CHAPTER 14

UPWIND TRAVEL OF REFLECTED WAVES

by E. P. Richey[1]

ABSTRACT

Wind waves in a lake have been observed to reflect from a barrier and to travel upwind for considerable distances. A model has been devised which provides a means of predicting the decay of these waves as a function of wind speed and direction with respect to the barrier. Two floating bridges across a deep lake have formed a convenient, full-scale test basin for the formation and observation of the reflected waves under a range of wind speeds and directions. Wave characteristics have been measured to a limited extent by photographic means, a portable wave probe and visually to provide some verification of the results computed from the model. The measured and the predicted wave heights and the zones influenced by the waves were found to be in general qualitative agreement.

INTRODUCTION

Reflected waves will be assuming a more important role in the design of marine structures. The objective of many of these structures is to provide shelter or shielding from wave energy, so transmission characteristics receive most attention, with reflected energy usually being a residual of only secondary interest. However, the pressures of the modern society are leading to a rapidly increased use of our space on and in the water. In addition to the more conventional structures, there are proposals out for floating airports, stadiums, marinas and the like. There are a few large floating bridges in operation and others in the design stages. In some circumstances waves reflecting from structures like these could cause undesirable interactions with those nearby and the general environment. A reconnaissance study was undertaken to put limits on "nearby" and "general" by assessing the parameters of upwind decay rate and areal extent of reflected waves as dependent upon wind speed, frequency and direction. A convenient field site for observing the reflection problems in full-scale was provided by a floating bridge installed recently across a deep lake.

SITE DESCRIPTION

Geography - A convenient field observation basin is formed by two floating bridges across Lake Washington. As shown on Figure 1, this lake forms the easterly boundary of the City of Seattle, in the State of Washington at the northwestern corner of the United States. The lake is about twenty miles long and mile and half wide, with its long axis in the north-south orientation. It is quite deep, especially through its midsection, where the bottom shelves off to a depth of 70 feet within 100 feet of shore and then to nearly a constant 200 feet within about a thousand feet of either

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shore. The lake level is controlled within a range of about one and one-half feet by a set of locks which separates the lake from the tidal waters of Puget Sound. Hills from one to two hundred feet high ring most of the lake on the east and west shores; Mercer Island, rising about 400 feet above the lake, divides the southern third into two channels.

Structures - Until recently, cross-lake traffic demands were met by a ferry system. The width and depth of lake and the absence of suitable foundation sites made conventional bridge or tunnel crossings impractical. However, a floating pontoon concrete structure 6400 feet long reaching from the west shore to Mercer Island near the southern end of lake (see Figure 2) was completed in 1940. Continued urban expansion led to a second, similar bridge completed in 1963 about three miles north of the first crossing. This one, the Evergreen Point Bridge, has a floating section 7,578 feet long. A typical pontoon has vertical side walls, a width of 60 feet and a draft of about eight feet. The two bridges, therefore, form clean-cut end boundaries on a deep-water basin about 19,000 feet in length and a mile and half in width.

Meteorology - The cyclonic weather systems typical of a mid-latitude (47°N) west coast climate generally dominate the area from late fall to early spring with winds mostly in the sector from the southeasterly to southwesterly direction. Important northerly winds occur during the summer season when the Pacific anticyclone is suitably situated, and in conjunction with the cold frontal systems that pass occasionally during the winter months. The main axis of the lake parallels the common wind directions, and the topography surrounding the lake exerts a marked steering effect on the winds at ground level. Neither the general meteorological conditions nor the site topography is conducive to the formation of winds from either the due westerly or easterly direction.

There are four weather stations in the vicinity of Lake Washington. The annual wind rose for one of these, the Seattle-Tacoma Airport, which lies about 6 miles from the south end of the lake is given as Figure 3 to show a measure of the speed, direction and frequency of concern in the wave generation within the basin between the two bridges. A wind gage installed on the Evergreen Point Bridge provides data for the wind effective over the basin, but has not been in operation long enough to allow compilation of any statistical information. Cross-correlation of readings concurrent with those at the airport station shows that the speed group of 8 - 12 miles per hour from the southerly sector as appearing on hourly weather reports, is the best index of minimum speed needed for the generation of waves of interest to this study. These waves are primarily fetch limited.

DECAY OF REFLECTED WAVES

Model for Analysis - A prediction equation for the decrease in the height of waves as they move upwind may be obtained through an adaptation of the work by Jeffreys (1925, 1926) who formulated that the power P per unit area transmitted from the wind to waves could be expressed as

$$P = B(U-C)^2 HC \tag{1}$$

in which B includes a numerical constant, the mass density of air, the wave number and a sheltering coefficient. The wind speed is denoted by U, and H and C represent the wave height and phase speed. Equation (1) is basically an application of the standard hydrodynamical drag equation to a moving, deformable boundary. In the definition sketch of Figure 4, points 1 and 3 along the incident and reflected wave rays, are equally distant from the reflecting surface or barrier at 2.

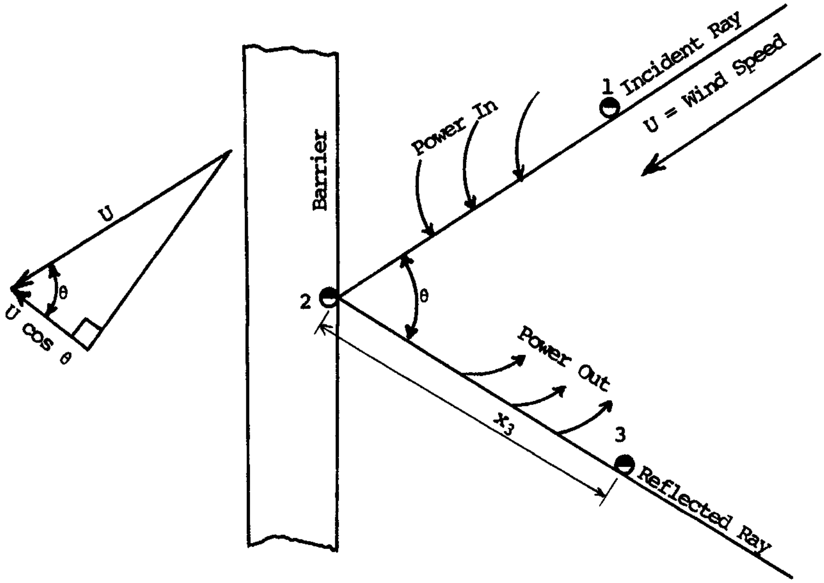

Figure 4. Definition Sketch

The energy flux of a wave system having a characteristic height H, entering the boundary at 1, plus the power added to it by the wind is equal to the energy flux at the downwind position 2, i.e.,

$$\frac{\gamma H_1^{\,2} C_{G_1}}{8} + 1/2 C_d \rho A V^2 C_{1,2} = \frac{\gamma H_2^{\,2} C_{G_2}}{8} \qquad (2)$$

wherein γ is the specific weight of water, C_G is a group velocity, C_d is a drag coefficient, V is the wind velocity relative to the wave, and $C_{1,2}$ is $1/2(C_1+C_2)$, the average phase speed. For a wave moving with the wind (from 1 to 2), the relative velocity is

$$V = U - C_{1,2} \qquad (3)$$

and the projected area normal to the wind is

$$A = 1/2(H_1+H_2) \tag{4}$$

All waves encountered in the test basin are in the "deep water" class so that the group speed is equal to one-half the phase speed, and then Eq. (2) may be written as

$$C_d\rho(H_1+H_2)(U-C_{1,2})^2 C_{1,2} = 1/4\gamma(H_2^2C_2-H_1^2C_1) \tag{5}$$

It is assumed here that the reflection coefficient at the barrier is unity, so that the reflected "H_2" is equal to the incident "H_2". The analysis could be adapted to any other known reflection characteristics.

Waves moving against the wind from 2 to 3 must do work on the surroundings so now

$$V = U\cos\theta + C_{2,3} \tag{6}$$

$$A = 1/2(H_2+H_3) \tag{7}$$

and Eq. (2) applied to this reach becomes

$$C_d\rho(H_2+H_3)(U\cos\theta+C_{2,3})^2 C_{2,3} = 1/4\gamma(H_2^2C_2-H_3^2C_3) \tag{8}$$

The division of Eq. (5) by Eq. (8) yields

$$\frac{(H_1+H_2)(U-C_{1,2})^2C_{1,2}}{(H_2+H_3)(U\cos\theta+C_{2,3})^2C_{2,3}} = \frac{H_2^2C_2 - H_1^2C_1}{H_2^2C_2 - H_3^2C_3} \tag{9}$$

in which the approximations surrounding the drag coefficient and some of the averaged terms have been minimized in this dimensionless form. The wave heights implied thus far have been any characteristic of the systems; hereafter the "$H_{i's}$" shall be regarded as the significant heights.

The distance or fetch, F_2, to the barrier is an implied known quantity in Figure 4; for a given wind speed and direction, the unknowns in Eq. (9) are the values of height and phase speed at points 1 and 3. One might assume a value for the fetch distance to point 1 and thereby reduce the unknowns to two, the height and speed at 3. However, the more convenient solution follows from selecting a value of H_3, then solving for where it occurs relative to the barrier, which is by formulation a distance equal to that to point 1. The equations additional to Eq. (9) needed for a solution may be obtained from published relationships among fetch, wind speed, and wave height and speed. Thus an additional but desirable unknown, the fetch F, is introduced. From the results given by Bretschneider (1958) the familiar parameters of gH/U^2 and C/U vs. gF/U^2 may be represented very closely by the equational forms

$$gH/U^2 = 0.0044(gF/U^2)^{0.38} \tag{10}$$

$$C/U = 0.082(gF/U^2)^{0.26} \tag{11}$$

in the range of $10^2 < gF/U^2 < 10^4$, which brackets all conditions of interest in the test basin.

For a given wind speed U and fetches F_1 and F_2, the ratio of Eq. (11) to (10) reduces to

$$(C_1/H_1)/(C_2/H_2) = (F_2/F_1)^{0.12} \tag{12}$$

The right hand side of the above equation is not far (14%) from unity for fetch ratios up to 3, so it is assumed that the linear relationship may be applied between 2 and 3 to obtain

$$C_3 = H_3/H_2C_2 \tag{13}$$

$$C_{2,3} = 1/2C_2(1+H_3/H_2) \tag{14}$$

The substitution of these two equations into Eq. (9) brings it to the final form:

$$\frac{(H_1+H_2)(U-C_{1,2})^2 C_{1,2}}{(H_1+H_3)[U\cos\theta+1/2C_2(1+H_3/H_2)]^2[C_2(1+H_3/H_2)]} = \frac{H_2^2C_2-H_1^2C_1}{H_2^2C_2-H_3^2(H_3/H_2)C_2} \tag{15}$$

Equation (15) can be solved by a computer in the following outline form:

1. Select U, θ, F_2 as fixed for one condition
2. Compute H_2, C_2 from Eqs. (10) and (11)
3. Select a value for H_3
4. By iteration solve Eqs. (10), (11) and (15) for F_1
5. The distance from the barrier to the point where the reflected wave decreases to the selected value for H_3 is

$$x_3 = F_2-F_1 \tag{16}$$

The mapping of the reflected waves on the test basin as predicted for the wind of U=20 mph, θ= 15° (S20W) is shown on Figure 2. Heights versus distance for three wind speeds and two values of θ as computed from Eq. 15 are given on Figure 5. Values of distance from this plot need to be referred to Figure 2 with the appropriate value of θ to determine where the rays of the reflected waves may intersect a shoreline, which determines the limiting value of "x_3". The ensuing discussions of the observations and measurements on the lake will bring out where these predictions agree and disagree with field conditions.

OBSERVATIONS AND MEASUREMENTS

Scope - The extent of the observations and measurements of field conditions was matched to the initial objective of the study, i.e., to make a reconnaissance of the limits to which waves reflecting from a barrier in deep water might extend under a range of natural conditions. Therefore, the field investigation was limited to the simpler techniques of photography, visual observations, and a sampling of wave heights using a portable wave gage and recorder.

Photography - A series of areal photographs for four occasions, and a motion picture sequence for one wind-wave condition were taken to ascertain wave lengths and zones where reflected waves could be identified. Although none of these is reproduced herein, the results do enter indirectly in support of other observations. A near-shore condition resulting from a steady southerly wind of about 20 mph is shown on Figure 6. The stepped breakwater in the foreground is about 3000 feet from the bridge. Groups of reflected waves with heights of nearly a foot are discernible over much of the picture, which was taken from a high building that shields the bay from southerly winds. A common network pattern of incident and reflected waves appears in the foreground. Figure 7 shows the source of the reflected waves for a somewhat slower wind speed. Figures 8 and 9* show the near-bridge and traffic conditions under an infrequent wind speed of 40 mph with higher gusts. Note the plumed waves moving out against the wind. Even here, the lee (north) side of the barrier shows no energy transmission. Some breaking of waves in the vicinity of the bridge begins at a speed of about 25 mph, and under the higher speeds like those in the last two photographs, considerable energy is expended in the reflection process.

Wave Height Measurements - A parallel-wire resistance gage and strip recorder were teamed as a portable unit to sample waves for a few different wind conditions. Four sites on the lake were chosen where accessible piers extended to water depths of about 15 feet. Since the bottom shelves off quite rapidly and few waves had lengths longer than 30 feet, shoaling effects at these sites was not important. The wave gage was not directionally sensitive so the reflected waves, when present, had to be sorted out visually by their orientation and direction of travel and suitably marked on the oscillograph record. Very commonly a group of reflected waves would dominate a site for a time, then would

*Figures 8 and 9. Courtesy Seattle Times, photographer J. Scaylea.

give way to an incident pattern. As distance upwind of the barrier increased, the number of reflected waves identifiable decreased, as well as their heights; components at the higher frequencies also tended to disappear due to the filtration process. A brief summary of the wave gage measurements appears in Table 1, with site locations A, B, C and D spotted on Figure 2, where the wave pattern forecast for U-20 mph θ=15° is shown. The sampling serves to give a good measure of period and height; no attempt was made to prepare comparative energy spectra. The maximum excursion of the reflected waves was traced visually

Table 1
Summary of Wave Gage Measurements

No.	Site	x_3 ft.	U mph	Dir.	θ deg.	i or r	T sec	L* ft	H ft	Sample
1	B		20	S	25	i	1.5	12	0.66	181
						r	2.0		0.84	145
2	A		10	SSE	45	i	1.7	15	0.54	58
						r	2.0		0.71	24
3	C		9	SSE	45	i	1.3	10	0.29	93
						r	1.2		0.40	38
	A		12	SE	65	i	1.4	10	0.87	71
						r	1.5		0.85	53
4	A	900	30	SSW	5	i	2.2	25	1.02	222
						r	2.5		1.17	78
	B	1800				i	2.1	23	1.17	132
						r	2.6		1.60	44
	C	4000				i	2.0	20	1.11	205
						r	2.2		1.00	12
5	D	2200	16	SSW	5	i	2.3	27	1.61	274
						r	2.5		1.83	143
6	B		10	SW	15	i	2.2	23	1.10	306
							2.2		1.39	105

i=incident r=reflected * $L=5.12T^2$

from the shoreline and from examination of the aerial photographs. The frequency with which reflected waves are discernible on the east side of the basin is markedly less than on the opposite shore, and none have been identified more than about 3000 feet from the bridge. However, on the west shore under favorable conditions reflected waves, usually in groups, can be detected as far as Denny Blaine (see Figure 2) which is about 8000 feet from the source. This distance would match H_3=0.4 feet on Figure 2.

Comparison of Analysis with Observations - The analysis assumes the winds to be constant in magnitude and direction, that the incident wave crests are normal to the wind vector, and that no energy (a known reflection coefficient could be accommodated) is lost in the reflection process at the barrier. None of these stipulations is strictly true, of course. Observations show that the waves do not grow uni-directionally as implied in the analysis and as illustrated on Figure 2, but tend to develop in a sector about 20° or so to either side of the mean wind direction. The steering effect of the lake valley does not seem to allow the angular spread up to 45° as referred to by Wiegel (1964, p. 230). Wave systems were difficult to categorize visually when the wind was especially gusty; no measure of turbulence levels was available.

The predicted heights of the reflected waves with distance from the barrier were in qualitative agreement with the observations up to the stage when breaking at the barrier became significant. The distance to the "zero-height" also agrees with the comments from observant sailors of small boats who notice the effect of the extra wave system on the trimming of their craft for optimum performance. When the analysis is matched to the wind speed, frequency and directional data, it does substantiate quite properly the observations concerning the relative frequencies of occurrence and upwind travel of reflected waves on the two sides of the lake. The heights and periods of the reflected waves were sampled under several different wind conditions, but the data needed to evaluate the energy spectra of these waves could not be acquired with the equipment available. Therefore, the change in the energy of the reflected system with distance from the source has not been evaluated.

CONCLUSIONS

The prediction analysis foretold quite well the general limits of travel of the reflected waves and the regions they influence as a function of wind speed and direction so long as the reflection process did not entail significant loss of energy in the reflection process. The analysis could be modified to correct for a known reflection coefficient. Both the analysis and observations indicate that the reflected waves in deep water can be identified for a considerable distance from their source; in some situations these waves could be an undersirable component and designs should be sought to minimize their effect on the environment. A more extensive and detailed set of field observations is needed to answer some questions raised by the study concerning (1) the reflection characteristics of the barrier as dependent upon incident wave height and direction, and (2) the energy spectrum in the reflected wave system at various distances from the source.

REFERENCES

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2. Bretschneider, C. L., "Revisions in Wave Forecasting; Deep and Shallow Water," Proc. Sixth Conference on Coastal Engineering, 1958.

3. Wiegel, Robert L., Oceanographical Engineering, Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 1964.

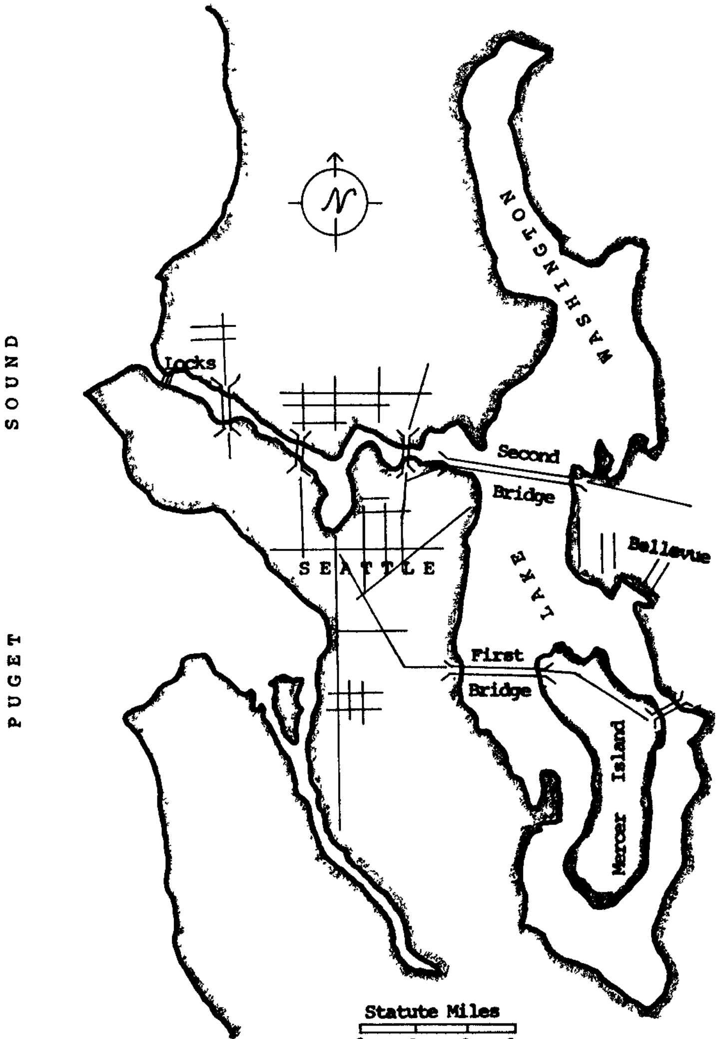
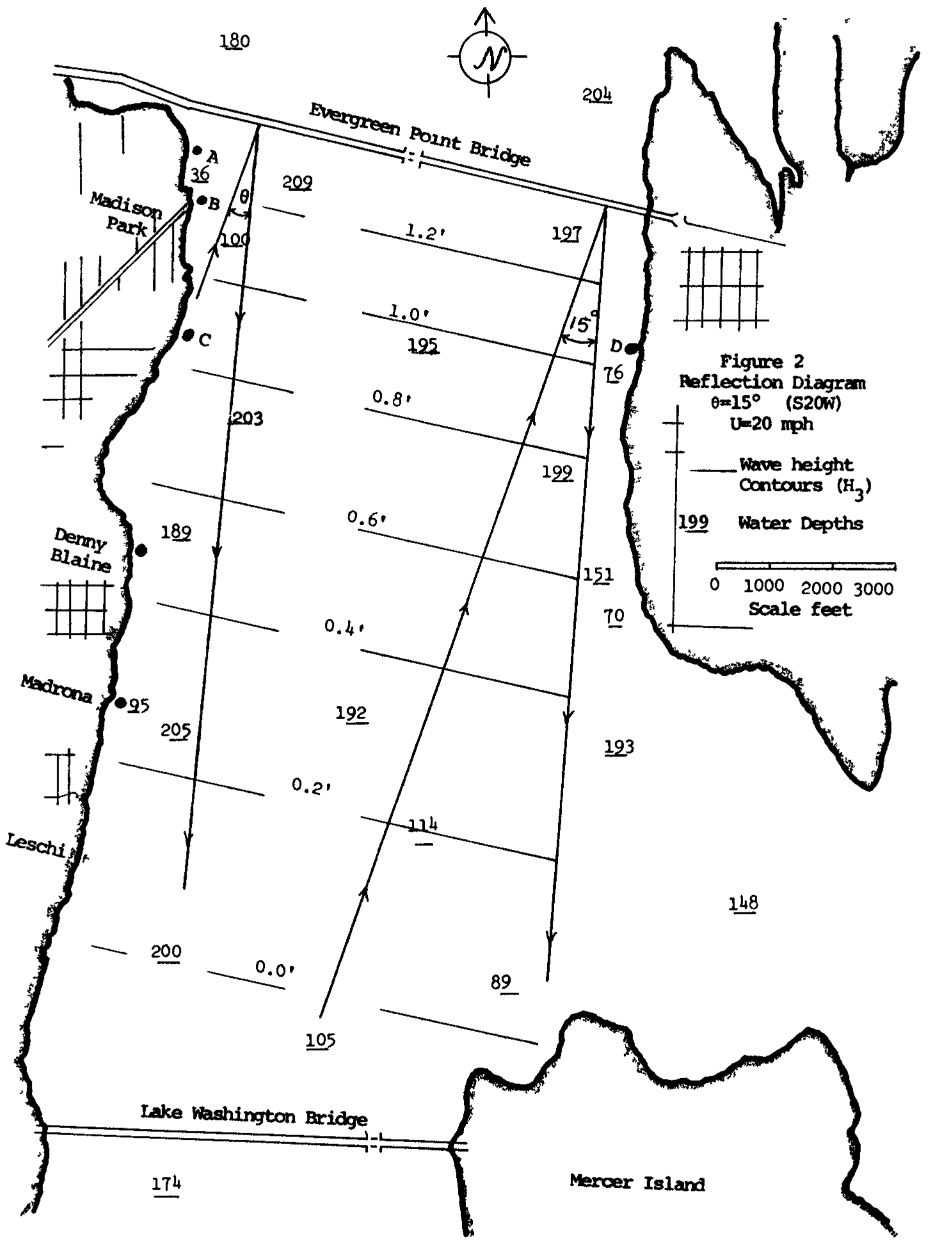


Figure 1. Location Map


180
204
Evergreen Point Bridge
A
36
B
Madison Park
θ
209
100
1.2'
197
C
1.0'
15°
195
D
76
Figure 2
Reflection Diagram
θ=15° (S20W)
U=20 mph
Wave height Contours (H_3)
199 Water Depths
0 1000 2000 3000
Scale feet
0.8'
203
192
189
Denny Blaine
0.6'
151
70
0.4'
Madrona
95
205
192
193
0.2'
114
Leschi
148
200
0.0'
89
105
Lake Washington Bridge
174
Mercer Island

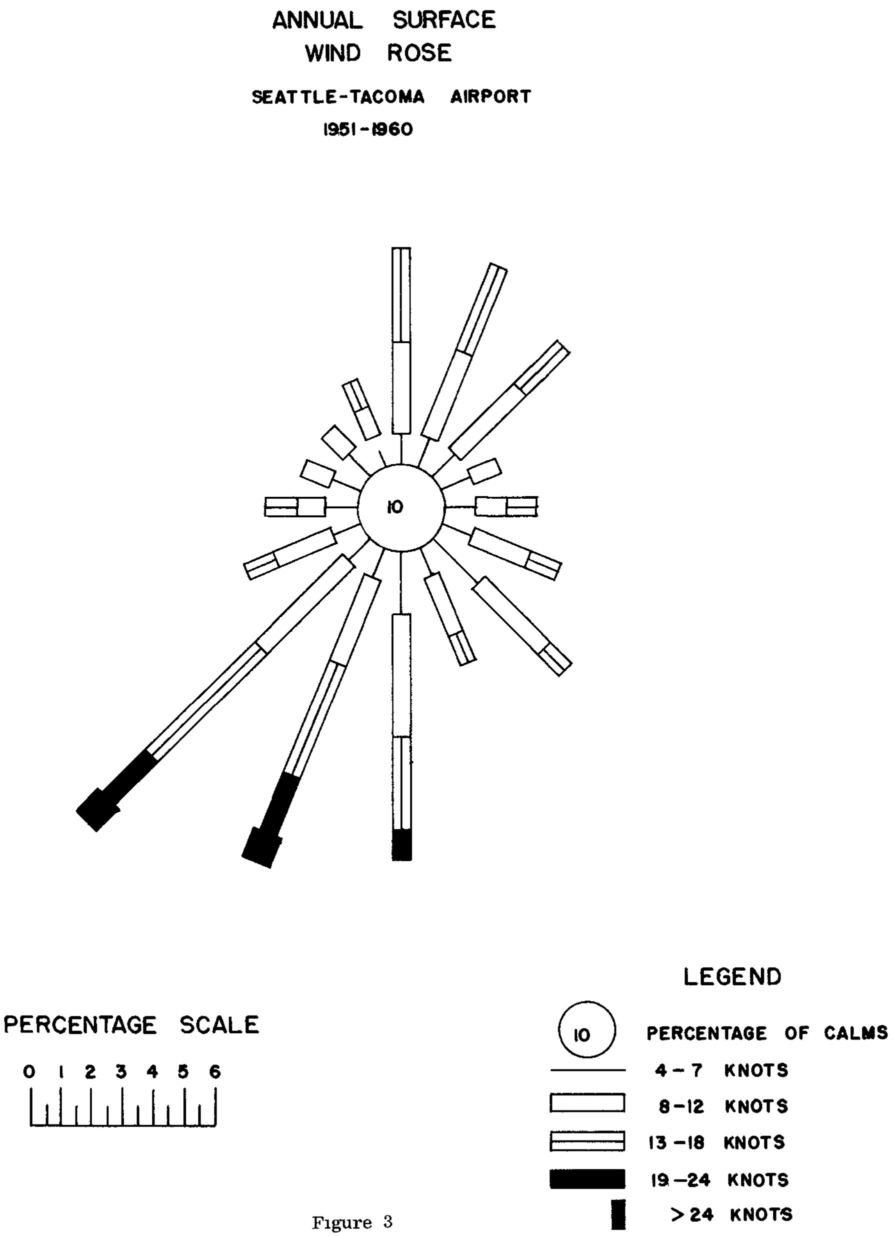

ANNUAL SURFACE
WIND ROSE
SEATTLE-TACOMA AIRPORT
1951-1960
10
PERCENTAGE SCALE
0 1 2 3 4 5 6
LEGEND
10
PERCENTAGE OF CALMS
4 – 7 KNOTS
8 – 12 KNOTS
13 – 18 KNOTS
19 – 24 KNOTS
> 24 KNOTS

Figure 3

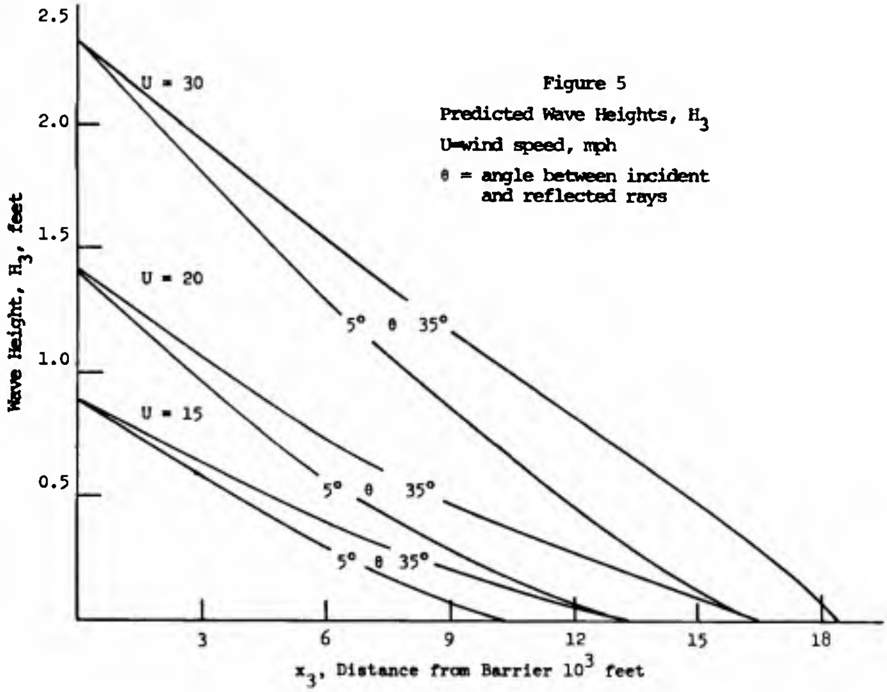


Figure 6. Waves at Madison Beach

Figure 7. Evergreen Point Bridge, U=20 mph

Figure 8. Evergreen Point Bridge U=40+mph

Figure 9. Evergreen Point Bridge U=40+mph