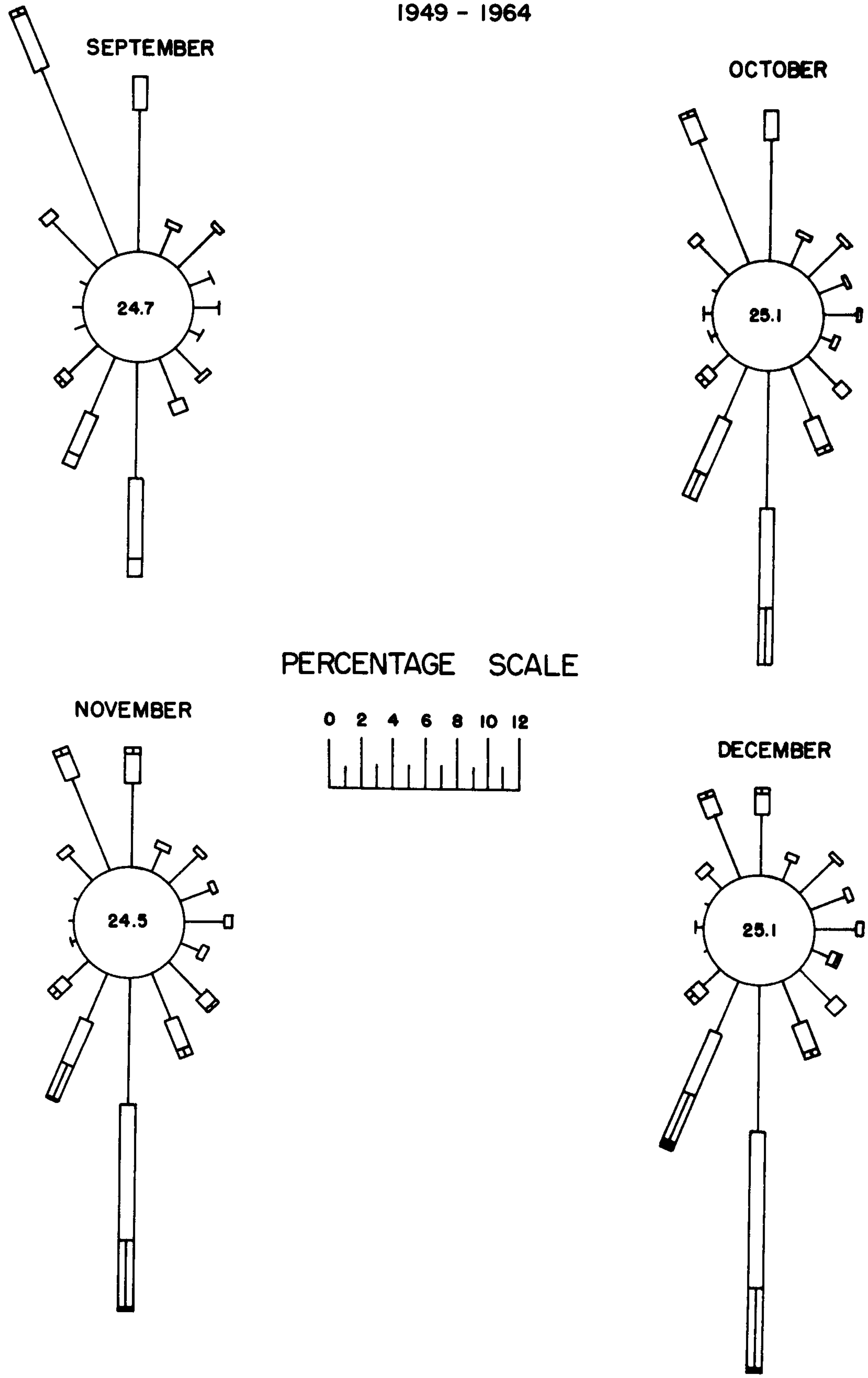


FIGURE 11

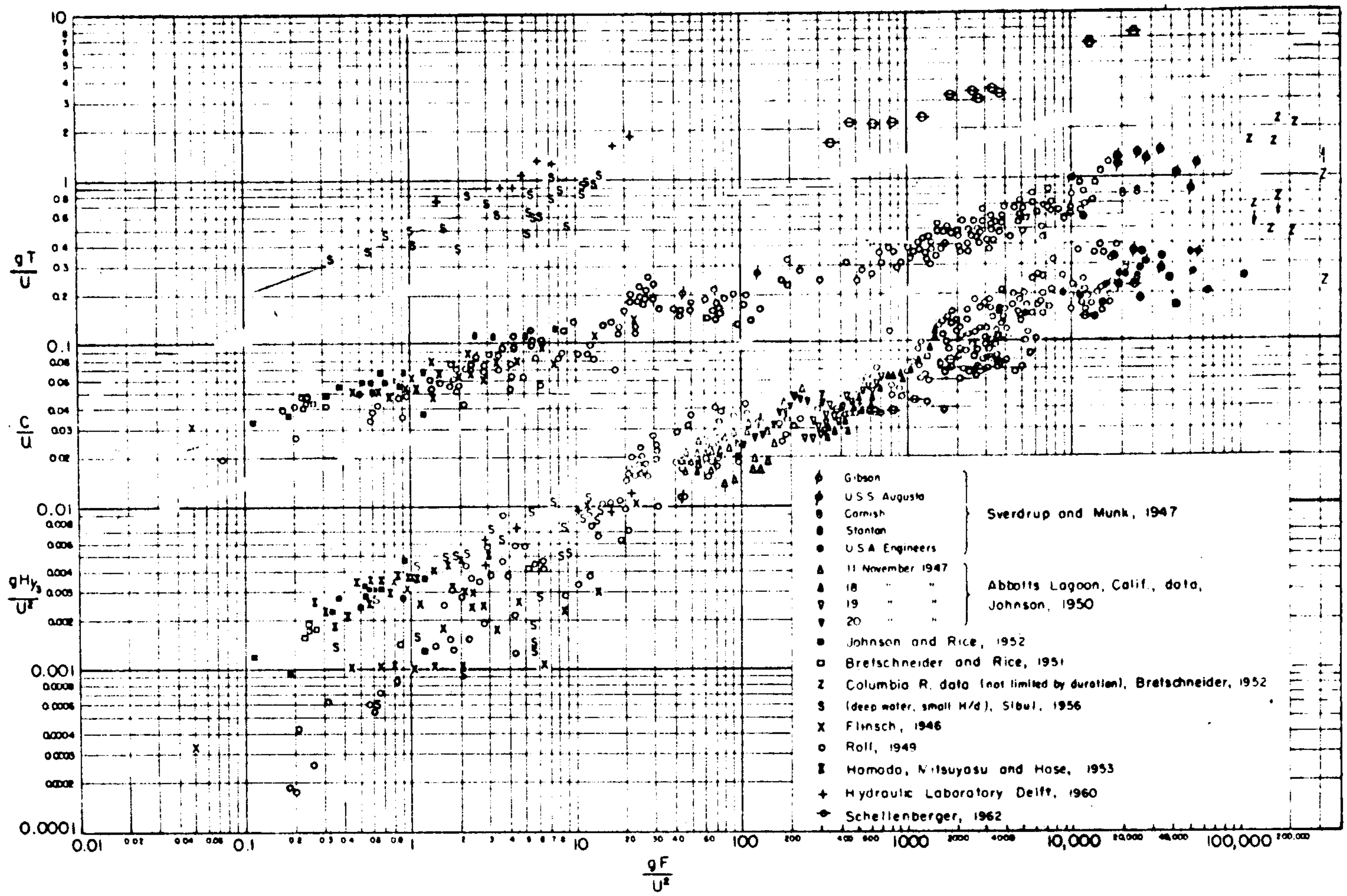
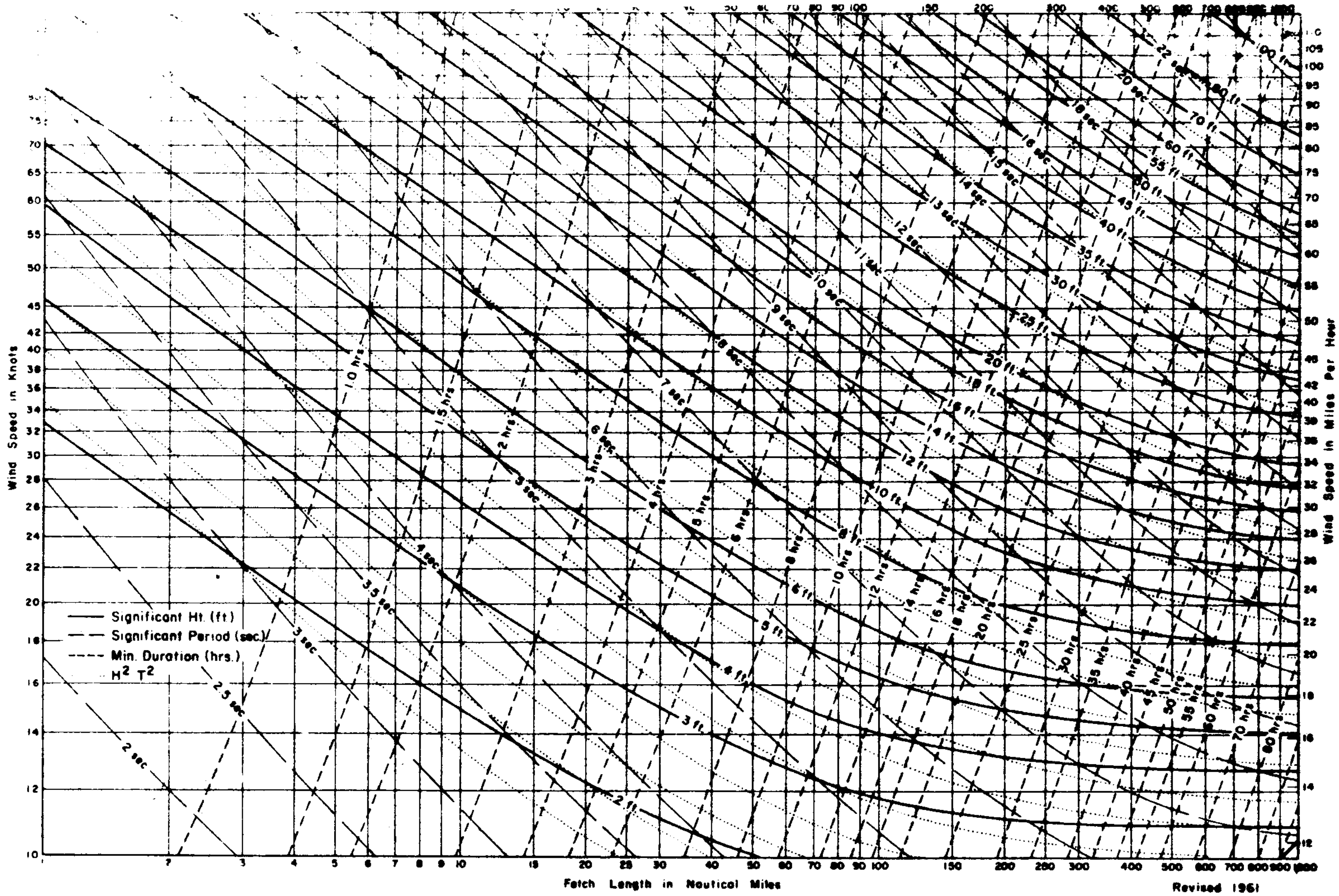


Figure 12 Relationships among fetch, wind velocity and wave height, period, and velocity (after Wiegel, 1961)



DEEP WATER WAVE FORECASTING CURVES AS A FUNCTION OF WIND SPEED, FETCH LENGTH, AND WIND DURATION

(for Fetches 1 to 1,000 miles)

FIGURE 13

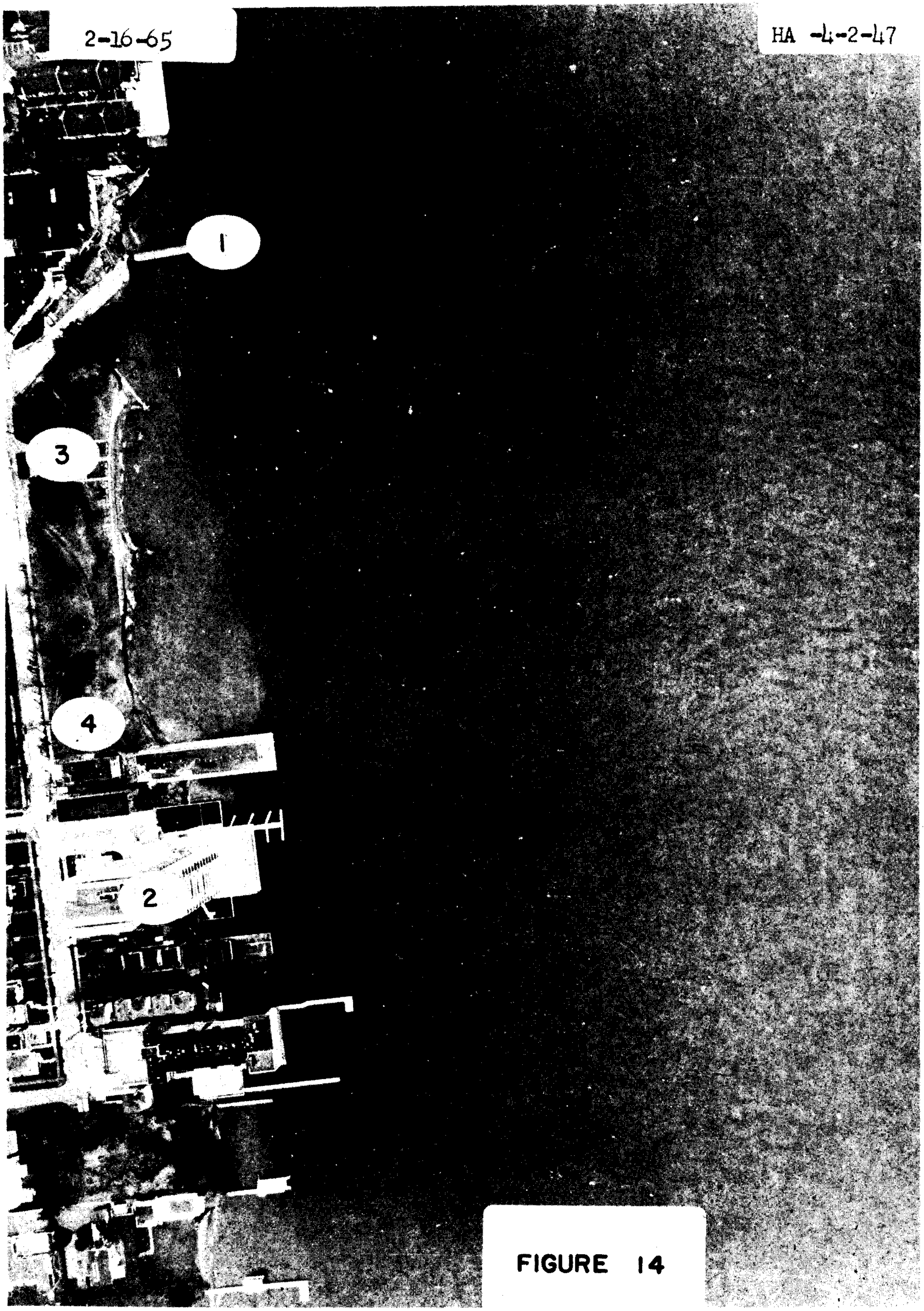


FIGURE 14

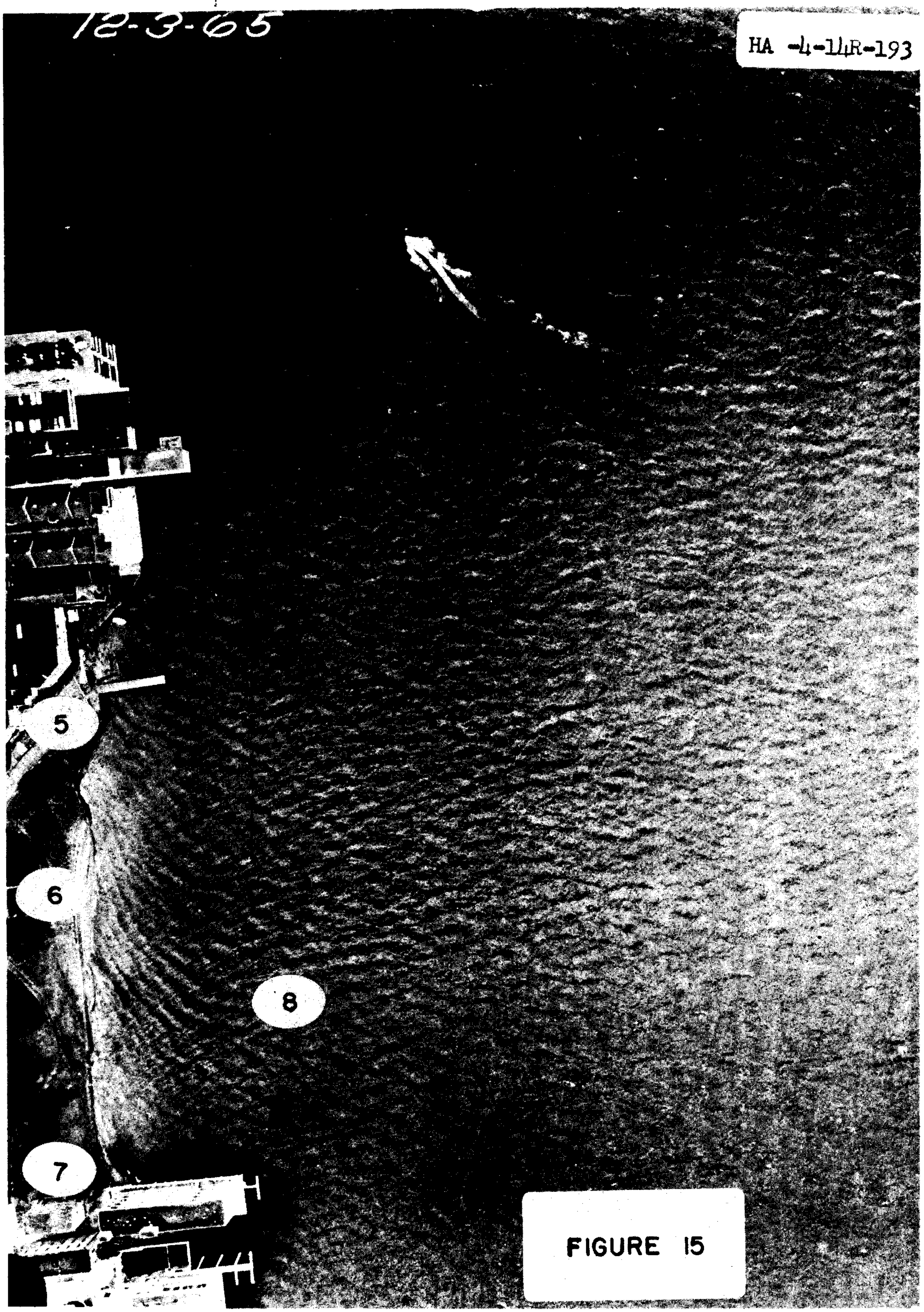


FIGURE 15

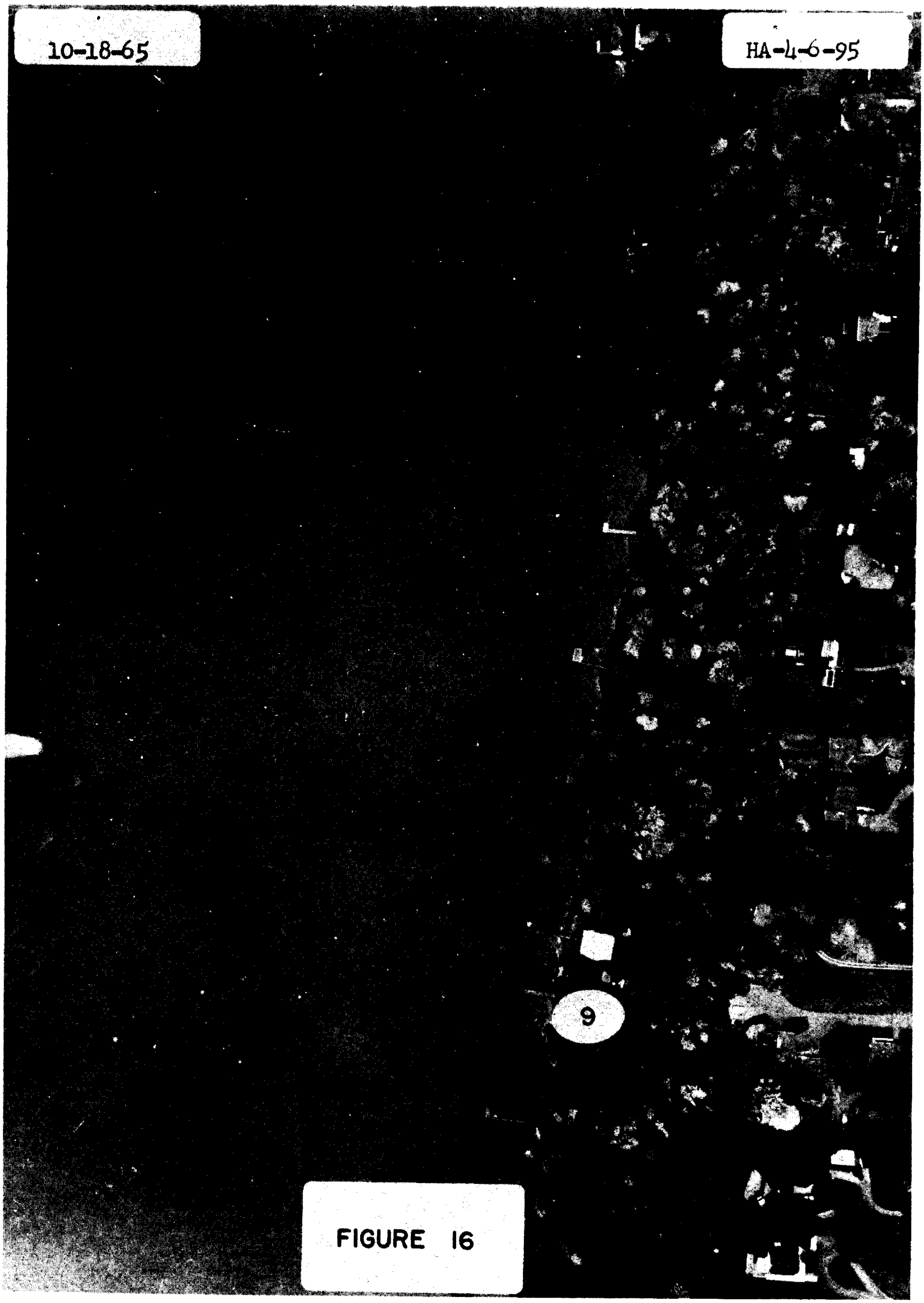


FIGURE 16

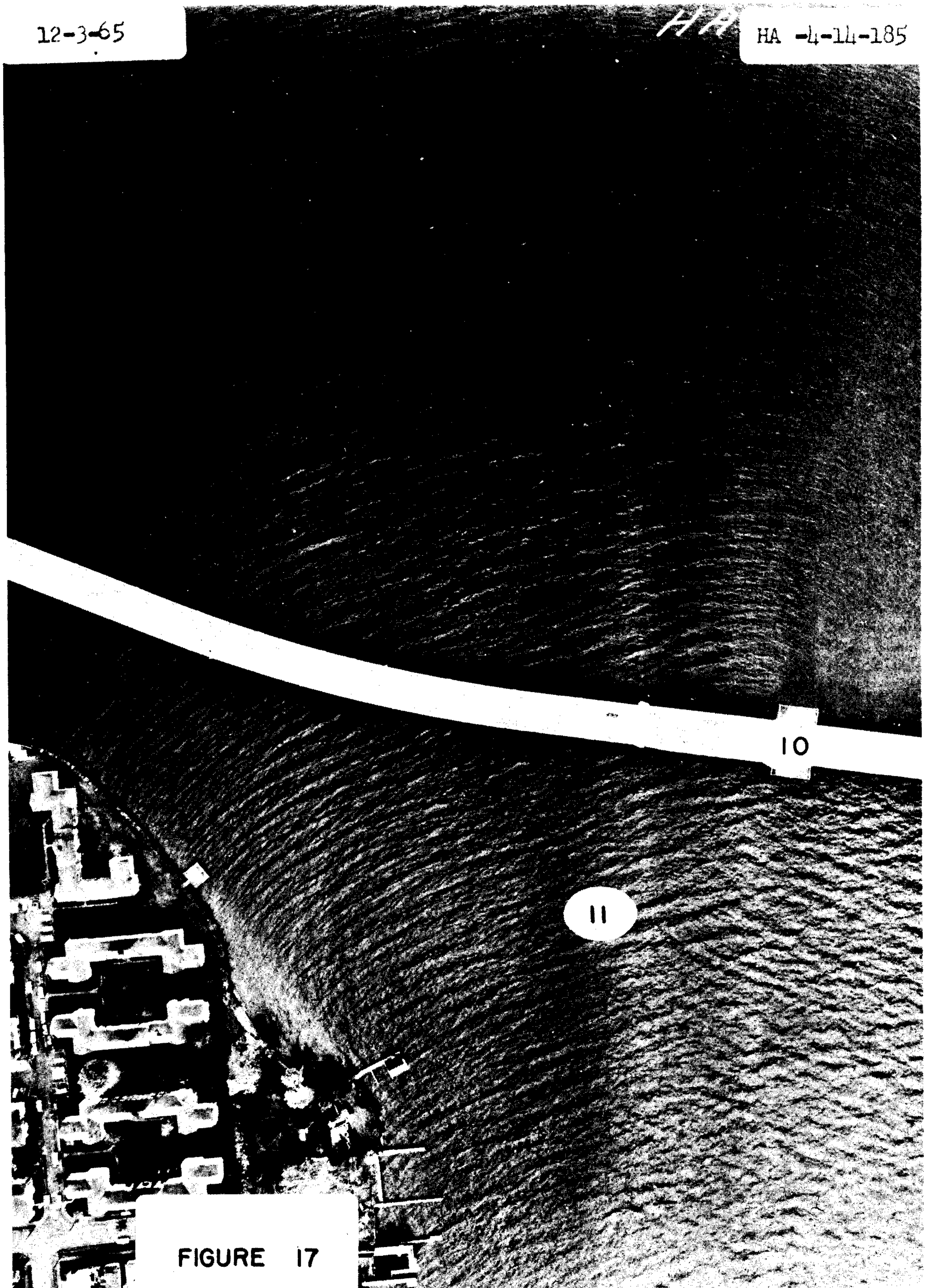


FIGURE 17

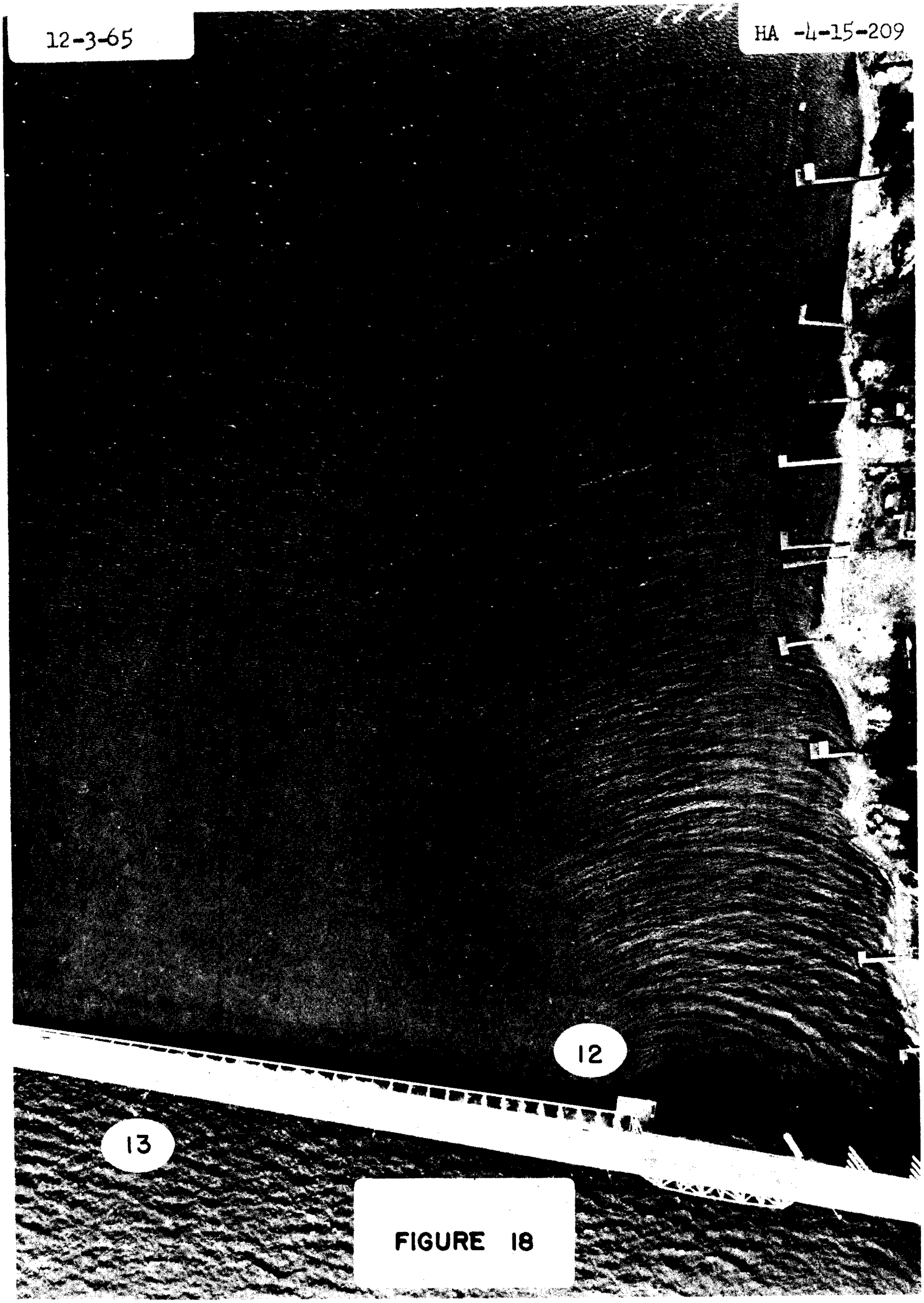


FIGURE 18

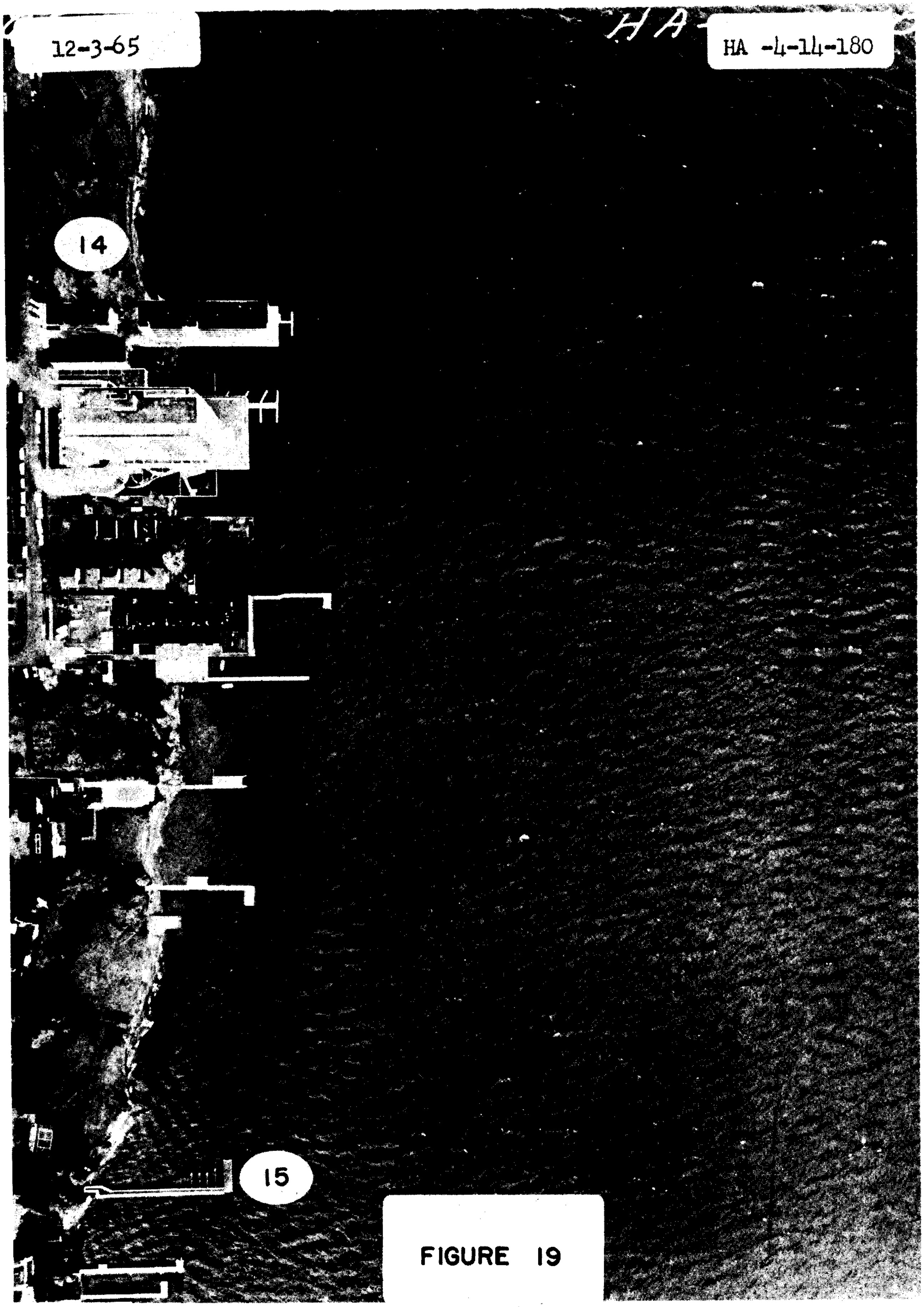


FIGURE 19

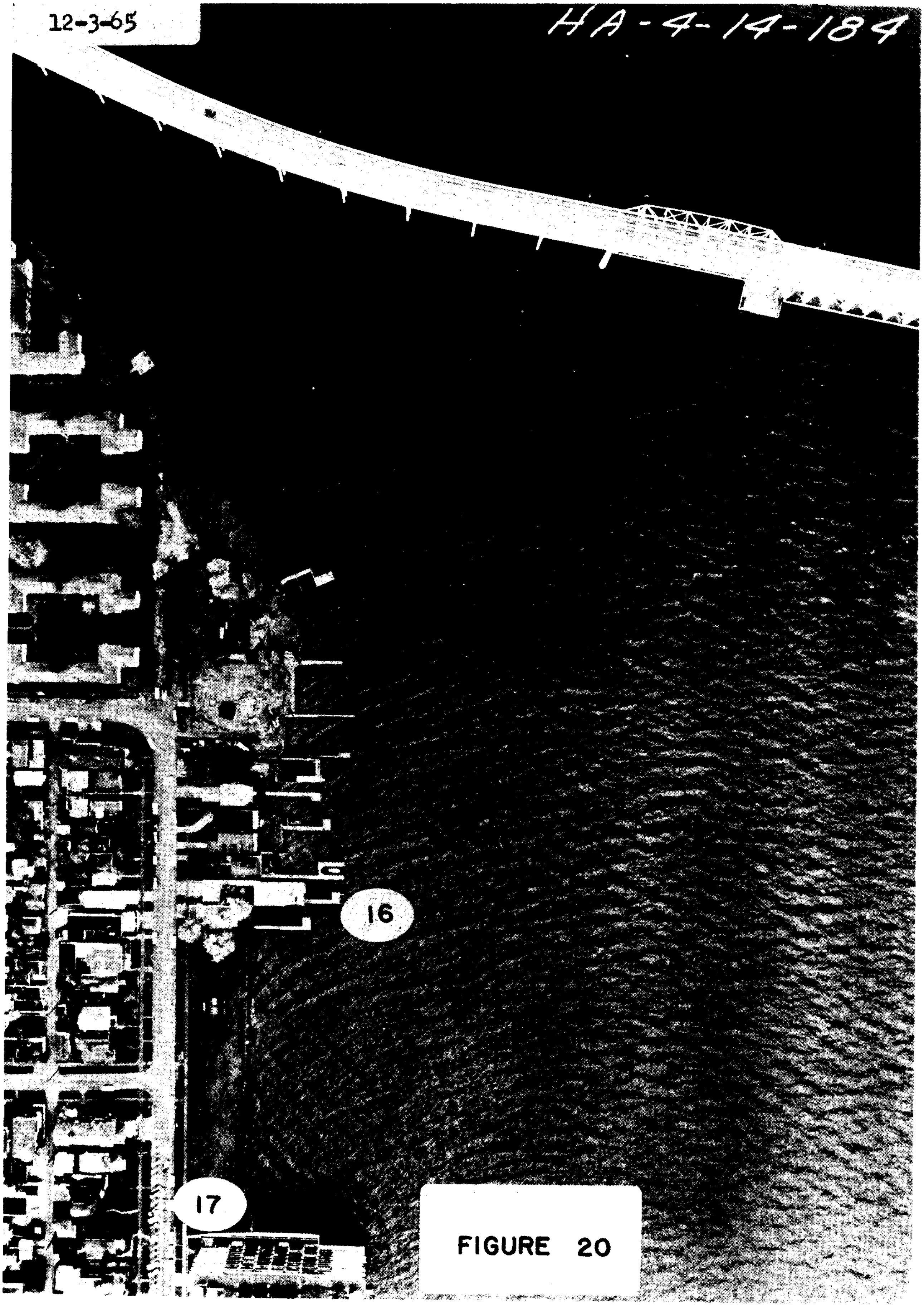


FIGURE 20

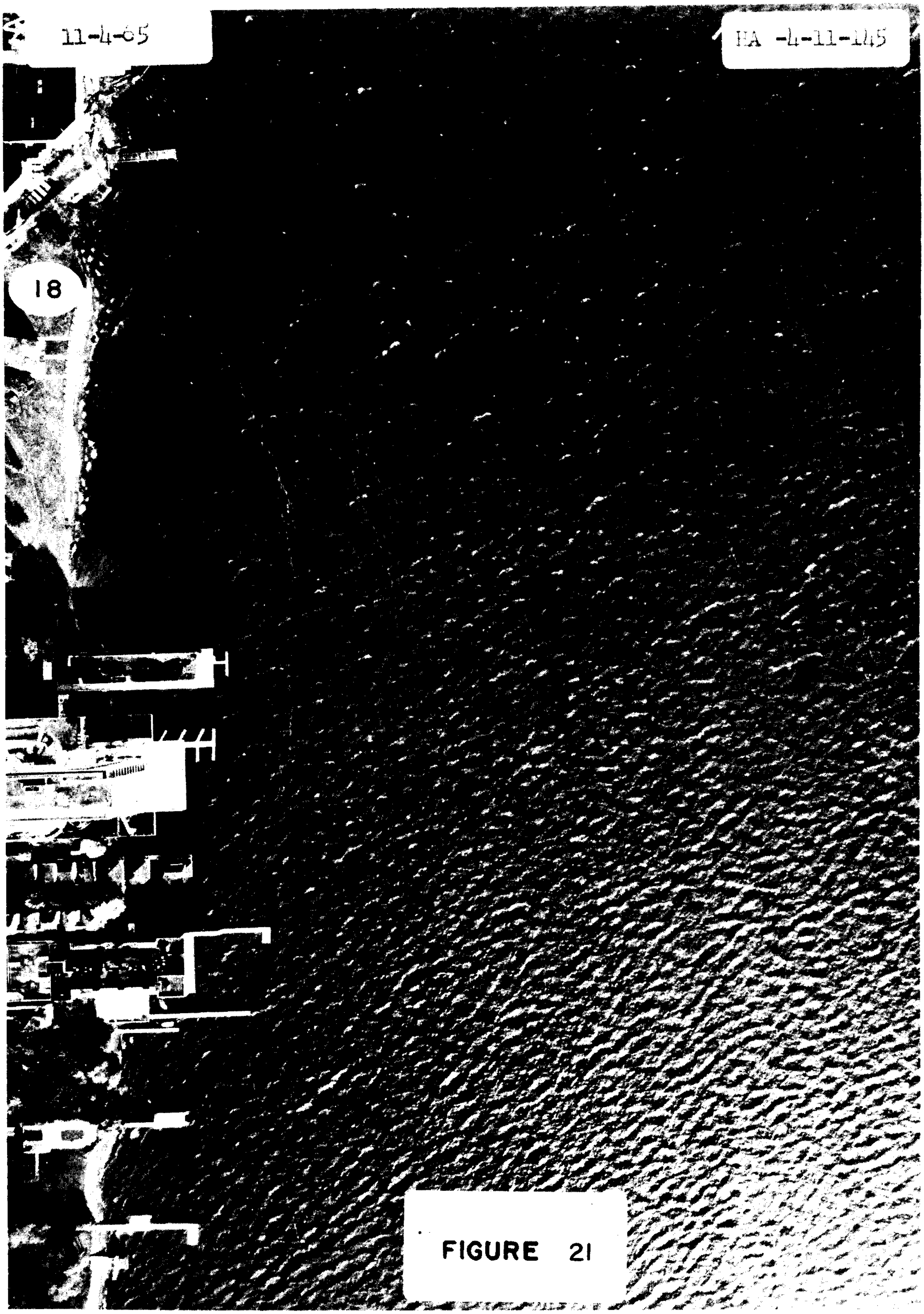


FIGURE 21

WAVE GAGE

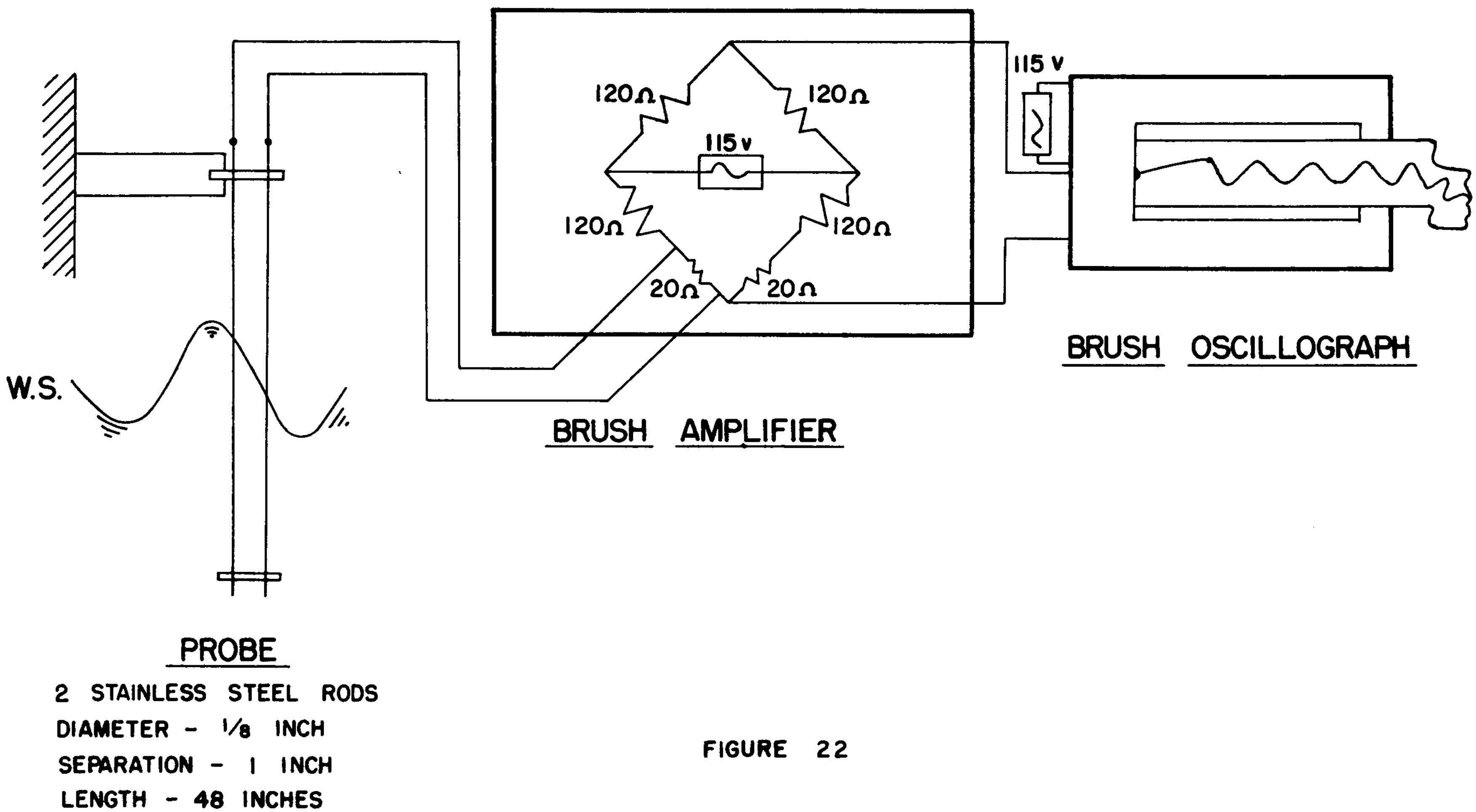


FIGURE 22

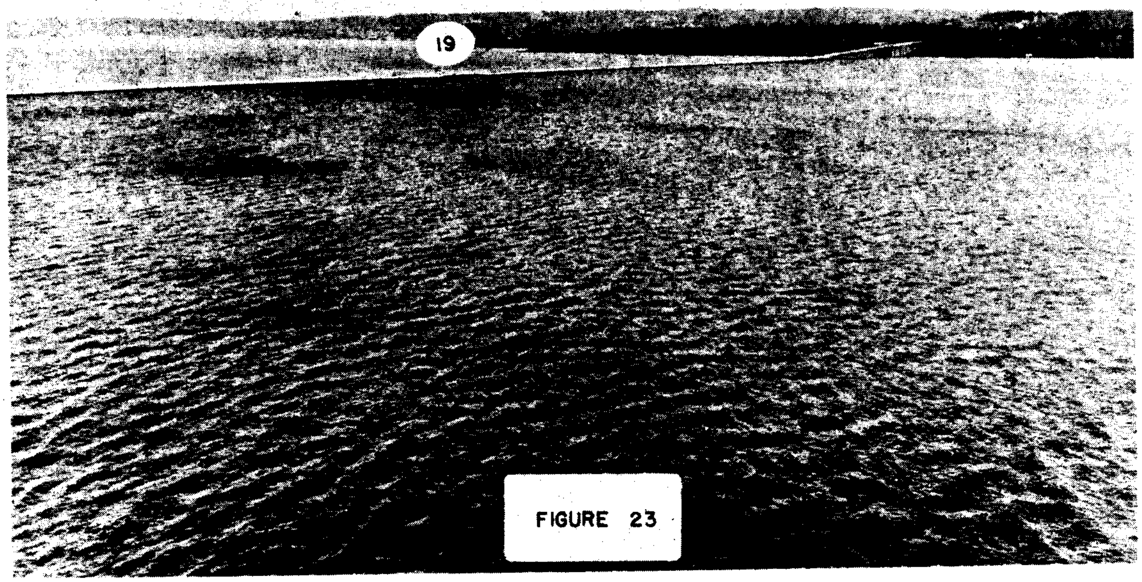


FIGURE 23

FIGURE 24

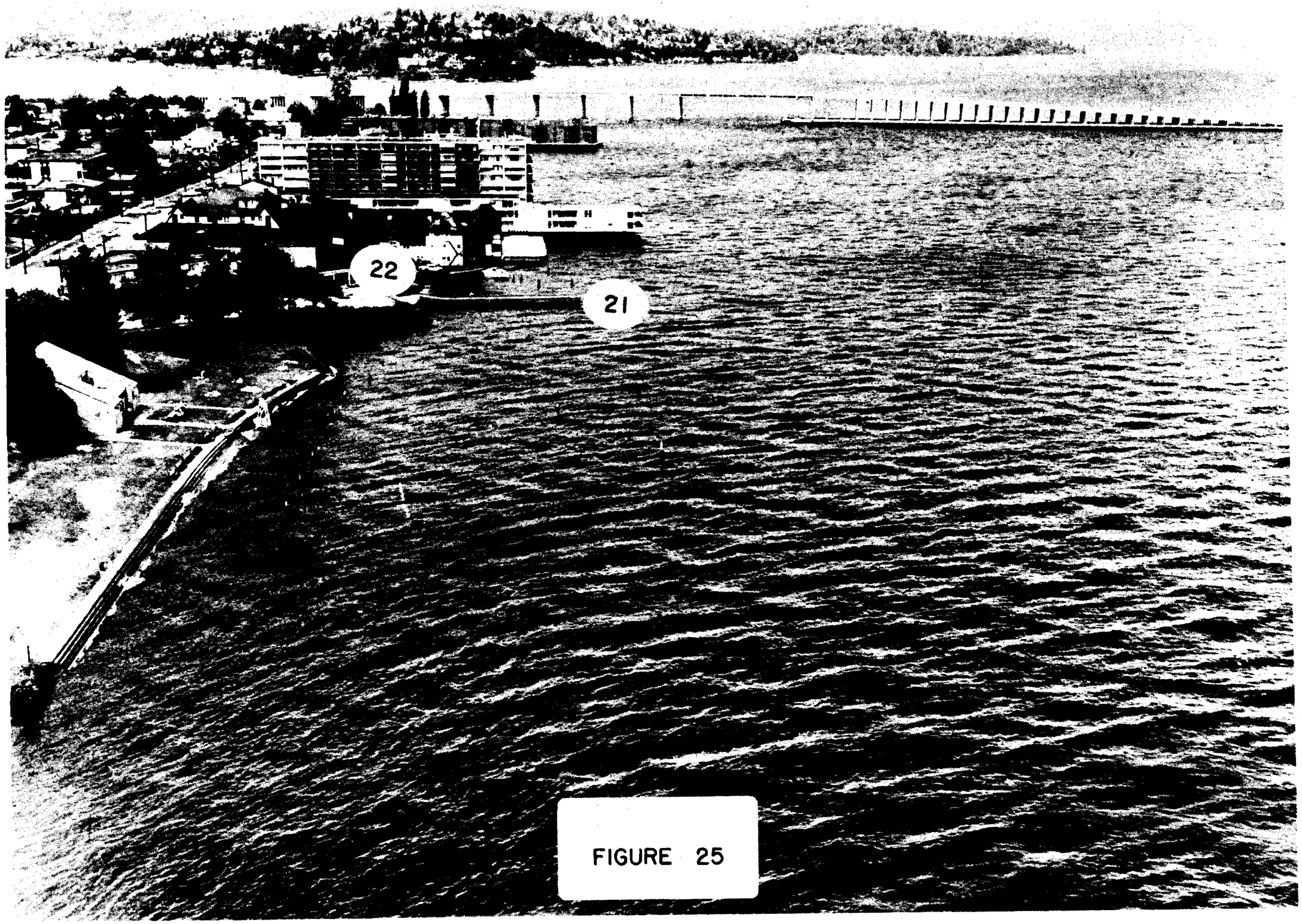


FIGURE 25

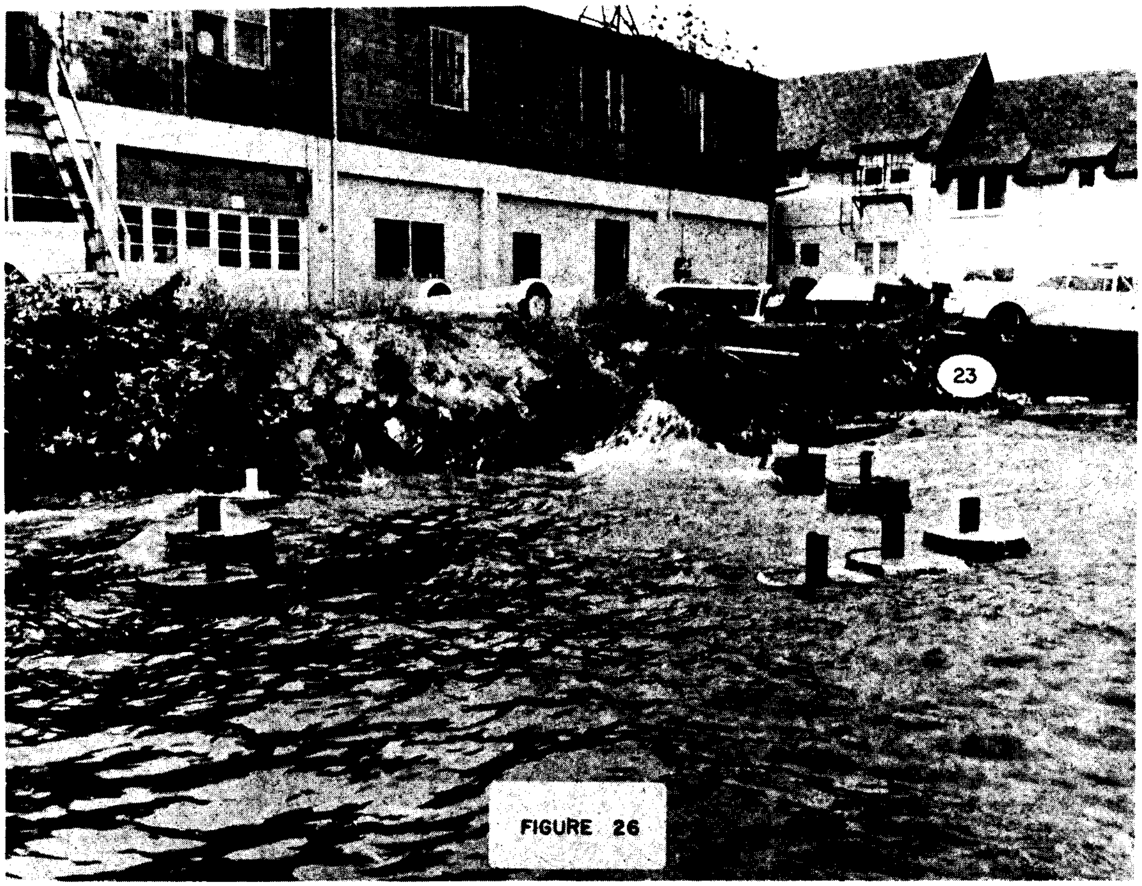


FIGURE 26

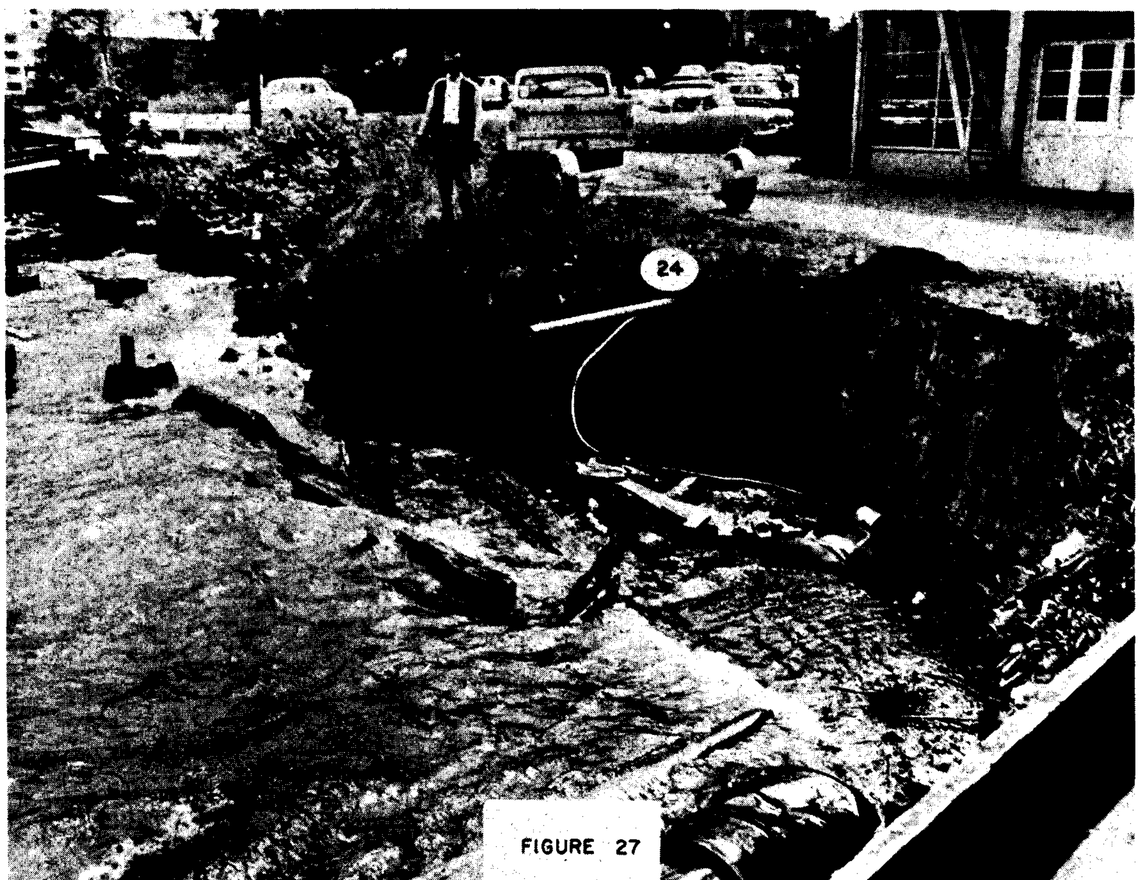


FIGURE 27

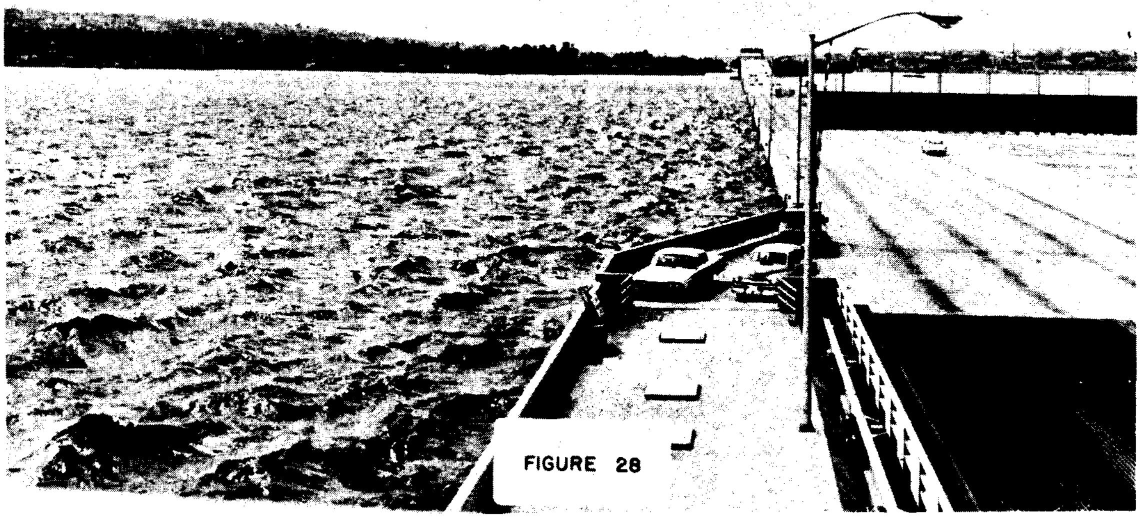


FIGURE 28

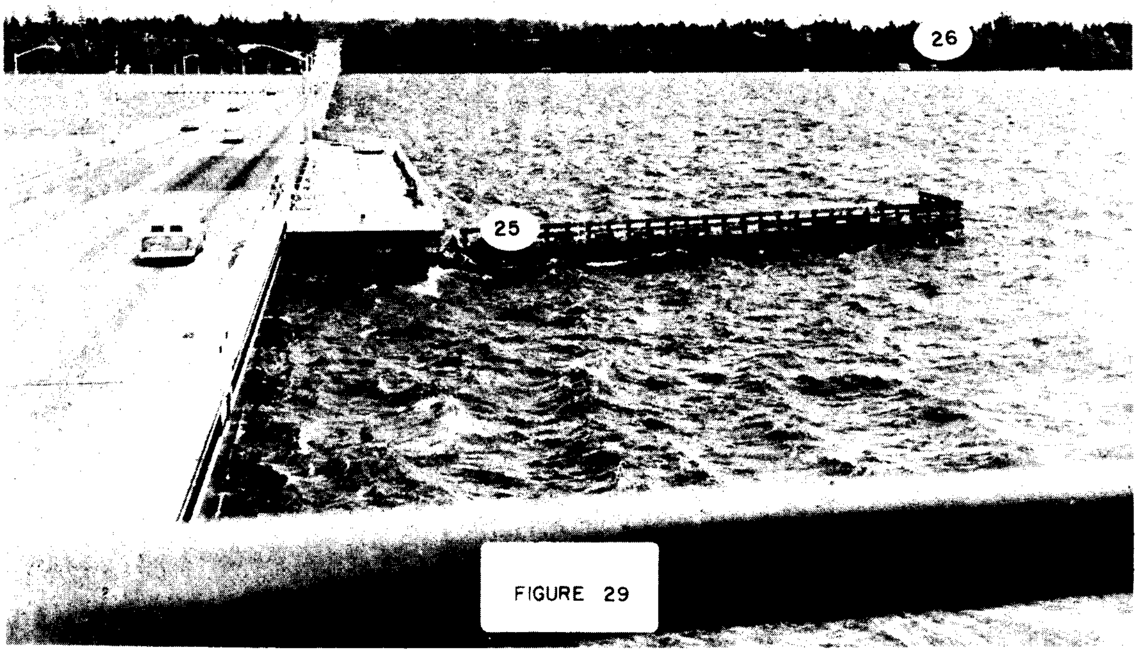


FIGURE 29

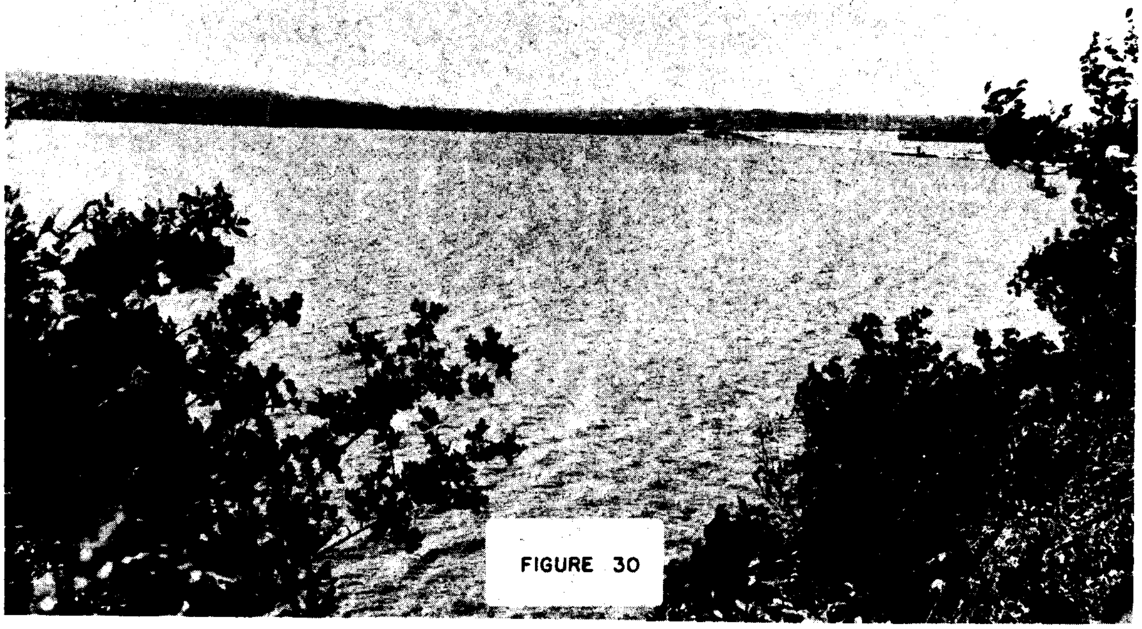


FIGURE 30

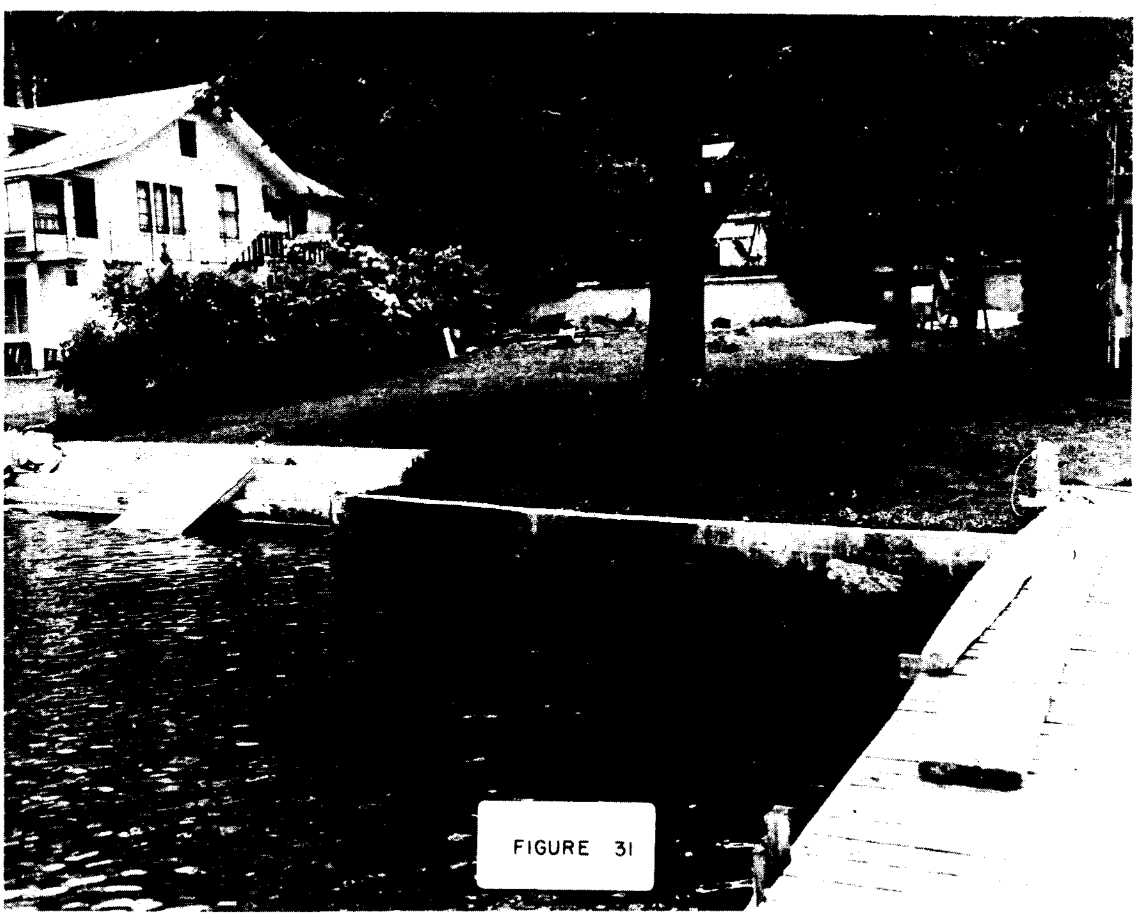


FIGURE 31

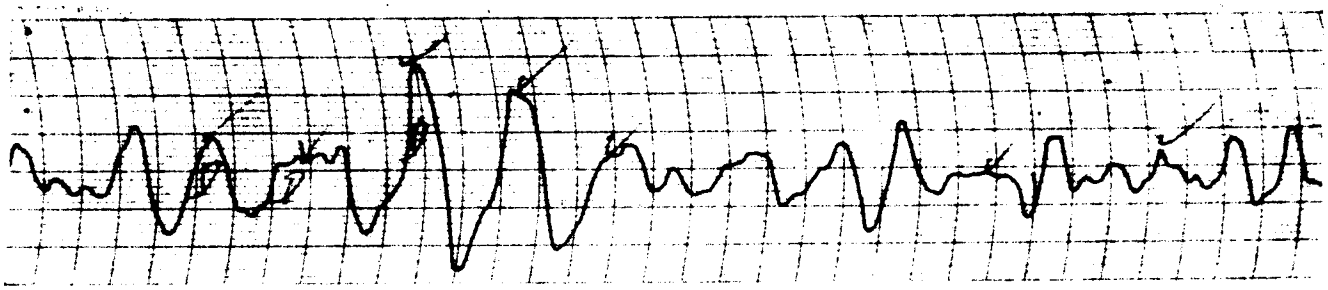


Fig. 32a Robinson site, March 19, 1966. Time: 1245-1305

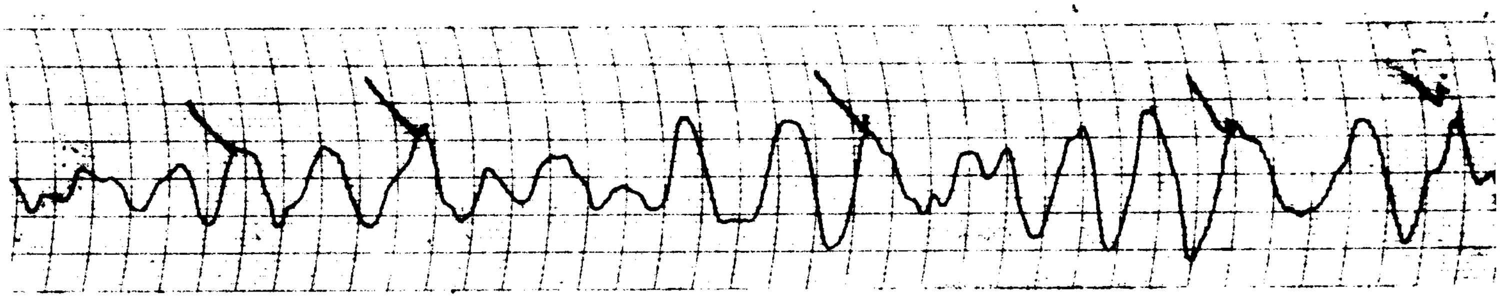


Fig. 32b Jones site, March 14, 1966. Time: 1415-1430

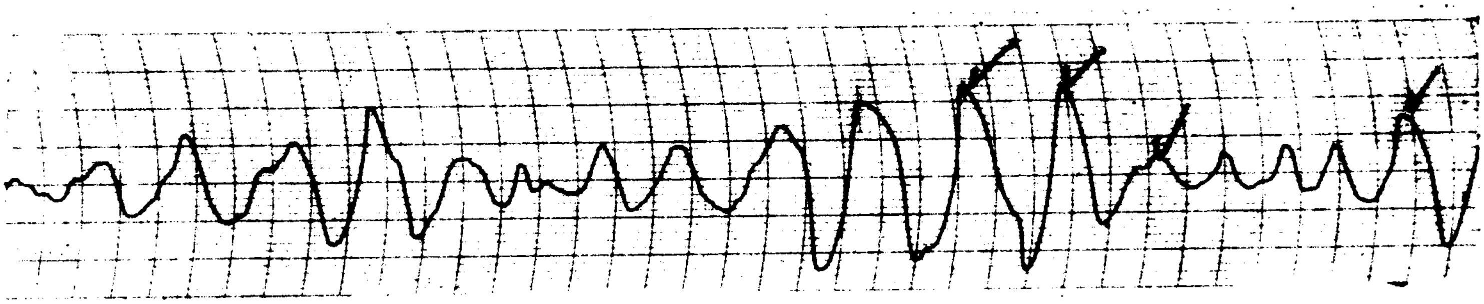


Fig. 32c Madison site, March 14, 1966. Time: 1300-1312

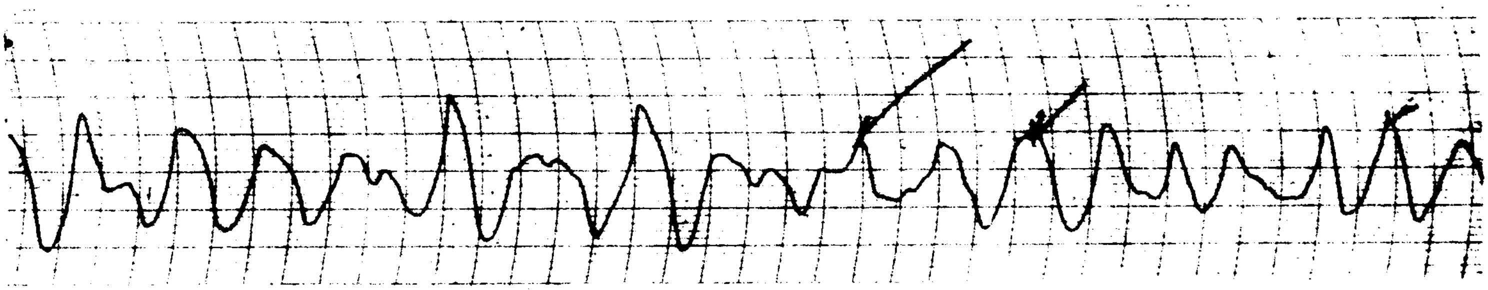


Fig. 32d Reed site, March 14, 1966. Time 1335-1345

Figure 32. Wave Records

Scale

Height: 1 mm per inch
Time: 5 mm per second

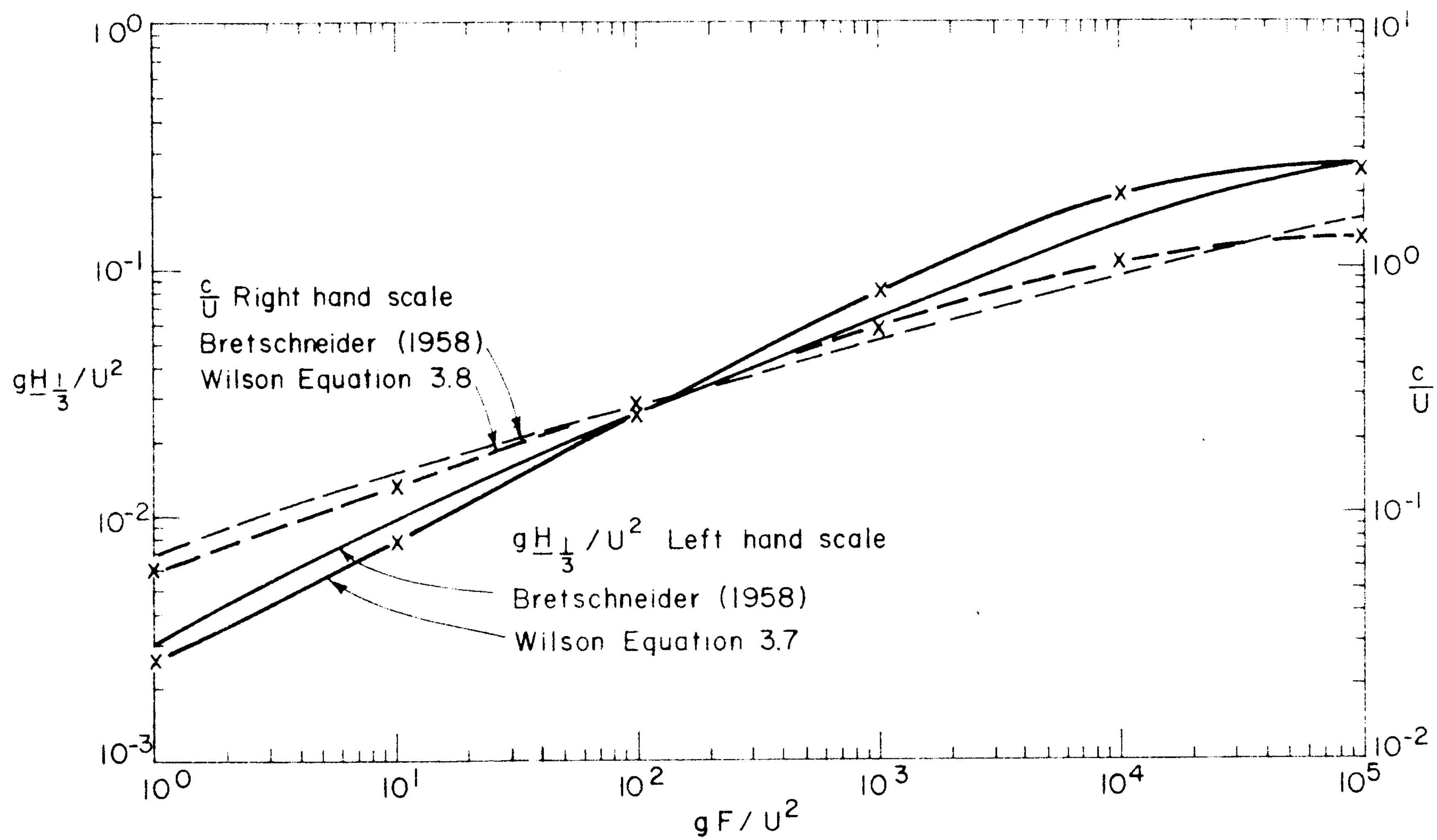


Figure 33. Bretschneider's and Wilson's Forms of S-M-B Bretschneider

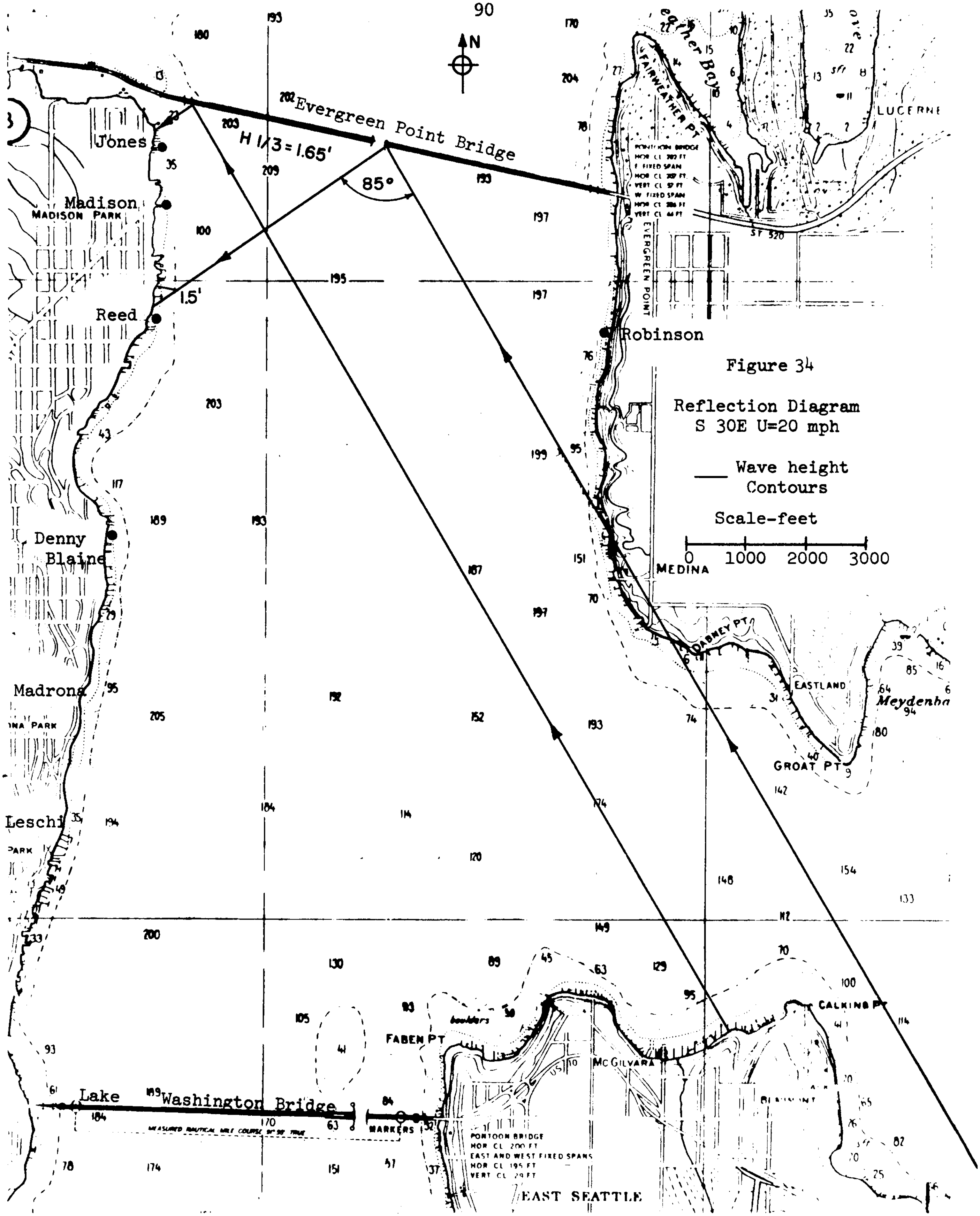


Figure 34

Reflection Diagram
S 30E U=20 mph

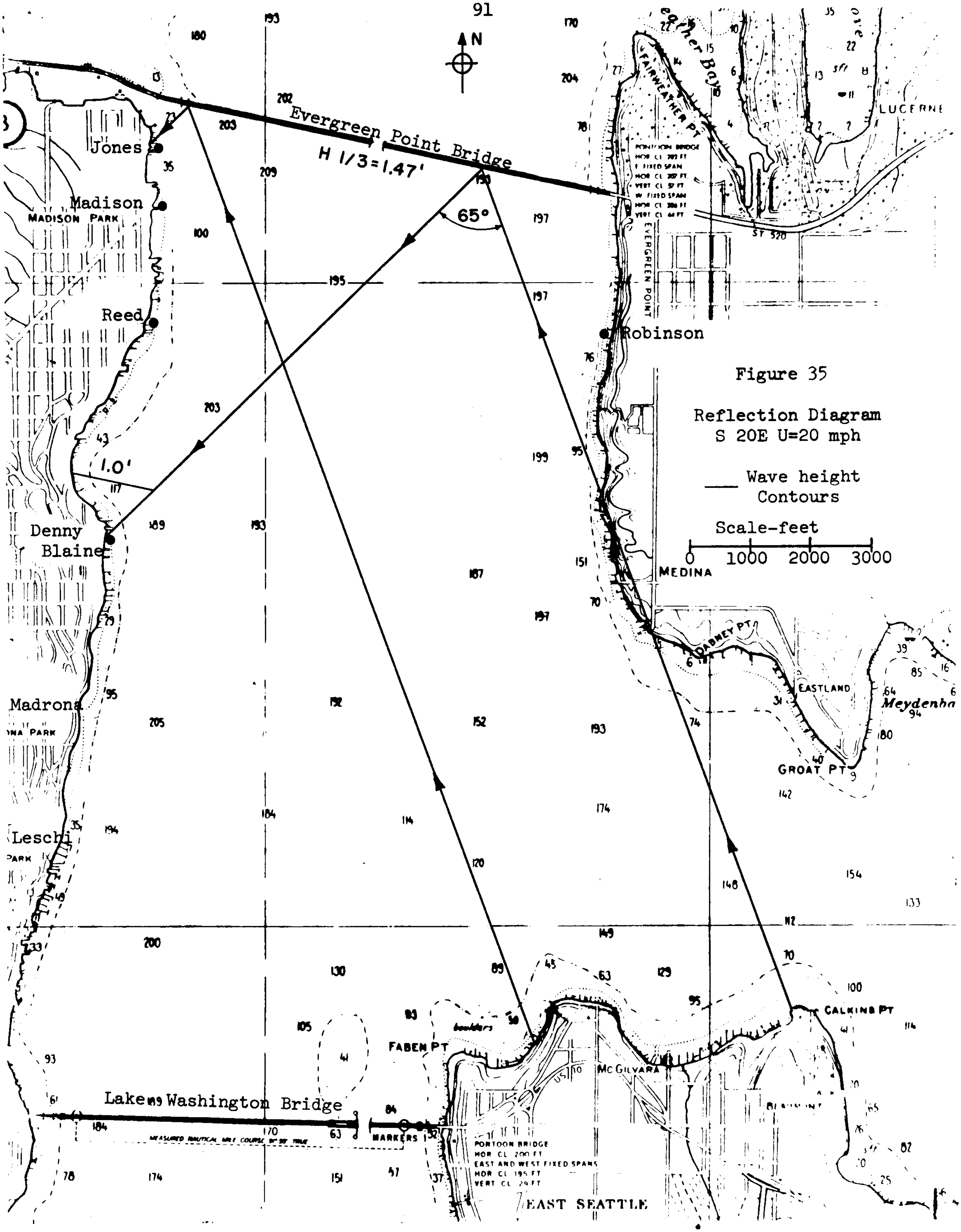


Figure 35

Reflection Diagram
S 20E U=20 mph

___ Wave height Contours

Scale-feet
0 1000 2000 3000

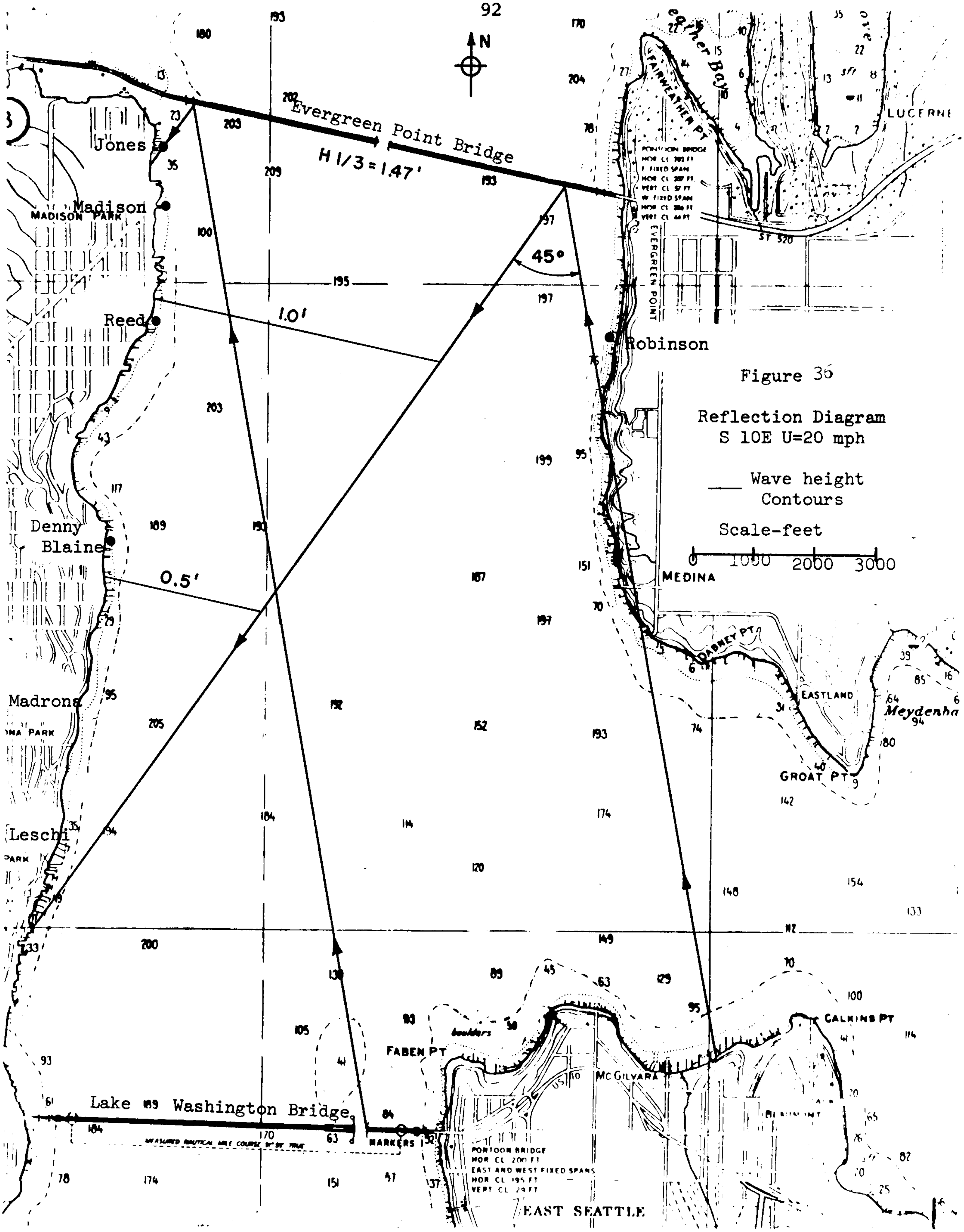
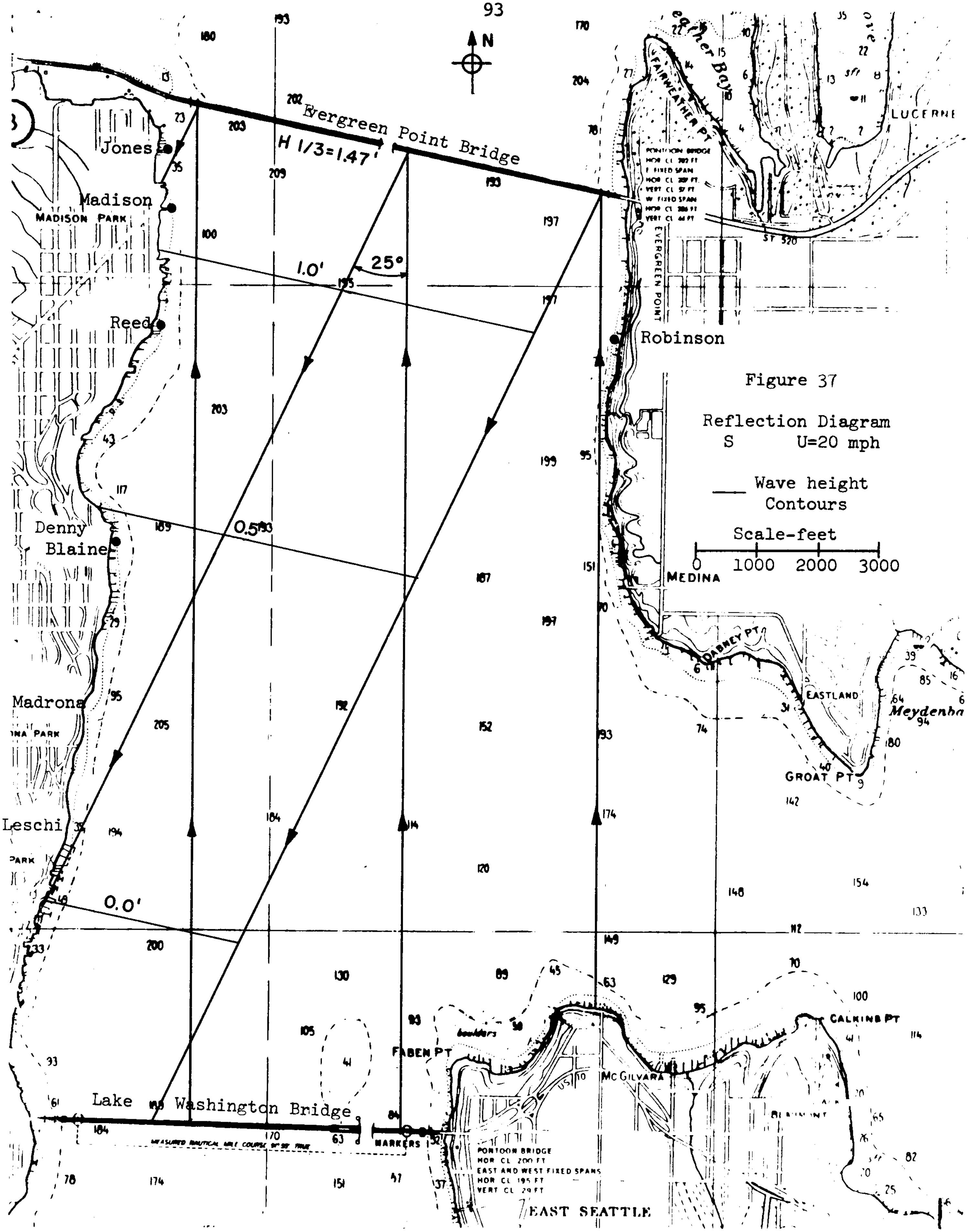


Figure 35

Reflection Diagram
S 10E U=20 mph


N
Evergreen Point Bridge
H 1/3=1.47'
25°
1.0'
0.5'
0.0'
Jones
Madison
Madison Park
Reed
Denny Blaine
Madrona
Leschi
Robinson
Medina
Evergreen Point
Fairweather Pt
Fairweather Bay
Lucerne
Dabney Pt
Eastland
Groat Pt
Meydenbauer
Calkins Pt
McGilvara
Faben Pt
Markers
Lake Washington Bridge
East Seattle
Pontoon Bridge
Hor Cl 200 Ft
East and West Fixed Spans
Hor Cl 195 Ft
Vert Cl 29 Ft
Measured nautical mile course
Figure 37
Reflection Diagram
S U=20 mph
Wave height Contours
Scale-feet
0 1000 2000 3000

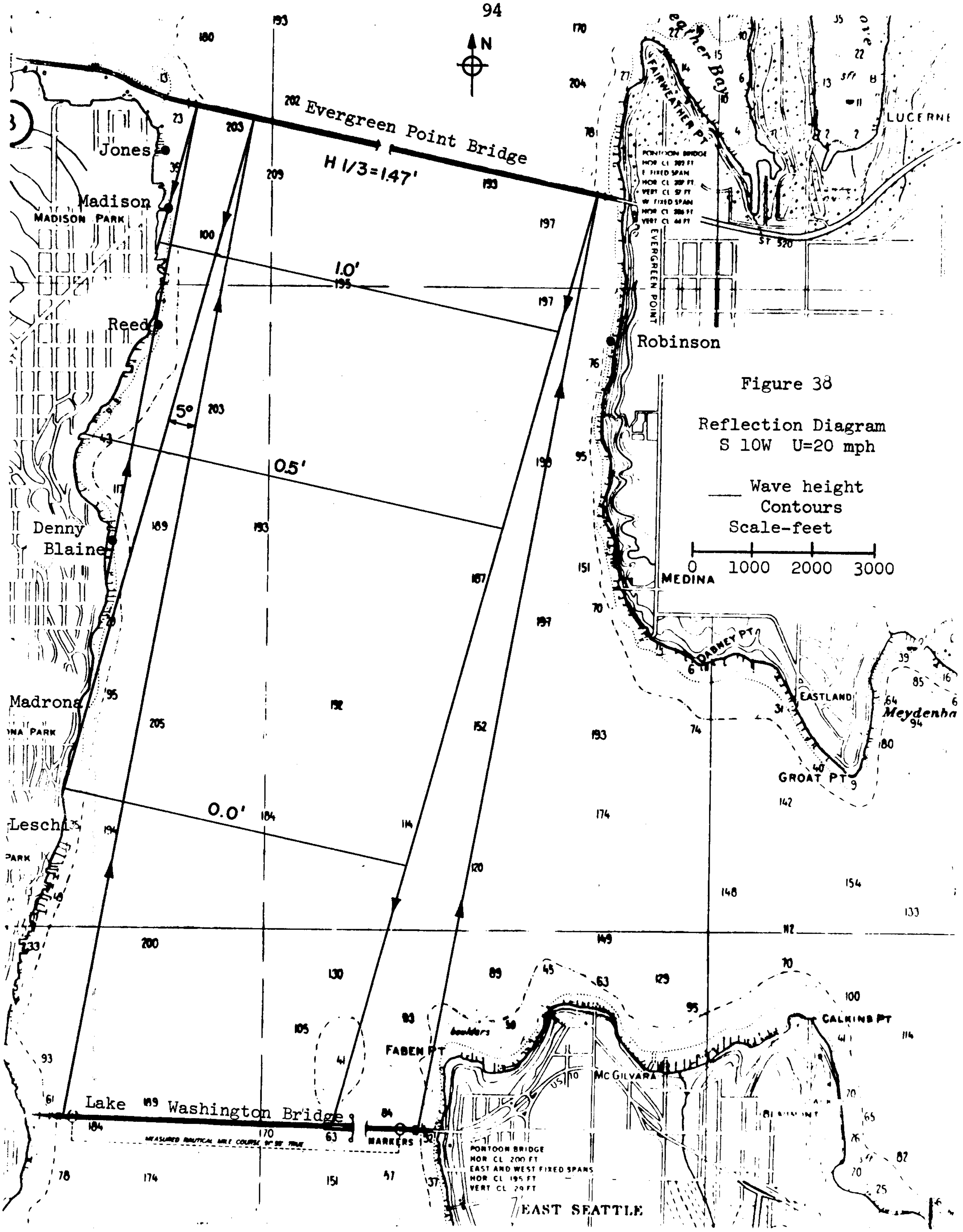


Figure 38

Reflection Diagram
S 10W U=20 mph

___ Wave height Contours

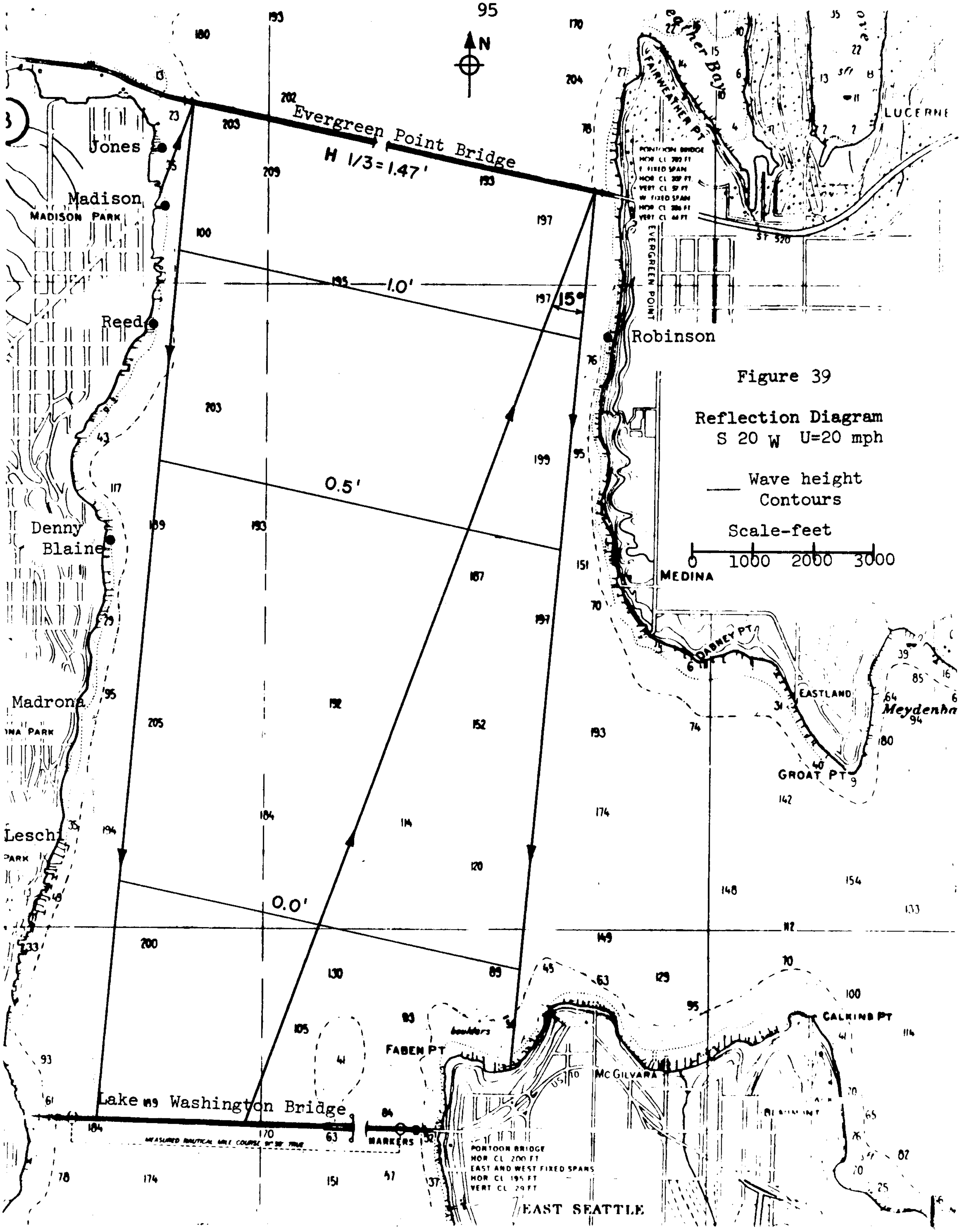


Figure 39

Reflection Diagram
S 20 W U=20 mph

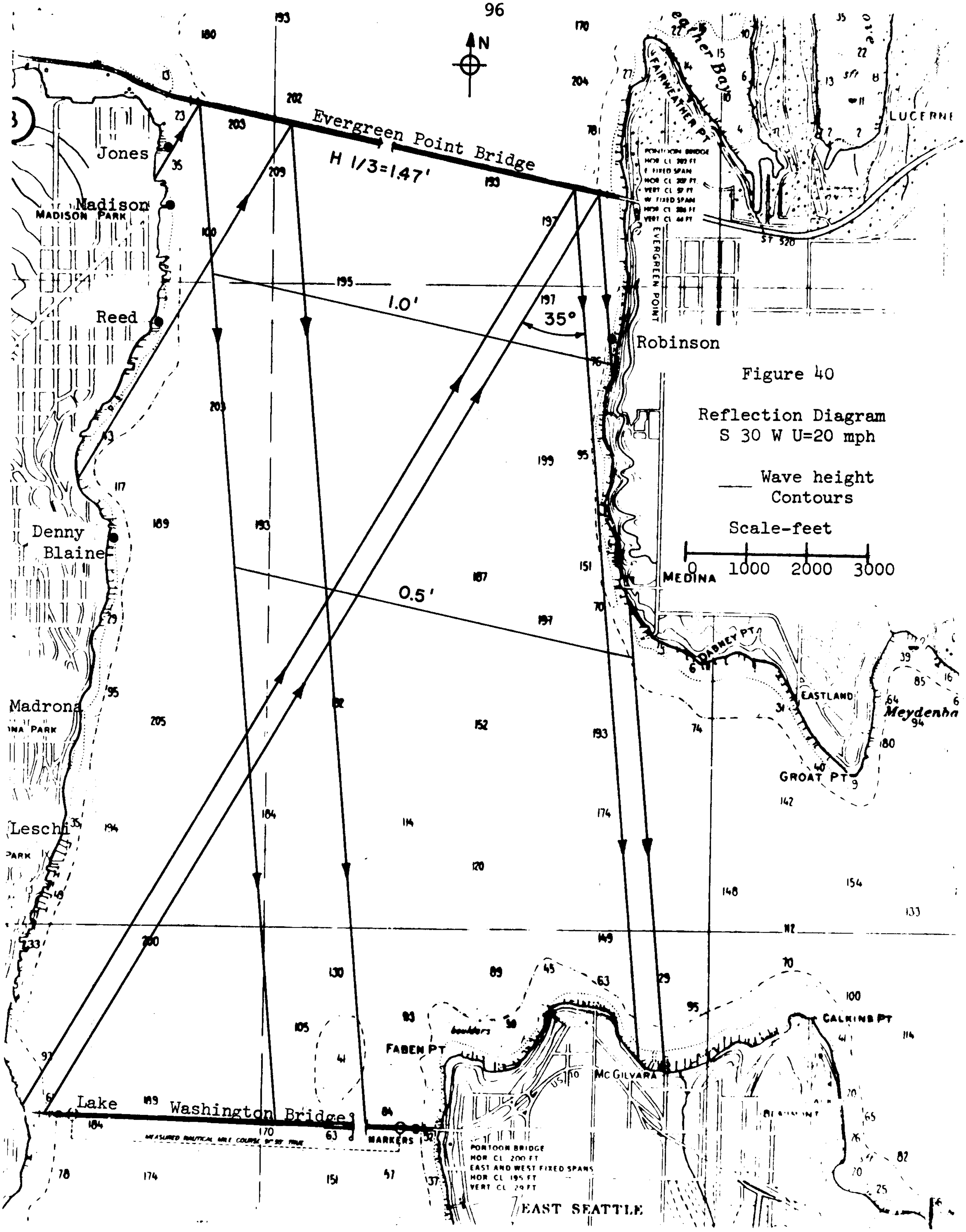


Figure 40

Reflection Diagram
S 30 W U=20 mph

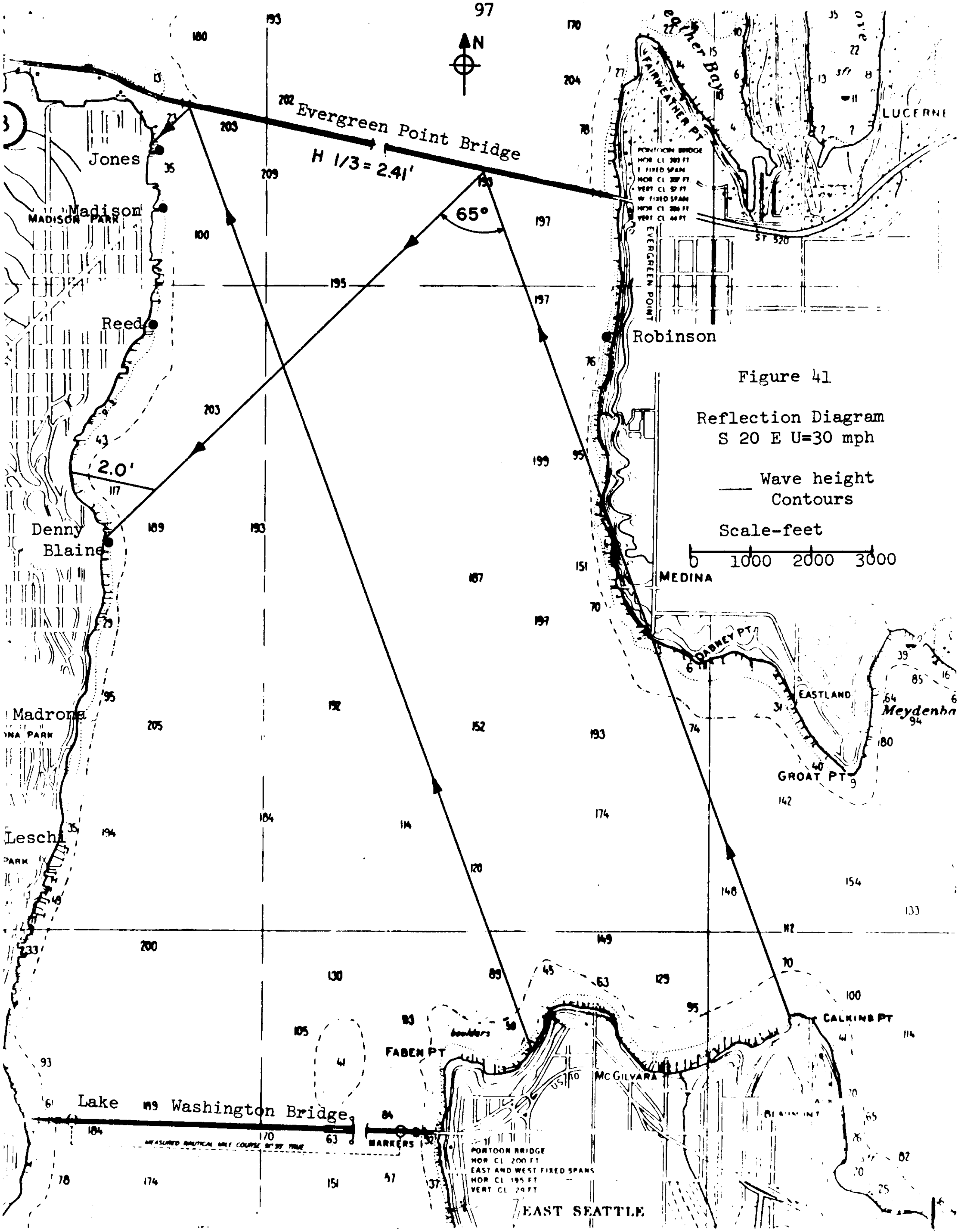


Figure 41

Reflection Diagram
S 20 E U=30 mph

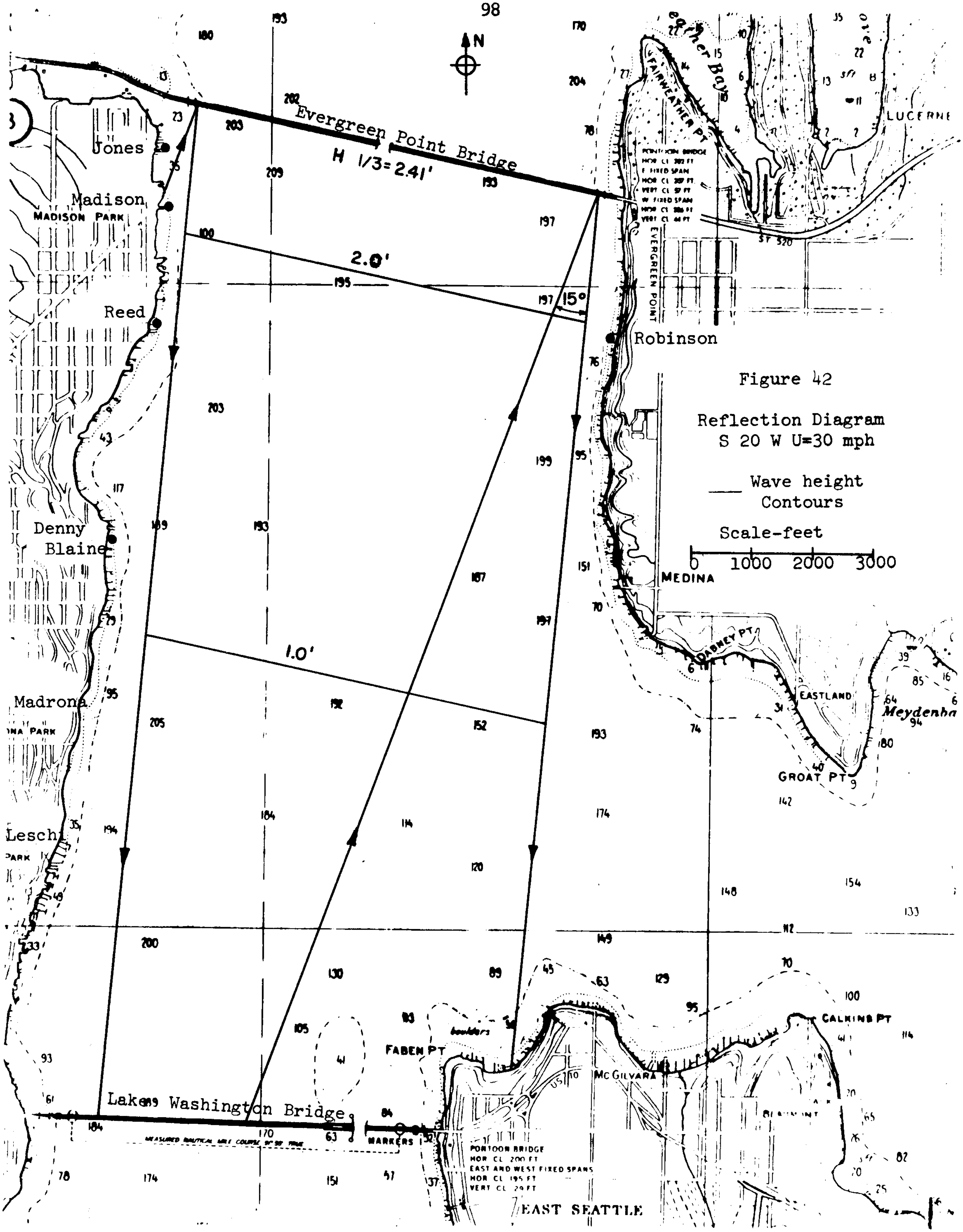


Figure 42

Reflection Diagram
S 20 W U=30 mph

TABLE 1

ANNUAL PERCENTAGE FREQUENCIES OF

SURFACE WIND DIRECTION AND SPEED, SEATTLE-TACOMA AIRPORT

(1951-1960) Seattle, Washington

Direction	0-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 Over	TOTAL	AVERAGE SPEED
N	+	1	3	3	+	+	+			8	11.8
NNE	+	1	3	3	+	+	+			7	11.9
NE	+	1	3	2	+	+				6	10.3
ENE	+	1	1	+	+	+				2	9.1
E	+	1	1	1	+	+				3	9.3
ESE	+	1	2	1	+	+	+			5	9.8
SE	+	2	3	1	+	+				6	9.1
SSE	+	1	2	1	+	+				4	9.8
S	+	2	4	3	1	+	+	+		9	12.2
SSW	+	1	3	4	2	1	+	+		11	14.6
SW	+	1	4	5	2	1	+	+		13	14.9
WSW	+	1	2	1	+	+	+	+	+	4	12.9
W	+	1	1	1	+	+	+			3	9.8
WNW	+	1	1	+	+					2	8.9
NW	+	1	1	+	+	+	+	+		2	9.5
NNW	+	+	1	1	+	+	+			3	11.8
CALM	10									10	
TOTAL	13	16	35	26	8	2	+	+	+	100	10.7

*From: "Decennial Census of United States Climate--Summary of Hourly Observations 120th Meridian Time Zone, Seattle, Washington, Seattle-Tacoma Airport, 1951-1960," Climatography of the United States No. 82 - 45, U. S. Dept. of Commerce, 1962, p. 15.

TABLE 2

ANNUAL PERCENTAGE FREQUENCY AND MEAN SPEED

OF SURFACE WINDS (1950-1959) SEATTLE, BOEING FIELD AIRPORT*

Direction	Wind Speed - M.P.H.							
	1-7	8-12	13-18	19-24	>24	Calm	Total %	Mean Speed
N	3.8	1.5	0.3	0.1	0		5.7	6.5
NNE	2.7	1.2	0.2	0	0		4.1	6.6
NE	2.5	1.0	0.1	0	0		3.6	6.2
ENE	1.3	0.5	0	0	0		1.8	5.9
E	1.0	0.2	0	0	0		1.2	5.3
ESE	1.3	0.3	0.1	0	0		1.7	5.7
SE	3.7	1.0	0.1	0	0		4.8	5.8
SSE	8.2	4.9	0.7	0	0		13.8	7.1
S	6.3	5.5	2.3	0.3	0.1		14.5	8.8
SSW	1.8	3.2	3.7	1.3	0.2		10.2	11.5
SW	1.5	2.5	2.6	1.1	0.2		7.9	12.5
WSW	0.9	1.1	0.9	0.3	0		3.2	10.5
W	0.8	0.4	0.1	0	0		1.3	7.0
WNW	0.7	0.5	0.1	0	0		1.3	6.6
NW	2.2	1.9	1.0	0.1	0		5.2	7.9
NNW	2.8	2.4	1.5	0.2	0		6.9	8.6
Calm						12.8	12.8	
Totals	41.5	28.1	13.7	3.4	0.5	12.8	100.0	7.7

*From: Climatography of the United States, Number 40-45, "Climatic Guide for Seattle, Washington and Adjacent Puget Sound Area," U. S. Department of Commerce Weather Bureau, Washington, D. C., January 1961, pp 32-33.

TABLE 3

ANNUAL PERCENTAGE FREQUENCY OF SURFACE

WINDS - SAND POINT N.A.S. - MAY 1949-APRIL 1964*

Wind Dir.	Frequency of Wind Speed Groups (Knots) 3-7	8-12	13-20	21-30	>30	Calm	Total
N	7.7	2.4	0.3	0	0		10.4
NNE	2.0	0.3	0	0	0		2.3
NE	3.1	0.2	0	0	0		3.3
ENE	1.7	0.2	0	0	0		1.9
E	1.9	0.2	0	0	0		2.1
ESE	1.1	0.2	*	0	0		1.3
SE	2.6	0.5	0.1	0	0		3.2
SSE	3.4	1.4	0.3	0	0		5.1
S	9.0	7.6	2.8	0.1	0		19.5
SSW	4.0	3.7	1.8	0.1	0		9.6
SW	2.3	0.9	0.3	0	0		3.5
WSW	0.5	*	0	0	0		0.5
W	0.5	*	0	0	0		0.5
WNW	0.3	0	0	0	0		0.3
NW	2.4	0.6	0.5	0	0		3.5
NNW	8.2	2.9	0.3	0	0		11.4
Calm						21.6	21.6
Total	50.7	21.1	6.4	0.2	0	21.6	100.0

*From: Frequency Summary of Monthly Aerological Records, Station: 24244 NAS, Seattle, Washington, Period: Pages 1-7: May 1949 - April 1964," November 30, 1964, Office of Navy Representative National Weather Records Center, Federal Building, Asheville, North Carolina.

WIND

Table 28. Percentage Frequency and Mean Speed of Surface Winds (1950 - 1959) , Seattle - Tacoma Airport

7440* January	Wind Speed (m.p.h.) 1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N	0.3	0.6	1.4	1.6	0.8	0.2	#			4.9	11.8
NNE	.2	.9	2.0	2.8	.6	.1	#			6.6	11.5
NE	.4	1.3	1.9	1.5	.1					5.2	9.7
ENE	.3	.5	.7	.2	#					1.7	8.9
E	.7	1.4	2.7	1.7	.2	#				6.7	9.7
ESE	.7	2.1	4.8	2.5	.3	#				10.4	10.0
SE	.6	1.9	4.6	1.9	.2	#				9.2	9.6
SSE	.3	1.3	2.7	1.1	.1	.1				5.6	10.1
S	.2	1.0	3.4	3.6	1.4	.5	.1			10.2	13.8
SSW	.1	.6	2.6	5.3	3.5	1.3	.2	.1		13.7	16.9
SW	.2	.6	1.8	3.4	3.0	1.5	.3	#		10.8	17.5
WSW	.1	.3	.5	.7	.3	.5	.1	#		2.5	15.1
W	.1	.3	.3	#	#	.1				.8	8.8
WNW	.1	.1	.1							.3	7.0
NW	.1	.2	.2	.1						.6	8.9
NNW	.1	.2	.4	.3						1.0	10.1
Calm										9.8	
Totals	4.5	13.3	30.1	26.7	10.5	4.3	.7	.1		100.0	11.7

6768* February	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N	.2	.6	1.7	1.5	.8	.1	#			4.9	11.9
NNE	.4	.7	2.5	2.3	.6	#				6.5	11.5
NE	.3	1.0	2.0	1.4	#					4.7	9.5
ENE	.2	.5	.9	.5	#					2.1	8.5
E	.6	1.1	2.1	1.7	.1					5.6	8.6
ESE	.4	1.8	3.2	1.7	.3	#				7.4	9.6
SE	.5	2.0	3.7	1.2	.1					7.5	8.9
SSE	.3	1.3	2.4	.8	.1	.1				5.0	9.8
S	.4	1.5	3.2	3.1	1.5	.3	.1			10.1	13.0
SSW	.2	.7	2.5	4.8	3.5	1.5	.2	.1		13.5	16.9
SW	.3	.6	2.1	3.8	3.6	2.0	.2			12.6	17.6
WSW	.1	.5	.7	.7	.6	.5	.1		#	3.2	15.6
W	.1	.3	.6	.2	.1	#	#			1.3	9.5
WNW	.1	.3	.2	.1	#					.7	8.2
NW	.1	.4	.4	.1	#					1.0	9.7
NNW	.1	.4	.8	.6	.2	.1	#			2.2	11.2
Calm										11.7	
Totals	4.3	13.7	29.0	24.5	11.5	4.6	.6	.1	#	100.0	11.5

7440* March	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N	.2	.4	1.5	2.2	.5	#				4.8	12.7
NNE	.2	.6	2.0	1.9	.5					5.2	11.2
NE	.4	.8	2.1	1.0	.1	#				4.4	9.7
ENE	.1	.6	.6	.3	#					1.6	8.3
E	.5	1.1	1.5	.9	.2	.1				4.3	9.5
ESE	.7	1.6	3.0	1.6	.2	.1				7.2	9.5
SE	.6	2.0	3.3	1.2	.1					7.2	9.0
SSE	.3	1.1	2.3	.9	.3	#				4.9	10.2
S	.3	1.1	3.2	3.3	1.0	.2	#			9.1	12.4
SSW	.2	.6	3.5	5.7	3.5	1.0	.1			14.6	15.8
SW	.2	.8	2.9	5.3	4.6	2.4	.4			16.6	17.7
WSW	.1	.3	1.1	1.8	1.0	.6	.1	#		5.0	15.8
W	.1	.4	.8	.4	.2	.1	#			2.0	11.2
WNW	.1	.4	.6	.1	#					1.2	7.8
NW	.1	.5	.7	.2						1.5	8.7
NNW	.1	.2	.7	.8	.3	#				2.1	12.0
Calm										8.3	
Totals	4.2	12.5	29.8	27.6	12.5	4.5	.6	#		100.0	12.1

7200* April	Wind Speed (m.p.h.) 1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N	0.2	0.7	2.4	3.1	0.8	0.1	#			7.3	12.9
NNE	.1	.7	2.6	3.0	.9	#				7.3	13.0
NE	.4	1.3	2.8	1.9	.3	#				6.7	10.3
ENE	.2	.5	1.3	.5	#	#				2.5	9.6
E	.3	1.0	1.2	.5	.1					3.1	8.9
ESE	.2	1.0	1.0	.6	.1	.1				3.0	9.1
SE	.4	1.6	2.4	.7	.1					5.2	8.7
SSE	.2	.9	2.0	.9	.2	.1				4.3	10.2
S	.4	1.0	2.6	2.7	.8	.2	#			7.7	11.8
SSW	.1	.6	3.0	3.9	1.8	.5				9.9	14.2
SW	.2	.8	3.4	5.5	4.4	1.7	.2			16.2	16.3
WSW	.1	.5	1.5	2.1	1.3	.4	#	#		5.9	15.0
W	.3	.7	1.3	.9	.1	.1				3.4	10.5
WNW	.1	.4	.8	.4	.1					1.8	9.6
NW	.2	.7	1.3	.7	.1					3.0	10.0
NNW	.1	.5	1.1	1.7	.4	#				3.8	13.1
Calm										8.9	
Totals	3.5	12.9	30.7	29.1	11.5	3.2	.2	#		100.0	11.7

7440* May	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N	.2	.9	3.3	4.2	.5	#				9.1	12.2
NNE	.2	.9	3.0	3.1	.4	#				7.6	11.9
NE	.3	1.4	3.4	3.0	.4	#				8.5	11.4
ENE	.1	.5	.9	.6	#					2.1	9.7
E	.4	.8	.8	.3	#					2.3	7.7
ESE	.2	.7	1.1	.3	#					2.3	8.2
SE	.2	1.3	1.8	.3	#					3.6	8.0
SSE	.1	1.0	1.4	.4						2.9	8.8
S	.1	1.5	3.3	1.6	.1					6.6	10.0
SSW	.2	1.0	3.4	3.8	1.0	.1				9.5	12.5
SW	.2	1.4	4.7	6.8	2.8	.6	#			16.5	14.4
WSW	.1	.6	2.4	2.5	.7	.2				6.5	13.0
W	.1	.7	1.9	1.0	.2	#	#			3.9	11.0
WNW	.1	.7	1.4	.4	#					2.6	9.8
NW	.1	.9	1.6	1.0	.1					3.7	9.9
NNW	.1	.5	1.4	2.4	.3	#				4.7	12.7
Calm										7.6	
Totals	2.7	14.8	35.8	31.7	6.5	.9	#			100.0	10.9

7200* June	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N	.2	.7	2.7	2.7	.5	#				6.8	12.0
NNE	.2	.7	2.3	2.8	.2	#				6.2	12.1
NE	.1	.7	2.6	2.0	.1	#				5.5	11.0
ENE	.1	.3	.8	.3						1.5	9.0
E	.2	.5	.7	.1	#					1.5	8.3
ESE	.2	.7	.6	.2	#					1.7	7.7
SE	.3	.8	1.3	.3						2.7	8.1
SSE	.1	.7	1.5	.3						2.6	8.5
S	.3	1.6	4.1	1.6	.1	#				7.7	9.5
SSW	.3	1.4	5.0	4.5	.9	.1	#			12.2	11.9
SW	.3	1.9	7.2	8.5	2.3	.6	#			20.8	13.3
WSW	.2	1.1	3.4	2.4	.6	.1				7.8	11.7
W	.2	1.1	2.6	1.2	.1					5.2	9.8
WNW	.1	.9	1.4	.5	#					2.9	9.2
NW	.1	.6	1.5	.7	#					2.9	9.7
NNW	#	.5	1.3	1.2	.2	#				3.2	11.8
Calm										8.8	
Totals	2.9	14.2	39.0	29.3	5.0	.8	#			100.0	10.5

WIND

Table 28. Percentage Frequency and Mean Speed of Surface Winds (1950 - 1959), Seattle - Tacoma Airport - Cont'd.

7440* July	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
	Wind Speed (m.p.h.)										
N--------	0.2	1.3	3.9	3.6	0.4	#				9.4	11.8
NNE------	.1	1.0	4.3	3.7	.3	#				9.4	11.8
NE-------	.3	1.4	3.3	2.9	.2	#				8.1	11.0
ENE------	.1	.6	1.0	.4	#	#				2.1	8.4
E--------	.2	.6	.2	.1	#					1.1	6.6
ESE------	.1	.3	.4	#						.8	7.6
SE-------	.2	.7	1.0	.1						2.0	7.5
SSE------	.1	.5	1.2	.2						2.0	8.6
S--------	.3	1.3	2.7	1.1	.1					5.5	9.1
SSW------	.3	1.2	4.6	2.3	.4	#				8.8	10.7
SW-------	.5	2.1	7.1	5.4	.9	.1				16.1	11.5
WSW------	.2	1.2	2.7	2.0	.2					6.3	10.9
W--------	.2	1.5	2.7	1.1	.2					5.7	9.8
WNW------	.1	.8	2.1	.8	#					3.8	10.2
NW-------	.2	1.1	2.0	1.3	#					4.6	10.2
NNW------	.1	.5	2.1	2.4	.2					5.3	11.8
Calm-----										9.0	
Totals---	3.2	16.1	41.3	27.4	2.9	.1				100.0	9.9

7440* August	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N--------	.3	.8	3.9	3.0	.1					8.1	11.2
NNE------	.3	1.2	4.0	2.8	.3					8.6	11.2
NE-------	.5	1.5	3.2	2.3	#					7.5	10.0
ENE------	.2	.6	.8	.3						1.9	7.9
E--------	.4	.8	.5							1.7	6.2
ESE------	.2	.7	.6	.1						1.6	7.1
SE-------	.4	1.0	1.3	.2						2.9	7.6
SSE------	.1	1.0	1.3	.2						2.6	8.1
S--------	.5	1.5	3.4	.9	.1					6.4	8.9
SSW------	.4	1.3	4.3	3.0	.5	.1				9.6	11.0
SW-------	.6	1.6	5.7	4.8	.8	.1	#			13.6	10.5
WSW------	.2	1.1	2.7	1.6	.1	#				5.7	10.6
W--------	.3	1.2	2.5	.8	.1	#				4.9	9.2
WNW------	.1	.9	2.3	.7	#					4.0	9.7
NW-------	.3	1.1	2.2	1.2	#					4.8	9.7
NNW------	.2	.5	2.1	2.0	.1	#				4.9	11.3
Calm-----										11.2	
Totals---	5.0	16.8	40.8	23.9	2.1	.2	#			100.0	9.2

7200* September	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N--------	.3	1.0	3.7	4.2	.6	.1				9.9	12.1
NNE------	.5	1.5	3.9	3.8	.6	.1				10.4	11.6
NE-------	.5	1.7	3.7	2.4	.3	#				8.6	10.4
ENE------	.2	.7	.7	.2						1.8	8.4
E--------	.4	1.0	.8	.1	#					2.3	6.8
ESE------	.3	1.0	1.5	.3						3.1	7.9
SE-------	.5	1.6	2.6	.5	#					5.2	8.1
SSE------	.3	1.1	1.7	.4	.1					3.6	8.5
S--------	.5	1.4	3.7	1.7	.3	.1				7.7	10.1
SSW------	.2	1.2	3.8	3.5	.8	.2	#			9.7	12.3
SW-------	.3	1.6	3.8	3.8	1.0	.3	#			10.8	12.5
WSW------	.3	.8	1.3	.9	.2	.1	#			3.6	10.3
W--------	.2	.9	1.4	.4	#	#				2.9	9.0
WNW------	.1	.8	1.0	.2	#					2.1	8.3
NW-------	.2	.7	1.3	.3	#					2.5	9.0
NNW------	.1	.7	1.5	1.4	.2	#				3.9	11.2
Calm-----										11.9	
Totals---	4.9	17.7	36.4	24.1	4.1	.9	#			100.0	9.5

Less than 0.05 percent
* Number of hourly observations

7440* October	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
	Wind Speed (m.p.h.)										
N--------	0.4	1.5	4.0	2.7	0.3	#				8.9	11.1
NNE------	.2	1.6	4.0	3.1	.8	.1				9.8	11.9
NE-------	.4	1.8	2.5	1.5	.2	#				6.4	10.0
ENE------	.2	.7	.6	.2	#	#				1.7	8.1
E--------	.5	1.0	1.2	.8	.1	.1				3.7	8.6
ESE------	.4	1.2	2.6	1.1	.2					5.5	9.4
SE-------	.4	1.5	4.1	1.5	#					7.5	9.6
SSE------	.2	1.2	2.5	1.1	.2	#				5.2	9.9
S--------	.4	1.8	3.7	3.3	1.5	.3	#			11.0	11.8
SSW------	.2	.8	3.0	3.8	2.2	.6	.1			10.7	14.8
SW-------	.2	.8	2.2	3.2	2.0	.6	#			9.0	14.9
WSW------	#	.4	1.1	.6	.4	.1	#			2.6	11.6
W--------	.2	.5	.6	.2	#	#				1.5	8.5
WNW------	.1	.4	.9	.1						1.5	8.1
NW-------	.2	.6	.8	.2						1.8	8.4
NNW------	.1	.5	1.1	.7	.1	#				2.5	10.0
Calm-----										10.7	
Totals---	4.1	16.3	34.9	24.1	8.0	1.8	.1			100.0	10.4

7200* November	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N--------	.3	.7	2.9	2.6	.8	.2	#			7.5	12.1
NNE------	.3	1.1	2.9	2.6	.4	.1				7.4	11.2
NE-------	.4	.9	1.8	1.2	.1	#				4.4	10.1
ENE------	.2	.5	.7	.4	#					1.8	8.3
E--------	.6	1.2	1.6	.7	.1					4.2	8.6
ESE------	.4	1.2	3.7	1.6	.5					7.4	10.2
SE-------	.6	2.6	5.2	2.2	.3					10.9	9.7
SSE------	.4	1.3	2.8	1.4	.2	#				6.1	10.2
S--------	.4	1.5	3.2	3.4	1.4	.3	.1	#		10.3	12.8
SSW------	.2	.7	1.9	3.5	2.1	1.0	.1			9.5	16.0
SW-------	.3	.8	1.8	2.8	2.1	1.0	.3	#		9.1	15.8
WSW------	.1	.4	.7	.6	.4	.3	#			2.5	13.3
W--------	.3	.3	.3	.1	#					1.0	7.9
WNW------	.1	.3	.3	#						.7	7.9
NW-------	.2	.3	.5	.1	#	.1	#	#		1.2	9.4
NNW------	.2	.3	.8	.3	#	.1	#			1.7	9.5
Calm-----										14.3	
Totals---	5.0	14.1	31.1	23.5	8.4	3.1	.5			100.0	10.5

7440* December	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N--------	.2	1.0	2.1	1.2	.3	#				4.8	11.3
NNE------	.2	.8	1.9	2.0	.5	#				5.4	11.8
NE-------	.3	.9	1.4	.8	.1	#				3.5	9.4
ENE------	.2	.6	.4	.1	.1					1.4	8.6
E--------	.6	1.3	1.5	.9	.3	#				4.6	9.3
ESE------	.5	2.1	3.8	2.5	.6	.1	#			9.6	10.8
SE-------	.5	2.7	4.8	2.2	.3	#				10.5	9.7
SSE------	.3	1.4	3.2	1.4	.3	#				6.6	10.4
S--------	.4	1.8	3.4	4.4	2.2	.5	#			12.7	13.3
SSW------	.1	.9	2.7	5.3	3.8	1.3	.2			14.3	16.2
SW-------	.3	.8	2.2	3.4	2.7	1.7	.4			11.5	16.6
WSW------	.1	.3	.4	.6	.2	.2	.1			1.9	14.6
W--------	.2	.2	.3	.1		.1				.9	9.7
WNW------	.1	.2	.1	#						.4	6.7
NW-------	.1	.2	.2	.1	#					.6	8.7
NNW------	.1	.3	.3	.1	#					.8	8.3
Calm-----										10.5	
Totals---	4.2	15.5	28.7	25.1	11.4	3.9	.7			100.0	11.5

Table 28. Percentage Frequency and Mean Speed of Surface Winds (1950 - 1959) , Seattle , Boeing Field Airport

7440* January	Wind Speed (m.p.h.) 1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total%	Mean Speed
N--------	0.5	2.1	1.8	0.7	0.4					5.5	7.4
NNE------	.6	1.5	1.5	.3	#					3.9	6.7
NE-------	.6	1.5	.8	.1						3.0	6.1
ENE------	.2	.9	.3	.1						1.5	6.0
E--------	.5	.5	.1	#						1.1	5.0
ESE------	.4	.8	.3	.2	#					1.7	6.7
SE-------	1.0	3.3	1.3	.3	#					5.9	6.5
SSE------	1.5	9.1	6.2	1.4	.1					18.3	7.5
S--------	2.1	5.8	7.0	3.7	1.2	.1	.1			20.0	9.6
SSW------	.4	1.1	2.5	4.9	2.4	.5	.1	#		11.9	14.4
SW-------	.2	.5	1.3	2.7	1.6	.3	.1			6.7	14.5
WSW------	.1	.3	.2	.3	.4	.1				1.4	11.8
W--------	.1	.3	.1	#	#					.5	6.0
WNW------	.1	.3	.1	#	#					.5	5.2
NW-------	.3	.7	.2							1.2	5.3
NNW------	.4	1.0	.7	.2	.2					2.5	7.7
Calm-----										14.4	
Totals---	9.0	29.7	24.4	14.9	6.3	1.0	.3			100.0	7.9

6768* February	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total%	Mean Speed
N--------	0.7	2.1	1.3	0.4	#					4.5	7.3
NNE------	.5	1.7	1.2	.2	#					3.6	7.0
NE-------	.5	1.7	.7	.1						3.0	6.0
ENE------	.3	.8	.2	#						1.3	5.7
E--------	.5	.6	.2	#						1.3	5.1
ESE------	.4	.8	.3	.1						1.6	6.3
SE-------	1.0	2.8	1.2	.1						5.1	6.0
SSE------	1.7	8.4	5.2	1.1	.1	#				16.5	7.3
S--------	2.1	5.3	5.8	3.4	.6	.1				17.3	9.3
SSW------	.6	1.0	2.2	5.2	2.9	.5	#	#		12.4	4.7
SW-------	.3	.8	1.8	3.1	2.0	.2	.1			8.3	14.6
WSW------	.3	.4	.6	.8	.3	#	#			2.4	11.5
W--------	.3	.3	.3	.1						1.0	7.2
WNW------	.2	.3	.2	#	#					.7	5.8
NW-------	.5	1.1	.6	.1	#					2.3	6.7
NNW------	.4	1.1	1.2	.7	.1					3.5	8.7
Calm-----										15.2	
Totals---	10.3	29.2	23.0	15.4	6.0	.8	.1			100.0	8.1

7440* March	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total%	Mean Speed
N--------	0.8	1.6	1.0	0.3	#					3.7	6.6
NNE------	.5	1.3	.8	.1						2.7	6.7
NE-------	.6	1.8	1.0	.1						3.5	5.8
ENE------	.2	.9	.4	.1						1.6	5.8
E--------	.3	.7	.3	.1	#	#				1.4	6.1
ESE------	.3	1.0	.5	.1	.1					2.0	7.1
SE-------	.9	2.6	1.0	.3	#					4.8	6.5
SSE------	1.3	6.7	4.9	.9	.1	#				13.9	7.4
S--------	1.5	4.8	6.4	3.2	.4	#				16.3	9.2
SSW------	.4	1.0	3.7	5.2	2.2	.4	#			12.9	14.1
SW-------	.2	1.1	3.0	4.6	2.6	.5	#			12.0	14.4
WSW------	.1	.7	1.3	1.4	.8	.1	#			4.4	12.2
W--------	.2	.3	.3	.2	.1					1.1	7.7
WNW------	.2	.3	.3	#						.8	6.4
NW-------	.5	1.3	1.0	.6	#					3.4	7.9
NNW------	.3	1.4	1.4	.9	.1					4.1	9.2
Calm-----										11.4	
Totals---	8.3	27.5	27.3	18.1	6.4	1.0				100.0	8.3

7220* April	Wind Speed (m.p.h.) 1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total%	Mean Speed
N--------	1.4	2.3	1.4	0.3	#					5.4	6.5
NNE------	.5	1.9	1.3	.1						3.8	6.9
NE-------	.5	2.3	1.0	.2	#					4.0	6.6
ENE------	.2	1.1	.5	.1						1.9	6.7
E--------	.4	.8	.1	#						1.3	5.4
ESE------	.5	1.1	.3	.1						2.0	5.8
SE-------	.9	2.2	.8	.1	.1					4.1	5.9
SSE------	1.0	5.3	3.8	.9	.1					11.1	7.5
S--------	1.0	4.0	4.9	2.3	.2					12.4	8.9
SSW------	.3	1.3	3.2	5.1	1.4	.2				11.5	13.2
SW-------	.3	1.1	2.6	3.3	1.4	.3	#			9.0	13.6
WSW------	.1	.8	1.5	1.5	.5	.1				4.5	11.8
W--------	.1	.6	.7	.3	.1	#				1.8	8.3
WNW------	.1	.6	.4	.3	#					1.4	8.2
NW-------	.6	1.7	2.3	1.8	.1					6.5	9.2
NNW------	.7	2.1	2.4	2.3	.4	#				7.9	9.7
Calm-----										11.4	
Totals---	8.6	29.2	27.2	18.7	4.3	.6				100.0	8.4

7440* May	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total%	Mean Speed
N--------	1.4	3.1	2.2	0.4	#					7.1	6.8
NNE------	.8	2.5	1.6	.3						5.2	6.8
NE-------	.7	2.6	1.5	.2	#					5.0	6.4
ENE------	.3	1.3	.8	.1						2.5	6.4
E--------	.4	1.1	.3							1.8	5.4
ESE------	.4	1.1	.3	#						1.8	5.4
SE-------	.8	2.0	.6	#						3.4	5.4
SSE------	.9	4.4	3.9	.3						9.5	7.1
S--------	.8	3.5	5.3	1.4	.1					11.1	8.7
SSW------	.2	1.5	3.4	2.8	.5	#				8.4	11.4
SW-------	.1	1.3	3.4	3.0	.8	.1				8.7	12.2
WSW------	.3	1.1	1.7	1.4	.3	#				4.8	10.2
W--------	.3	.9	.7	.3	.1					2.3	7.7
WNW------	.1	.8	.7	.2	#					1.8	8.3
NW-------	.5	1.7	2.8	2.1	.1					7.2	9.8
NNW------	.7	2.1	3.4	2.9	.4					9.5	10.1
Calm-----										9.9	
Totals---	8.7	31.0	32.6	15.4	2.3	.1				100.0	8.0

7200* June	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total%	Mean Speed
N--------	1.4	3.3	1.6	0.3						6.6	6.1
NNE------	.9	2.0	1.0	.1						4.0	6.1
NE-------	.5	2.0	1.0	.1						3.6	6.2
ENE------	.4	1.0	.6							2.0	5.6
E--------	.4	.7	.1							1.2	5.1
ESE------	.2	.9	.2							1.3	5.3
SE-------	.8	2.0	.6	#						3.4	5.5
SSE------	.8	4.5	3.7	.2						9.2	7.0
S--------	.6	4.1	5.6	1.7	.1					12.1	8.7
SSW------	.3	2.1	5.5	3.6	.3	#				11.8	10.8
SW-------	.3	2.1	4.3	3.3	.5	.1				10.6	11.2
WSW------	.4	1.7	2.2	1.2	.3	#				5.8	9.6
W--------	.3	1.2	.9	.2	#					2.6	7.5
WNW------	.2	.8	.9	.1						2.0	7.6
NW-------	.4	1.9	2.5	1.3	.2					6.3	9.2
NNW------	.6	2.4	2.8	2.2	.3					8.3	9.3
Calm-----										9.2	
Totals---	8.5	32.7	33.5	14.3	1.7	.1				100.0	7.5

TABLE 6

WIND

Table 28. Percentage Frequency and Mean Speed of Surface Winds (1950 - 1959) , Seattle , Boeing Field Airport - Cont'd.

7440* July	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
	Wind Speed (m.p.h.)										
N	1.6	3.5	2.0	0.3						7.4	6.5
NNE	1.1	2.5	1.6	.2						5.4	6.4
NE	.7	2.4	1.5	.2						4.8	6.5
ENE	.3	1.4	.7	#						2.4	6.0
E	.4	.8	.2							1.4	5.1
ESE	.3	.7	.2	#						1.2	4.9
SE	.6	1.6	.5							2.6	5.3
SSE	.6	3.4	2.7	.2						6.9	6.9
S	.6	3.3	4.3	.7	#					8.9	8.2
SSW	.2	1.8	4.1	1.9	.2					8.2	10.0
SW	.2	1.7	4.0	1.8	.2					7.9	10.3
WSW	.3	1.0	2.2	1.0	.1					4.6	9.5
W	.1	1.0	.9	.3	#					2.4	7.9
WNW	.2	1.0	1.1	.2						2.5	8.0
NW	.9	2.3	3.9	2.2	.1					9.4	9.4
NNW	1.2	3.3	4.6	3.1	.3					12.5	9.2
Calm										11.5	
Totals	9.3	31.7	34.5	12.1	.9					100.0	7.5

7440* August	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N	1.8	3.6	1.6	0.1						7.1	5.8
NNE	.8	2.2	.9	.1						4.0	6.1
NE	.6	2.3	.9	.1						3.9	5.9
ENE	.3	1.3	.4	#						2.0	5.5
E	.3	.5	.1							.9	4.7
ESE	.6	.6	.1							1.3	4.6
SE	.9	2.0	.4							3.3	4.9
SSE	.9	4.9	3.0	.1						8.9	6.6
S	.7	4.3	4.7	1.0	#	#				10.7	8.1
SSW	.3	1.9	3.3	1.9	.2					7.6	10.0
SW	.3	1.7	3.2	1.9	.1					7.2	10.0
WSW	.2	1.2	1.6	.8	.1					3.9	9.4
W	.3	1.0	.7	.1	#					2.1	7.3
WNW	.2	.9	1.1	.1	#					2.3	7.8
NW	.7	3.2	3.9	1.6	.1					9.5	8.5
NNW	1.0	3.5	4.5	2.5	.2					11.7	9.0
Calm										13.6	
Totals	9.9	35.1	30.4	10.3	.7					100.0	7.1

7200* September	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N	1.3	2.9	1.5	0.3	#					6.0	6.3
NNE	.9	2.0	1.2	.1						4.2	6.4
NE	.6	2.3	1.3	.1						4.3	6.2
ENE	.1	1.2	.5	#						1.8	6.2
E	.3	.6	.2							1.1	5.0
ESE	.4	.7	.1							1.2	4.8
SE	1.3	2.5	.6	#						4.4	5.0
SSE	2.0	6.6	4.3	.5						13.4	6.6
S	1.6	5.0	5.0	1.4	.2					13.2	8.0
SSW	.3	1.3	2.8	2.1	.4	#				6.9	10.8
SW	.3	1.2	1.9	1.7	.4	#				5.5	10.7
WSW	.2	.8	.8	.6	.1					2.5	8.9
W	.2	.7	.4	#						1.3	6.2
WNW	.2	.7	.4	#						1.3	7.1
NW	.7	2.3	3.1	1.3	#					7.4	8.7
NNW	1.0	3.0	3.7	2.4	.1					10.2	9.0
Calm										15.3	
Totals	11.4	33.8	27.8	10.5	1.2					100.0	7.2

7440* October	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
	Wind Speed (m.p.h.)										
N	1.4	2.7	1.5	0.2						5.8	6.1
NNE	1.0	2.2	1.0	.1	#					4.3	6.0
NE	.5	1.5	.9	.1						3.0	6.2
ENE	.2	1.0	.6	#						1.8	5.9
E	.3	.6	.3	#						1.2	5.6
ESE	.5	.6	.3	.1						1.5	5.7
SE	1.6	3.4	1.4	.1	#					6.5	5.9
SSE	1.8	8.4	6.2	.6	.1	#				17.1	6.9
S	1.6	5.5	5.6	2.8	.3	#				15.8	8.7
SSW	.4	1.3	2.5	3.6	1.2	.2	#			9.2	12.6
SW	.3	1.0	1.4	1.6	.7	.1				5.1	11.8
WSW	.2	.4	.5	.5	.1					1.7	9.6
W	.2	.4	.1	#	#					.7	5.7
WNW	.2	.5	.2	#						.9	5.5
NW	.8	2.0	1.8	.3						4.9	7.0
NNW	.9	2.6	2.6	.7	#					6.8	7.7
Calm										13.7	
Totals	11.9	34.1	26.9	10.7	2.4	.3				100.0	7.3

7200* November	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N	1.2	2.5	1.3	0.3	0.2					5.5	6.7
NNE	.9	1.8	1.6	.3	.1					4.7	7.0
NE	.6	1.7	.8	.1						3.2	5.9
ENE	.2	.8	.3	.1						1.4	6.3
E	.4	.6	.2	#						1.2	5.1
ESE	.6	.9	.5	.2						2.2	6.5
SE	1.3	3.7	1.6	.3	#	#				6.9	6.4
SSE	2.0	9.3	6.8	1.1	#					19.2	7.2
S	2.0	6.8	5.3	3.0	.5	.2	#			17.8	8.9
SSW	.5	1.0	1.8	3.7	1.8	.2	#			9.0	12.4
SW	.3	1.0	1.3	1.9	1.1	.3				5.9	12.6
WSW	.2	.2	.4	.4	.2	#				1.4	10.8
W	.2	.3	.1	#		#				.6	5.6
WNW	.2	.2	.1	#						.5	5.3
NW	.4	1.3	.7	.1	#	#				2.5	6.8
NNW	.7	1.6	1.0	.4	.1		#			3.8	7.8
Calm										14.2	
Totals	11.7	33.7	23.8	11.9	4.0	.7				100.0	7.6

7440* December	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & over	Total %	Mean Speed
N	0.8	1.9	0.9	0.2	#					3.8	6.2
NNE	.6	1.4	1.0	.2						3.2	6.6
NE	.4	1.3	.5	.1						2.3	6.2
ENE	.2	.6	.2	#						1.0	5.2
E	.3	.5	.1	#						.9	5.7
ESE	.5	.7	.3	.1						1.6	5.8
SE	1.4	3.6	1.6	.3						6.9	6.2
SSE	1.8	11.5	7.8	1.2						22.3	7.2
S	1.8	6.2	6.6	3.3	.4	.1				18.4	9.1
SSW	.4	1.4	3.5	4.9	2.5	.4	#			13.1	13.8
SW	.4	.7	1.4	2.5	1.5	.4				6.9	14.2
WSW	.1	.2	.3	.4	.3	#				1.3	11.2
W	.1	.3	.1		#					.5	6.6
WNW	.1	.1	.1	#						.3	3.6
NW	.3	.8	.2		#					1.3	5.9
NNW	.6	1.2	.5	.1	#					2.4	6.3
Calm										13.8	
Totals	9.8	32.4	25.1	13.3	4.7	.9				100.0	7.5

\# Less than 0.05 percent

* Number of Hourly Observations

(m. p. h.) refers to statute miles per hour

Refer to Graphs G and H for annual surface wind rose

TABLE 7

TABLE 8

PERCENTAGE FREQUENCY OF SURFACE WINDS

SAND POINT N.A.S. - MAY 1949-APRIL 1964

JANUARY

Wind Dir.	Frequency of Wind Speed Groups* 3-7	8-12	13-20	21-30	>30	Total
N	4.6	1.8	0.8	0	0	7.2
NNE	1.9	0.4	0.1	0	0	2.4
NE	3.6	0.4	0	0	0	4.0
ENE	2.5	0.3	0	0	0	2.8
E	2.9	0.4	0.1	0	0	3.4
ESE	1.2	0.4	0.2	0	0	1.8
SE	2.6	1.0	0.2	0	0	3.8
SSE	3.2	1.6	0.7	0	0	5.5
S	8.4	8.6	6.0	0.4	0	23.4
SSW	3.3	3.7	2.7	0.3	0	10.0
SW	1.3	0.7	0.3	0	0	2.3
WSW	0.3	0.1	0	0	0	0.4
W	0.3	0	0	0	0	0.3
WNW	0.3	0	0	0	0	0.3
NW	1.2	0.3	0.1	0	0	1.6
NNW	5.0	1.8	0.6	0.1	0	7.5
Calm						23.3
Total	42.6	21.5	11.8	0.8	0	100.0

FEBRUARY

Wind Dir.	Frequency of Wind Speed Groups* 3-7	8-12	13-20	21-30	>30	Total
N	5.9	1.8	0.5	0	0	8.2
NNE	1.3	0.2	0	0	0	1.5
NE	2.3	0.2	0	0	0	2.5
ENE	1.5	0.1	0	0	0	1.6
E	2.1	0.2	0.1	0	0	2.4
ESE	1.1	0.4	0.1	0	0	1.6
SE	2.2	0.6	0.1	0	0	2.9
SSE	3.1	1.8	0.4	0	0	5.3
S	9.3	8.5	4.3	0.3	0	22.4
SSW	3.2	3.9	2.9	0.2	0	10.2
SW	1.5	0.8	0.3	0.1	0	2.7
WSW	0.3	0.1	0	0	0	0.4
W	0.4	0	0	0	0	0.4
WNW	0.2	0	0	0	0	0.2
NW	1.8	0.4	0.1	0	0	2.3
NNW	6.7	2.0	0.6	0	0	9.3
Calm						26.1
Total	42.9	21.0	9.4	0.6	0	100.0

MARCH

N	5.8	1.5	0.3	0	0	7.6
NNE	1.0	0.2	0	0	0	1.2
NE	1.7	0.2	0	0	0	1.9
ENE	1.2	0.2	0	0	0	1.4
E	1.3	0.3	0	0	0	1.6
ESE	1.0	0.3	0.1	0	0	1.4
SE	2.6	0.8	0.3	0	0	3.7
SSE	4.1	1.6	0.3	0	0	6.0
S	10.2	10.1	4.6	0.2	0	25.1
SSW	3.3	4.8	3.6	0.2	0	11.9
SW	1.8	1.3	0.5	0	0	3.6
WSW	0.4	0.2	0.1	0	0	0.7
W	0.4	0.1	0	0	0	0.5
WNW	0.2	0	0	0	0	0.2
NW	1.6	0.6	0.2	0	0	2.4
NNW	5.7	2.0	0.4	0	0	8.1
Calm						22.7
Total	42.3	24.2	10.4	0.4	0	100.0

APRIL

N	6.5	2.0	0.2	0	0	8.7
NNE	1.4	0.2	0	0	0	1.6
NE	2.2	0.2	0	0	0	2.4
ENE	1.1	0.2	0	0	0	1.3
E	1.3	0.2	0	0	0	1.5
ESE	1.1	0.2	0.1	0	0	1.4
SE	2.6	0.4	0.1	0	0	3.1
SSE	3.8	1.3	0.3	0	0	5.4
S	9.8	9.1	3.0	0.1	0	22.0
SSW	3.8	4.4	2.1	0.1	0	10.4
SW	2.1	1.6	0.6	0	0	4.3
WSW	0.5	0.2	0	0	0	0.7
W	0.6	0.1	0	0	0	0.7
WNW	0.3	0.1	0	0	0	0.4
NW	1.8	0.6	0.1	0	0	2.5
NNW	7.9	4.2	0.5	0	0	12.6
Calm						21.0
Total	46.8	25.0	7.0	0.2	0	100.0

* Wind speed in knots

TABLE 9

PERCENTAGE FREQUENCY OF SURFACE WINDS

SAND POINT N.A.S. - MAY 1949-APRIL 1964

MAY

Wind Dir.	Frequency of Wind Speed Groups* 3-7	8-12	13-20	21-30	>30	Total
N	9.7	3.5	0.2	0	0	13.4
NNE	2.1	0.3	0	0	0	2.4
NE	2.6	0.3	0	0	0	2.9
ENE	1.8	0.1	0	0	0	1.9
E	1.8	0.2	0	0	0	2.0
ESE	1.2	0.2	0	0	0	1.4
SE	2.8	0.4	0	0	0	3.2
SSE	3.6	1.3	0.1	0	0	5.0
S	10.1	7.2	0.8	0	0	18.1
SSW	4.7	4.0	0.8	0	0	9.5
SW	2.5	1.1	0.3	0	0	3.9
WSW	0.7	0.3	0	0	0	1.0
W	0.5	0.1	0	0	0	0.6
WNW	0.3	0.1	0	0	0	0.4
NW	2.0	0.7	0	0	0	2.7
NNW	9.0	4.8	0.3	0	0	14.1
Calm						17.5
Total	55.4	24.6	2.5	0	0	100.0

JUNE

Wind Dir.	Frequency of Wind Speed Groups* 3-7	8-12	13-20	21-30	>30	Total
N	9.4	3.5	0.2	0	0	13.1
NNE	2.7	0.4	0	0	0	3.1
NE	3.6	0.4	0	0	0	4.0
ENE	1.7	0.1	0	0	0	1.8
E	1.7	0.1	0	0	0	1.8
ESE	1.4	0.1	0	0	0	1.5
SE	2.9	0.3	0	0	0	3.2
SSE	4.2	1.3	0.1	0	0	5.6
S	10.0	7.1	0.8	0	0	17.9
SSW	5.6	3.8	0.6	0	0	10.0
SW	3.4	1.2	0.1	0	0	4.7
WSW	0.6	0.2	0	0	0	0.8
W	0.4	0.1	0	0	0	0.5
WNW	0.4	0	0	0	0	0.4
NW	2.1	0.6	0	0	0	2.7
NNW	9.0	3.8	0.2	0	0	13.0
Calm						15.9
Total	59.1	23.0	2.0	0	0	100.0

JULY

Wind Dir.	3-7	8-12	13-20	21-30	>30	Total
N	12.5	4.5	0.1	0	0	17.1
NNE	3.8	0.6	0	0	0	4.4
NE	4.4	0.4	0	0	0	4.8
ENE	1.8	0.1	0	0	0	1.9
E	1.5	0.1	0	0	0	1.6
ESE	1.1	0	0	0	0	1.1
SE	2.7	0.1	0	0	0	2.8
SSE	3.2	0.8	0	0	0	4.0
S	8.0	4.7	0.3	0	0	13.0
SSW	4.4	2.5	0.4	0	0	7.3
SW	3.5	1.1	0	0	0	4.6
WSW	0.6	0.2	0	0	0	0.8
W	0.5	0.1	0	0	0	0.6
WNW	0.3	0	0	0	0	0.3
NW	2.9	0.9	0	0	0	3.8
NNW	11.7	4.7	0.2	0	0	16.6
Calm						15.3
Total	62.9	20.8	1.0	0	0	100.0

AUGUST

Wind Dir.	3-7	8-12	13-20	21-30	>30	Total
N	10.4	2.8	0.1	0	0	13.3
NNE	3.1	0.3	0	0	0	3.4
NE	4.0	0.2	0	0	0	4.2
ENE	1.6	0	0	0	0	1.6
E	1.3	0	0	0	0	1.3
ESE	0.8	0	0	0	0	0.8
SE	2.4	0.2	0	0	0	2.6
SSE	3.0	0.7	0	0	0	3.7
S	8.5	5.1	0.4	0	0	14.0
SSW	5.5	3.7	0.4	0	0	9.6
SW	3.7	1.0	0.1	0	0	4.8
WSW	0.8	0.1	0	0	0	0.9
W	0.6	0	0	0	0	0.6
WNW	0.5	0	0	0	0	0.5
NW	4.0	1.0	0	0	0	5.0
NNW	11.9	3.3	0.1	0	0	15.3
Calm						18.4
Total	62.1	18.4	1.1	0	0	100.0

* Wind speed in knots

TABLE 10

PERCENTAGE FREQUENCY OF SURFACE WINDS

SAND POINT N.A.S. - MAY 1949-APRIL 1964

SEPTEMBER

Wind Dir.	Frequency of Wind Speed Groups* 3-7	8-12	13-20	21-30	>30	Total
N	9.0	2.2	0.1	0	0	11.3
NNE	2.0	0.3	0	0	0	2.3
NE	3.6	0.2	0	0	0	3.8
ENE	1.6	0.1	0	0	0	1.7
E	1.6	0.1	0	0	0	1.7
ESE	0.8	0.1	0	0	0	0.9
SE	2.3	0.3	0	0	0	2.6
SSE	2.9	0.7	0	0	0	3.6
S	7.3	5.2	1.1	0	0	13.6
SSW	3.8	2.9	0.8	0	0	7.5
SW	2.4	0.5	0.2	0	0	3.1
WSW	0.6	0	0	0	0	0.6
W	0.5	0	0	0	0	0.5
WNW	0.3	0	0	0	0	0.3
NW	4.2	0.6	0	0	0	4.8
NNW	12.8	3.9	0.3	0	0	17.0
Calm						24.7
Total	55.7	17.1	2.5	0	0	100.0

OCTOBER

Wind Dir.	Frequency of Wind Speed Groups* 3-7	8-12	13-20	21-30	>30	Total
N	7.5	2.0	0.1	0	0	9.6
NNE	1.8	0.3	0	0	0	2.1
NE	3.0	0.2	0	0	0	3.2
ENE	1.7	0.2	0	0	0	1.9
E	2.0	0.2	0	0	0	2.2
ESE	0.8	0.3	0.1	0	0	1.2
SE	2.6	0.9	0.1	0	0	3.6
SSE	3.6	1.9	0.4	0	0	5.9
S	8.5	7.1	3.0	0.1	0	18.7
SSW	3.5	3.8	1.8	0.1	0	9.2
SW	1.5	0.6	0.2	0	0	2.3
WSW	0.3	0.1	0	0	0	0.4
W	0.4	0.1	0	0	0	0.5
WNW	0.3	0	0	0	0	0.3
NW	2.9	0.5	0	0	0	3.4
NNW	8.4	1.8	0.2	0	0	10.4
Calm						25.1
Total	48.8	20.0	5.9	0.2	0	100.0

NOVEMBER

Wind Dir.	3-7	8-12	13-20	21-30	>30	Total
N	5.5	1.8	0.4	0	0	7.7
NNE	1.6	0.4	0	0	0	2.0
NE	2.7	0.2	0	0	0	2.9
ENE	2.0	0.3	0	0	0	2.3
E	2.4	0.6	0.1	0	0	3.1
ESE	1.2	0.5	0.1	0	0	1.8
SE	3.1	0.9	0.2	0	0	4.2
SSE	3.2	1.9	0.6	0	0	5.7
S	8.2	8.7	4.3	0.3	0	21.5
SSW	3.2	3.1	2.3	0.2	0	8.8
SW	1.8	0.9	0.4	0.1	0	3.2
WSW	0.3	0.1	0	0	0	0.4
W	0.3	0	0	0	0	0.3
WNW	0.2	0	0	0	0	0.2
NW	2.4	0.5	0.1	0	0	3.0
NNW	6.3	1.7	0.4	0	0	8.4
Calm						24.5
Total	44.4	21.6	8.9	0.6	0	100.0

DECEMBER

Wind Dir.	3-7	8-12	13-20	21-30	>30	Total
N	3.9	1.4	0.3	0	0	5.6
NNE	1.3	0.3	0	0	0	1.6
NE	3.0	0.2	0	0	0	3.2
ENE	2.3	0.2	0	0	0	2.5
E	2.5	0.3	0.1	0	0	2.9
ESE	1.1	0.4	0.3	0	0	1.8
SE	2.8	0.8	0.1	0	0	3.7
SSE	3.0	1.9	0.4	0	0	5.3
S	9.4	10.0	5.1	0.3	0	24.8
SSW	3.7	4.2	3.3	0.5	0	11.7
SW	1.6	0.7	0.4	0	0	2.7
WSW	0.3	0.1	0	0	0	0.4
W	0.5	0.1	0	0	0	0.6
WNW	0.2	0	0	0	0	0.2
NW	1.4	0.5	0.1	0	0	2.0
NNW	4.5	1.2	0.2	0	0	5.9
Calm						25.1
Total	41.5	22.3	10.3	0.8	0	100.0

* Wind speed in knots

TABLE 11

WIND DATA OBSERVATIONS TAKEN AT THREE HOUR INTERVALS

SEATTLE-TACOMA AIRPORT, SEATTLE, WASHINGTON 1965*

	February 16		October 18		November 4		December 3	
Hour	Direction	Speed (knots)	Direction	Speed (knots)	Direction	Speed (knots)	Direction	Speed (knots)
01	20	15	16	4	20	11	11	6
04	10	10	21	7	22	6	13	5
07	21	12	19	10	21	14	17	3
10	21	17	19	13	18 X	12	19	14
13 X[†]	20	11	18 X	11	19	9	19 X	17
16	21	11	23	3	17	6	20	13
19	20	10	15	3	16	5	21	11
22	20	16	22	9	18	6	19	11

*From: "Local Climatological Data, Seattle-Tacoma Airport," U. S. Department of Commerce, Weather Bureau, Asheville, N. C. February, October, November and December, 1965.

†"X" denotes observations nearest to flight time.

WIND DATA OBSERVATIONS

THE EVERGREEN POINT BRIDGE

SEATTLE, WASHINGTON 1965

February 16			October 18			November 4			December 3		
Time	Direction	Speed (mph)	Time	Direction	Speed (mph)	Time	Direction	Speed (mph)	Time	Direction	Speed (mph)
0000	SW	28	0500	S	17	0500	S	24	0500	ESE	2
0800	S	27	0930	S	25	0900 X	S	25	0900	SSW	16
1600 X	SW	22	1300 X	SW	22	1300 X	S	22	1300 X	S	25
			1400	WSW	25	1500	S	15			
			1500	S	22	1700	S	13			
			1600	SSE	18	2100	S	21			
			1700	S	18						
			1800	S	15						
			1900	S	15						

*From the 'Log', The Evergreen Point Bridge Control Tower.

TABLE 12

SURFACE WEATHER OBSERVATIONS
1965
U. S. Naval Air Station
Seattle, Washington

	February 16			October 18			November 4			December 3		
Time (LST)	Direction	Speed (kts.)	Character	Direction	Speed (kts.)	Character	Direction	Speed (kts.)	Character	Direction	Speed (kts.)	Character
0055	16	10	G17	15	08		18	10		06	02	
0155	14	06	G14	15	07		22	15	G19	16	02	
0255	14	06		14	08		18	10	G14	02	04	
0355	18	10		15	10		18	12		33	03	
0455	17	12		18	13	G19	19	10		00	00	
0555	15	10	G16	18	13	G18	18	13		00	00	
0655	18	12	G20	17	13	G18	17	14	G19	08	04	
0755	18	12	G20	19	17	G21	17	13	G19	13	06	
0855	18	14	G22	16	10		17	14	G20	19	04	
0955	18	12	G18	18	12	G18	17 X	12	G18	16	16	
1055	19	12	G21	18	09		17	14		21	06	
1155	19	15	G22	17	14		18	20	G25	15	02	
1255	18	14	G22	18 X	09		16	12		20 X	16	G22
1355	18 X†	14	G20	17 X	09	G15	17	10		21	12	G24
1455	18	13		16	06		16	10		20	14	G22
1555	19	14	G19	17	10		15	10		20	10	G18
1655	18	12	G19	18	10		16	12		20	14	G26
1755	18	13		15	08		15	13		20	11	G20
1855	17	10		18	10		16	13	G21	20	12	G21
1955	18	08		18	11		17	08		20	14	
2055	18	12		18	10		15	08		19	14	G23
2155	18	08		18	10		17	10		18	11	
2255	18	08		21	08		17	12		18	10	
2355	19	08		33	06		17	10		16	14	

*From: "Surface Weather Observations," U. S. Naval Air Station, Seattle, Washington, February 16, October 18, November 4, December 3, 1965. U. S. Department of Commerce, Asheville, North Carolina.

†Denotes observations nearest to flight time.

TABLE 13

MISCELLANEOUS WIND DATA

Sand Point Naval Air Station
1966

Evergreen Point Bridge			Sand Point Naval Air Station		
Time	Direction	Speed	Time	Direction	Speed
March 4, 1966					
1600	140	12 G23	1600	ESE	20
March 14, 1966					
0930	S	17			
1130	SSW	20-30			
1200	SSW	30-35	1200	180	14 G19
1300	SSW*	30-35	1300	180	14 G19
1400	SSW	30-40	1400	180	10
1430	S	25-35	1500	180	G23
1445	S	20-25			
1500	S	20-25			
March 15, 1966					
0900	S	25+ all day			
1400	S	G30-40			
1600	S	20			
March 19, 1966					
			1200	200	13
			1230	190	16
			1300	210	14
			1330	180	17 G26
			1400	180	12
April 1, 1966					
1020	SW	40	1000	200	15
1100	SW	10-12	1100	210	15
1200	SW	10	1200	220	12
April 4, 1966					
1500	SE	12	1500	140	5

*Waves breaking over bridge rail.

Evergreen Point Bridge			Sand Point Naval Air Station		
Time	Direction	Speed	Time	Direction	Speed
April 14, 1966					
1300	S	18	1300	190	10
April 18, 1966					
	NW	24-29	1600	00	18 G25
June 28, 1966					
			0600	180	10
			0700	180	6
			0800	200	10
			0900	200	8
			1000	190	12 G20
			1100	180	12 G20+
			1200	190	12 G20+
			1300	190	10
			1400	220	12
			1500	220	8 G16
			1600	210	8

TABLE 14

SUMMARY OF WAVE GAGE MEASUREMENTS

DATE	TIME	SITE	WIND VEL.	WIND DIR.	INCIDENT OR REFLECTED	WAVE LENGTH (ft)	WAVE PERIOD (sec)	$\bar{H}$-1/3 (ft)	SAMPLE SIZE	COMMENTS
1/11/66	1-2:30 P.M.	MADISON	*20mph	S	I		1.5	0.66	181	
					R		2.0	0.84	145	
2/11/66	11:10 A.M.	JONES	*10mph	SSE	I		1.7	0.54	58	Wind dying dur-
					R		2.0	0.71	24	ing measurement
2/22/66	2:30 P.M.	REED	SP- 8kts	SSE	I		1.3	0.29	93	No noticeable
					R		1.2	0.40	38	wind at time of measurement
2/22/66	1:40 P.M.	JONES	SP-10kts	ESE	I		1.4	0.87	71	
					R		1.5	0.85	53	
3/14/66	2:15 P.M.	JONES	*35mph	S-SSW	I		2.2	1.02	222	
					R		2.5	1.17	74	
3/14/66	1:00 P.M.	MADISON	*30-35mph	SSW	I	20-30'	2.1	1.17	132	
					R		2.6	1.60	44	
3/14/66	1:45 P.M.	REED	*35mph	SSW	I		2.0	1.11	205	
					R		2.2	1.00	12	
3/19/66	12:45 P.M.	ROBINSON	SP-16kts	SSW	I		2.3	1.64	274	
					R		2.5	1.83	143	
4/1/66	11:30 A.M.	MADISON	*10mph	SW	I	20'	2.1	1.10	306	Winds to 40mph
					R		2.2	1.39	105	at 11:00 A.M. died to 10mph by 11:30

*Evergreen Point Bridge
SP-Sand Point Naval Air Station