CHAPTER 4

THE CHARACTERISTICS OF WIND-WAVES GENERATED IN THE LABORATORY

by

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A B S T R A C T

Wind-wave characteristics were recorded in the laboratory for the primary purposes of (a) analysis of the probability distribution of wave height and wave period with wind speed, water depth, and fetch length as major parameters, and (b) comparison of the test results with existing theory and empirical formulae.

An important aspect of this study was to test the validity of the Tucker and Draper method (Draper, 1966) for the presentation of ocean wave data as applicable to wave-data analysis for simulated wind waves. It was interesting to note that some corrections were necessary when the method proposed by Draper at the 10th Coastal Engineering Conference was used for analyzing waves generated in the laboratory. Approximately a positive 20% correction was necessary for this study in which the wave spectra distribution is of very narrow range, the wave width parameter $\varepsilon = \sqrt{1-(T_c/T_z)^2}$ varies from 0.25 to 0.50, where T_c and T_z represent crest wave period and zero-crossing wave period, respectively. However, only a negative 5% correction was necessary when the method was used to analyze sea waves (ε = 0 73 to 0 76) measured off the shoreline near Look Laboratory Therefore, it was concluded that the Tucker and Draper Method is quite feasible for engineering purposes in analyzing wind-waves having a spectral width parameter of 0.60 to 0.75

The experimental data were compared with those wave heights predicted by the Darbyshire formulas (Francis, 1959) developed for ocean waves. A significant correction factor was necessary for laboratory waves produced by low-speed winds.

The "fetch graph" was prepared and compared with those developed theoretically by Hino (1966) and empirically by Ijima and Tang (1966) at the 10th Conference on Coastal Engineering, Tokyo, Japan Comparison was also made with the previous empirical formulae by Bretschneider (1951, 1957), Sverdrup and Munk (1947), and Wilson (1961,1962). The experimental results compared well with the Hino theory for both wave heights and wave periods, and fairly well with Bretschneider's fetch graph for wave heights The difference in the comparison of wave data with other investigators is illustrated in this paper.

It is recommended that further study be made with emphasis on (a) theoretical and experimental studies of wind-wave characteristics on pre-existing waves, particularly moving storms, (b) wave-energy spectra involving stochastic characteristics and extreme values of wind waves

INTRODUCTION

Wind-generated water waves are considered the most significant phenomenon confronted by ocean engineers in the design of protective shoreline structures and the prediction of response of offshore floating structures moored in the open sea This type of wave is distributed in random form compared to the long-period waves generated from an artificial disturbance, such as earthquakes and underwater explosions. The spectrum of the wind-waves varies with wind speed, wind duration, and fetch over which the wind blows. The topography of the local ocean bottom is often the governing factor in the modification of wave spectra in shallow water.

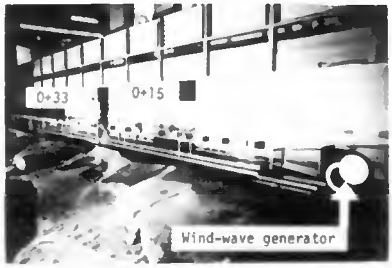
One of the problems is how to present the wave data in forms which can be used by ocean engineers for design purposes. The most widely accepted method is the use of the significant wave (i e., the average of the highest one-third of the waves) as the design wave. The significant wave may be determined from field measurements during several storms, or it can be predicted by wave forecasting or hindcasting techniques, such as those suggested by Sverdrup-Munk-Bretschneider (1951, 1957), Pierson-Neumann-James (1955) and Darbyshire (1963). Based on the significant wave, many shore structures have been designed with certain safety factors. In recent years, some questions have been raised as to whether or not a structure should be designed for maximum wave height (extreme values), allowing due consideration for the frequency distribution. The distribution of wave periods becomes more important when resonance is of major concern Therefore, the method of presenting wave data requires further investigation in order to provide ocean engineers not only with significant wave data, but with extreme values and frequency distribution as well.

At the 10th International Conference on Coastal Engineering in Japan, L. Draper (1966) presented a method of analyzing and presenting sea-wave data as a plea for uniformity. The method is simple and meritorious in sea-wave applications, but its validity as applied to simulated wind waves generated in the laboratory needed to be determined. This paper describes the experimental results of wind-wave characteristics obtained by this author who has applied this method for both laboratory and sea waves. The data have also been compared with existing theoretical and empirical formulae which are commonly used in coastal engineering

The primary objectives of the experimental investigation are to· (a) analyze the frequency distribution of wind-waves simulated in the laboratory and/or measured in the Pacific Ocean; and (b) compare the test results with existing methods of wave prediction by theoretical or semi-empirical approaches, (c) evaluate the applicability of the simplified Tucker and Draper method for analyzing wind-waves generated in the laboratory and/or ocean; (d) calibrate the pilot wind-wave flume and establish criteria for the wave-generating mechanism of the large wind-wave flume.

EXPERIMENTAL EQUIPMENT

The laboratory experiments were conducted in a wind-wave flume (9 inches wide, 13 inches high, and 48 feet long) with a blower-generator capable of simulating wind speeds from 9 to 44 feet/second (Fig. 1). The flume is a pilot model of a large wind-wave flume (4 feet wide, 6.25 feet high, and 180 feet



(a) View from wind-wave generator end

(b) View from absorbing-beach end

Fig. 1 - The pilot wind-wave flume

long) being constructed at the Look Laboratory of Oceanographic Engineering. The wind speed depends on the blowing opening; water depth, and fetch length in the flume.

A plexiglas absorbing-beach of 1:12 slope is located at the leeward end of the flume. Wave height and wave period pick-ups were installed at two stations having a fetch length of 15 feet (0 + 15) and of 33 feet (0 + 33), respectively, from the wind-generator. Two wave gages of submerged electrode type and a direct-writing oscillograph were used to sense and record the waves. A pitot-tube was used to measure wind velocity pressure, which in turn determines the wind speed. The pressure was read from a portable manometer. The effects of temperature and barometric pressure were insignificant. Wind velocities were measured at both fetch stations with a number of measurements sufficient to define the profiles along three vertical sections.

EXPERIMENT PROCEDURE AND TEST RESULTS

The preliminary tests included the measurements of wind speeds, wave heights, and wave periods as a function of blower opening, water depth, and fetch distance along the flume A relationship between the wind speed and blower opening was established. Twenty-two test conditions were formulated with four water depths and six wind speeds for each depth. A thorough analysis of wave characteristics in a water depth of 4 inches was made and compared with the values computed by the Tucker and Draper method (Draper, 1966) developed for analyzing ocean waves at the National Institute of Oceanography, England.

Since the wind-waves generated in the pilot flume are of narrow spectral distribution, no attempt has been made to conduct a power-spectral analysis of the wave data collected Instead, only a spectral width parameter based on the reproducibility of wind-waves in the flume is presented. It was found that the reproductivity of wind-waves is valid with relation to the significant wave heights and periods. However, there are some discrepancies in the wave spectral width parameters. It is planned to collect more wave data to facilitate the analysis of extreme values and to study the dependence of wind-wave characteristics on pre-existing waves, includeing the effect of moving storms

The test results showing the relationship between average wind speeds and blower openings are presented in Fig 2. It should be noted that the average wind speeds at Station 0+33 (33 feet along the flume from the wind-wave generator) are generally higher than those measured at Station 0+15 because the cross section of the air stream at Station 0+33 was decreased as higher waves were presented, thus increasing the wind speed above water surface for a given discharge of air flow During the tests, the wind speed for each run was gradually brought up to the desired level in order to avoid undesirable surges in the flume. This procedure was also necessary in order to have the wind-wave system developed in a reasonably short time

The average magnitudes of wave heights equal to or greater than 10 percent, 33 percent, 50 percent and 100 percent of all waves measured are compared in Fig. 3.

The significant wave heights as a function of wind speed, fetch location, and water depth are compared in Fig. 4. The maximum significant wave height measured under various test conditions varied from 0 9 to 1.9 inches at the fetch Station 0+33, and from 0 55 to 1.4 inches at Station 0+15. Similarly, the relationship between wave period and wind speed for the different fetch locations and water depths is compared in Figs. 5 and 6. The average wave period varies from 0.43 to 0.66 seconds at Station 0+33 and from 0.26 to 0.52 seconds at Station 0+15 It is shown that wave period increases with wind speed and fetch. Generally, the measured wave heights and wave periods increase with wind speed. However, they tend to decrease when wind speed reacher certain values, as shown in Figs 4 and 6. This is perhaps because of the turbulance of the water surface for higher wind speeds. The relationship between significant wave heights and mean wave periods is shown in Fig. 7. The experimental

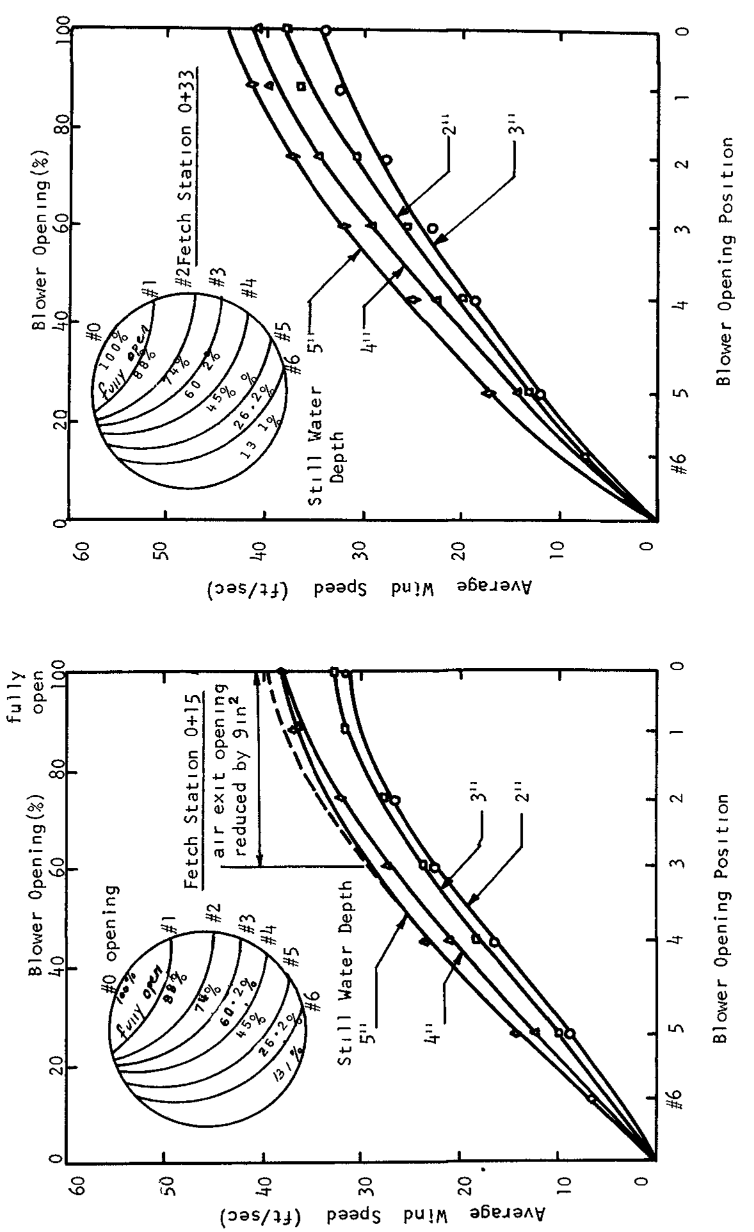


Fig. 2. Wind speed versus blower opening at the fetch Stations 0+15 and 0+33

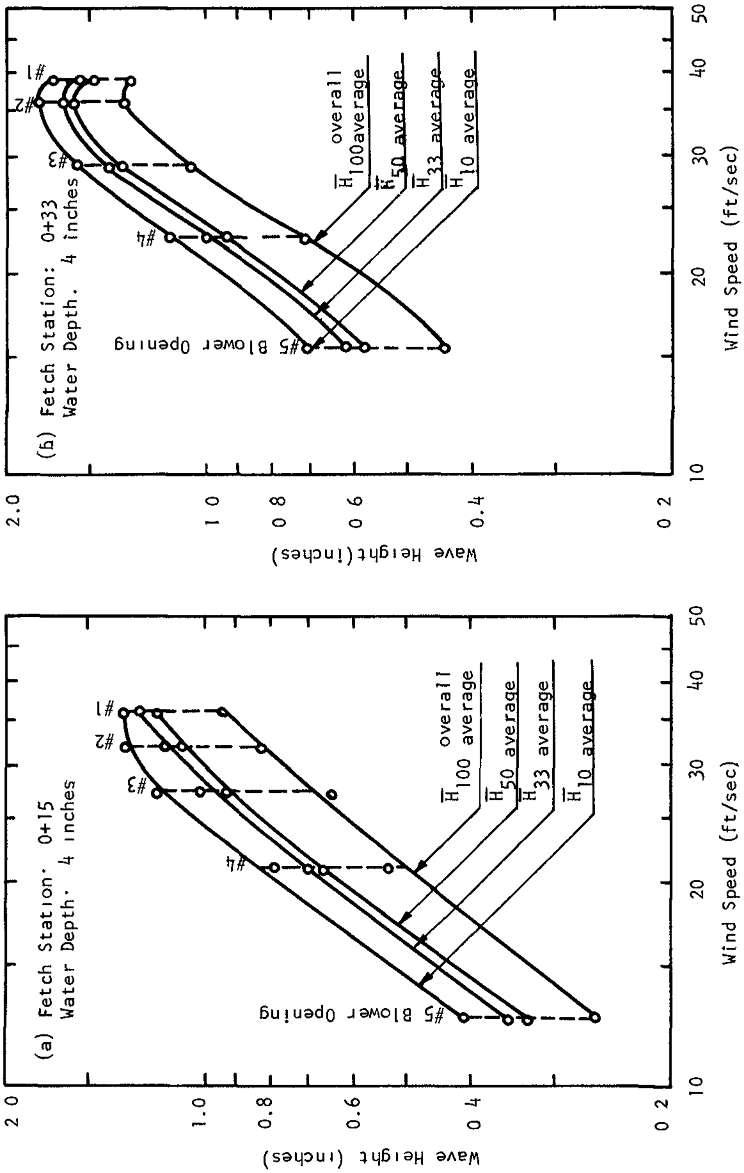


Fig 3 Wave height versus wind speed at fetch stations 0+15 and 0+33 (Water depth 4 inches)

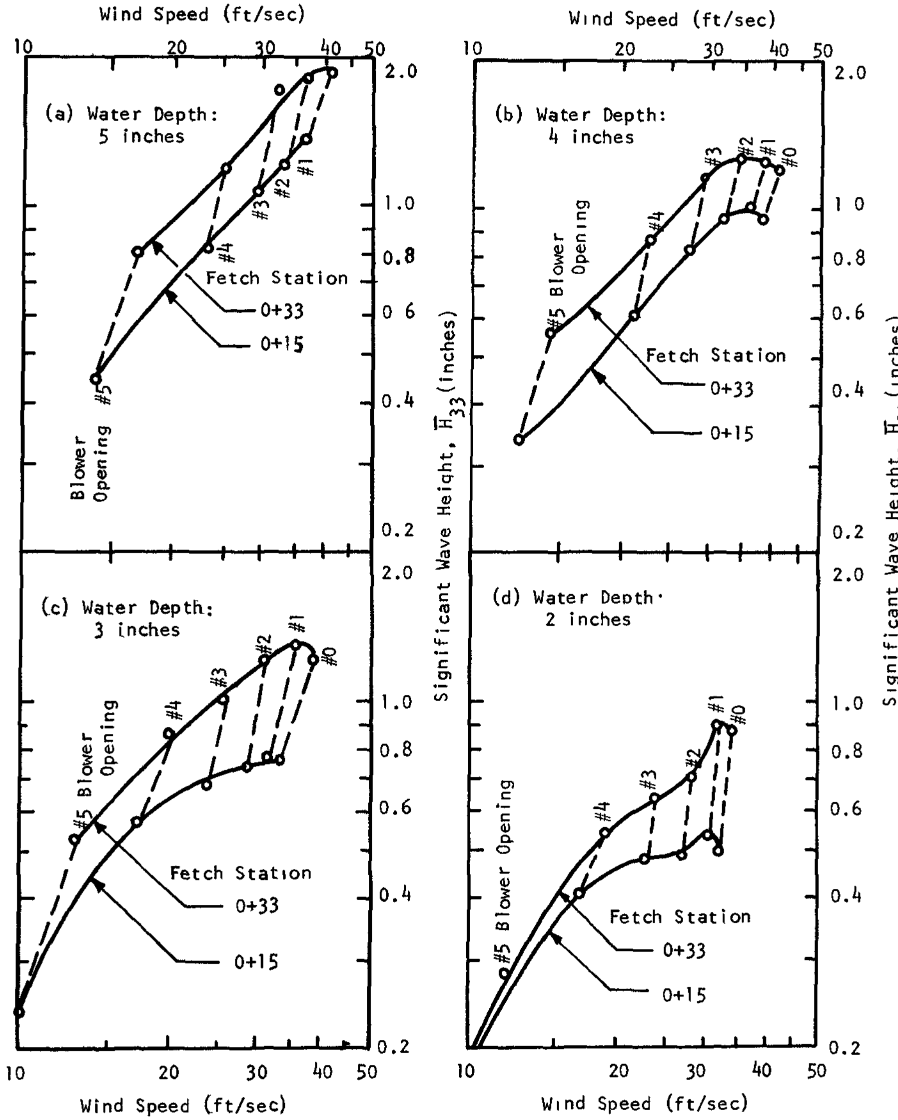


Fig. 4 Comparison of significant wave heights between the fetch stations 0+15 and 0+33

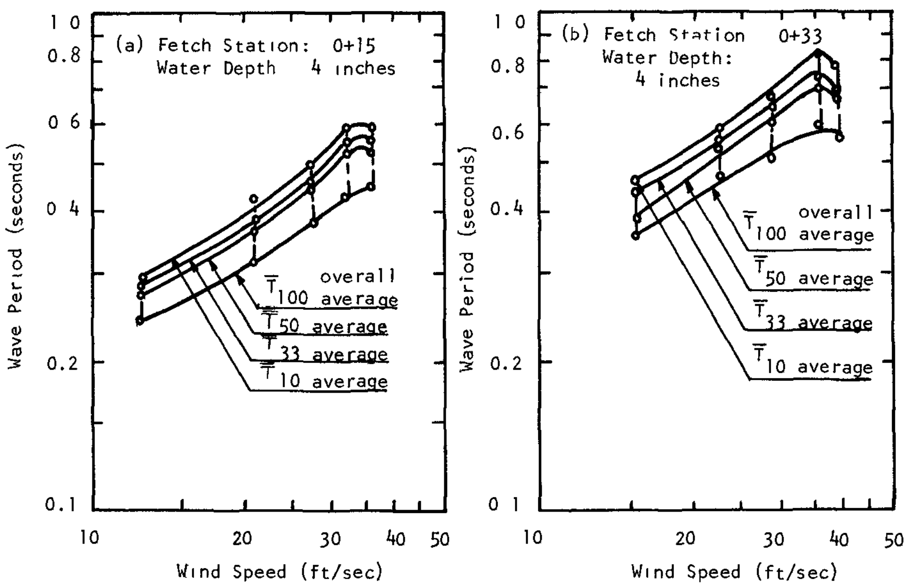


Fig. 5 Wave period versus wind speed at the fetch stations 0+15 and 0+33 (Water depth: 4 inches)

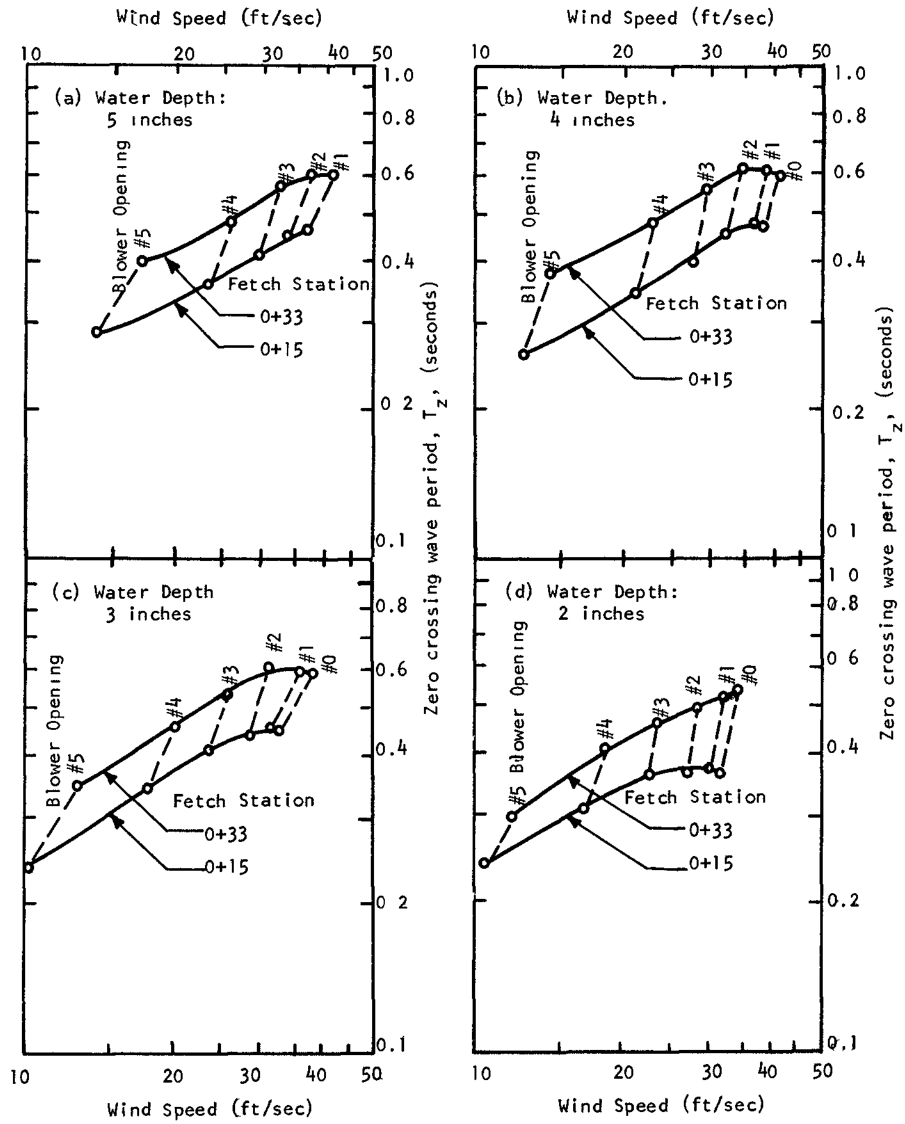
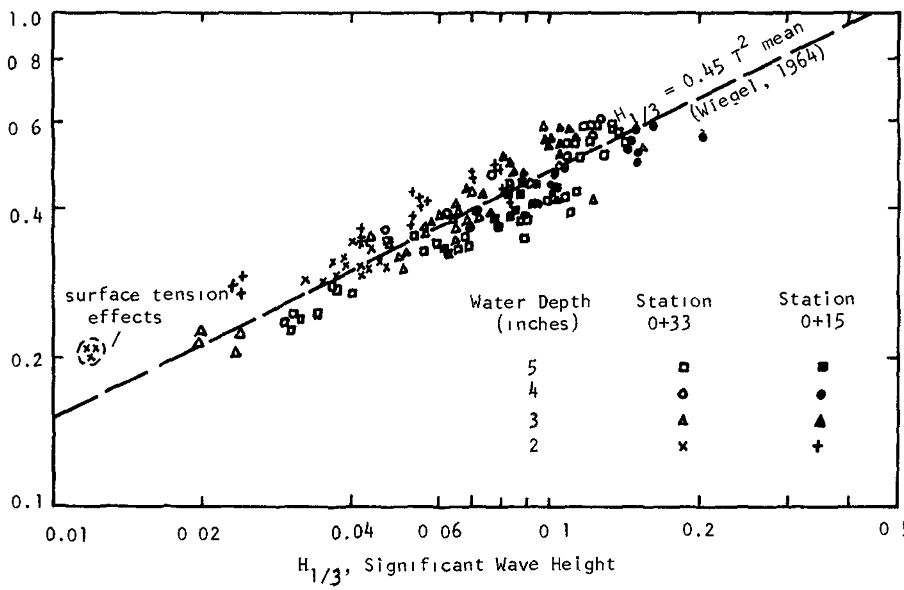


Fig. 6 Comparison of zero-crossing wave periods between the fetch stations 0+15 and 0+33



NOTE The relationship of $H_{1/3} = 0.45\ T^2_{mean}$ was established by Weigel (1964) and based on Sibul (1955) experimental data collected in the wind-wave flume of the University of California, Berkeley, Calif.

Fig. 7 Relationship between significant wave height and average wave period.

data coincided very well with the empirical formula ($H_{1/3} = 0.45\ T^2_{mean}$) proposed by Wiegel (1964) and depicted in the figure as a dashed line.

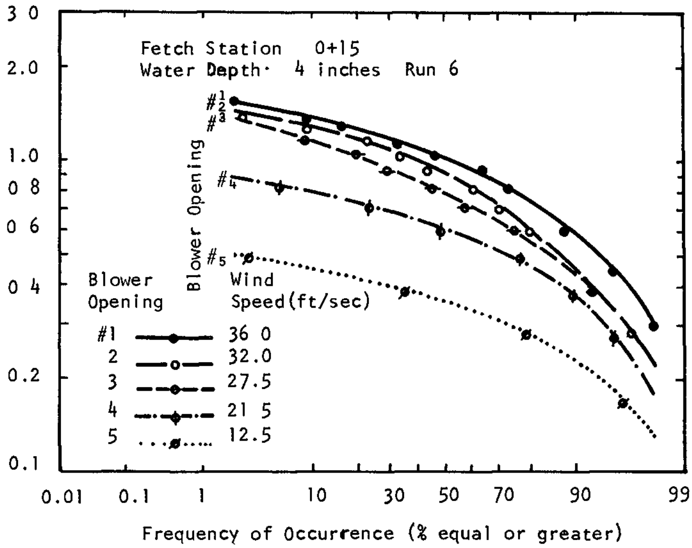
FREQUENCY ANALYSIS OF WAVE HEIGHT AND WAVE PERIOD

A thorough analysis was made of the frequency of occurrence of wave heights and wave periods for run No. 6, during which time the still water depth was maintained at 4 inches and tests were conducted for five wind conditions. The frequency of occurrence or percentage of excess for the two fetch locations was compared to the significant wave heights and wave periods (Figs. 8 and 9). On the average, the wave height and wave period measured at Station 0+33 were 14 percent greater than at Station 0+15

ANALYSIS OF WAVE DATA BY TUCKER AND DRAPER METHOD

The experimental wave data were further analyzed by a method developed by the National Institute of Oceanography, England (Tucker, 1961; Draper, 1966). According to Draper, this method of analysis is the result of theoretical studies of the statistical properties of sea waves and the analysis of numerous wave data collected in the sea, with due consideration of the results of many users. Because of the simplicity of the method, which is of merit in field applications, it is considered advisable to analyze the wave data collected in the laboratory in order to determine the validity of the technique, i e , to determine whether or not it is equally applicable to both sea waves and wind-waves generated in the laboratory The general procedure of analysis is given in Appendix A.

Comparing the significant wave heights as determined from the Tucker and Draper method and from normal frequency analysis, it was found that a positive correction of approximately 21% was necessary for wind-waves generated in the Look Laboratory, of which the wave-spectra distribution was of very narrow range; $H_{max} = 1.3\ H_s$ against $H_{max} = 1.6\ H_s$ for sea waves The wave spectral width parameter, $\varepsilon = \sqrt{1 - (T_c/T_z)^2}$ varied from 0.25 to 0.50, where T_c is crest wave period, and T_z is zero-crossing period. This means that the significant wave heights were approximately 21% underestimated by the Tucker and Draper method. However, the significant heights of sea-waves off the Look Laboratory as computed by this method were very close to the actual values needed; this is within engineering accuracy. In this case, the sea-waves have a larger wave spectral width parameter of 0.73 to 0.76 than the wind-waves simulated in the laboratory (ε = 0.25 to 0.50). Based on the above test results, the corrected significant wave height factors for data analysis by Tucker and Draper method is applicable to the laboratory and sea-waves measured at the Look Laboratory are shown in Fig 10. It may be concluded that analysis of sea-waves by the Tucker and Draper method is feasible for engineering purposes but certain corrections are necessary to analyze laboratory wind-waves, particularly of narrow wave spectra distribution. The prediction is quite satisfactory when the wave spectral width parameter is between 0.60 and 0.75.



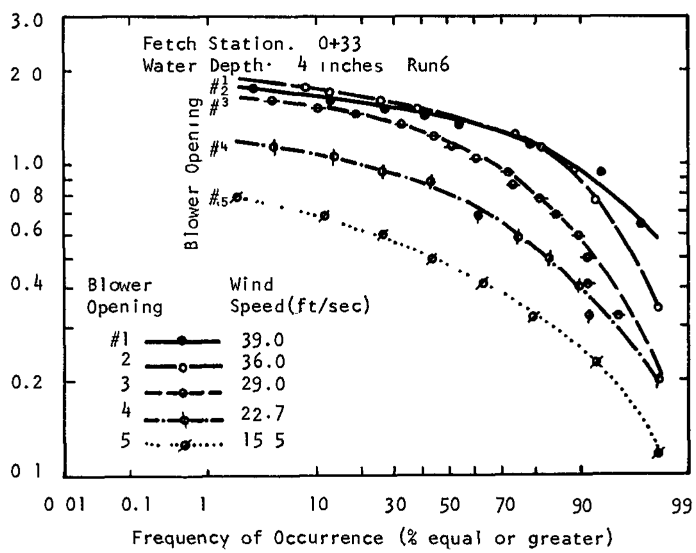
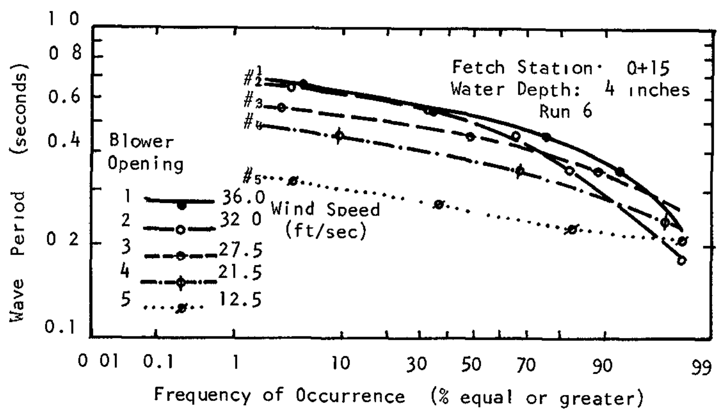


Fig 8 Frequency analysis of wave height at the fetch stations 0+15 and 0+33 (water depth: 4 inches)



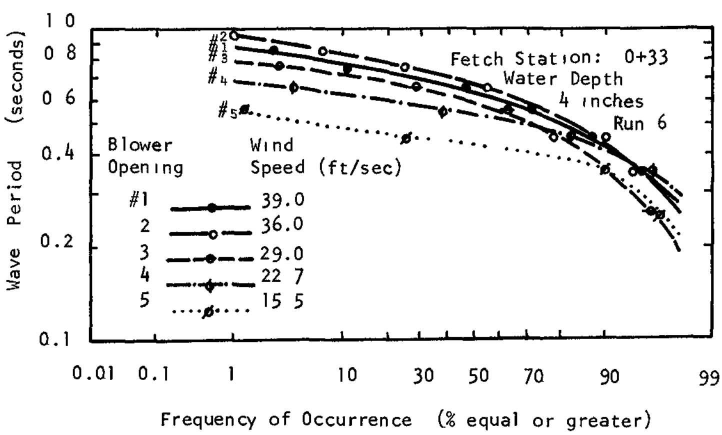


Fig 9 Frequency analysis of wave period at the fetch stations 0+15 and 0+33 (water depth. 4 inches)

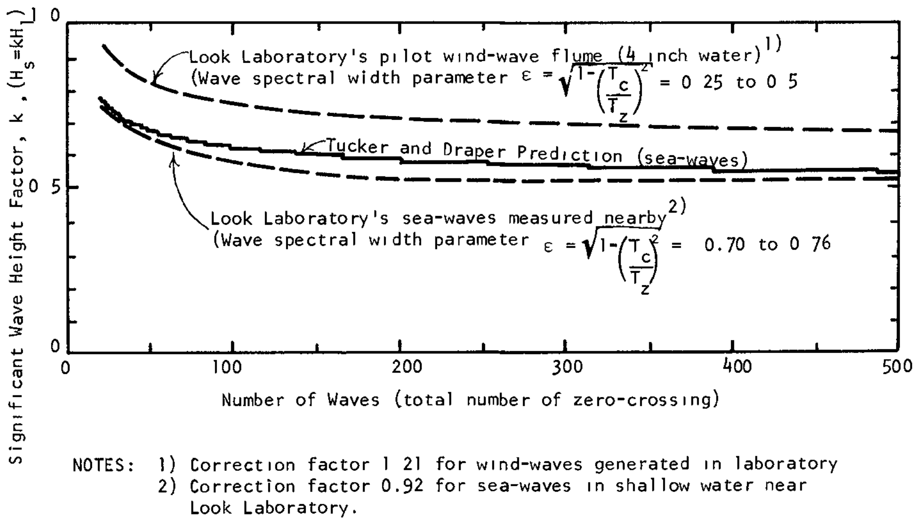


Fig 10 Significant wave height factor for data analysis by Tucker and Draper method

It must be pointed out that, according to Draper (1966), the wave heights must be corrected for: a) response of the recording instrument, and b) attenuation of waves with water depth if the wave height is measured as a function of pressure fluctuation of the sea bottom.

During this study, the response of the recording instrument was investigated by comparing the recorded wave heights at different periodic oscillations The experimental apparatus is shown in Fig 11. It consists of a mechanical drive connected to a wire-resistant wave probe excited to oscillatory motion. The amplitude of oscillation was kept constant, but the frequency of oscillation was varied in order to determine the effect of frequency response on the recorded wave amplitudes As shown in Fig 12, the recorded wave height is slightly higher for waves of high frequency (greater than 4 cps) than for waves of low frequency There was a maximum 9 percent error observed in the interval of frequencies from 1 to 10 cps However, there was no significant effect of frequency of wave heights for wave periods between 0 20 and 1.0 seconds, which covers the majority of wave periods measured under this study Therefore, it is concluded that the effect of the response of the recording instrument can be ignored, although the wave height at any frequency from 5 cps up to 10 cps could be over-estimated by 3 to 9 percent

The water level variations in the tests were sensed by wire resistance techniques. Therefore, it was not necessary to make any corrections for the attenuation of waves with water depth

A comparison of the mean zero-crossing period (T_z) and mean crest period (T_c) with average wave period was made and there proved to be no significant difference (less than 6 percent among these parameters) Therefore, it is considered advisable to use the mean zero-crossing period as the relevant average wave period for civil engineering purposes, as recommended by Draper

For engineering applications, the significant wave height and a spectral-width parameter, ε, may be used to describe the statistical distribution of wave heights. The significant wave height may be determined by the analysis of statistical distribution of waves. The spectral-width parameter, $\varepsilon = \sqrt{1-\left(\frac{T_c}{T_z}\right)^2}$, may vary from zero to unit. When ε approaches unity, the waves would cover a wide range of frequencies. For waves having a narrow range of frequencies, such as swells and tsunami waves, ε would be nearly zero

In the selection of design waves, it is customary to use maximum wave height or the average of the highest 1/10 of waves, in lieu of the significant wave height, for designing important fixed structures It is interesting to note that the ratio of the maximum wave height to the significant wave height varies from 1.2 to 1 3, as compared with 1.60 for wind-waves in the ocean, as estimated by Darbyshire and Draper (1963) This is because the laboratory-generated wind-waves have a much narrower wave spectrum than ocean waves.

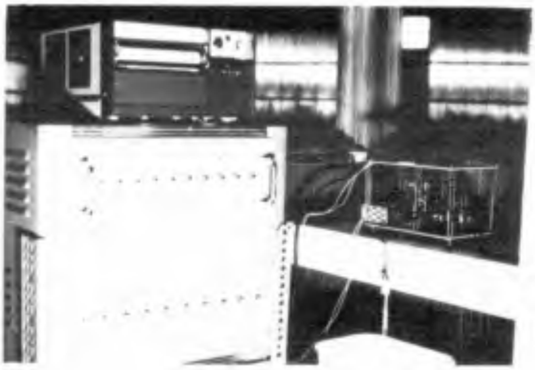


Fig. 11 Experimental apparatus for evaluation of frequency response of the wire-resistance wave gage.

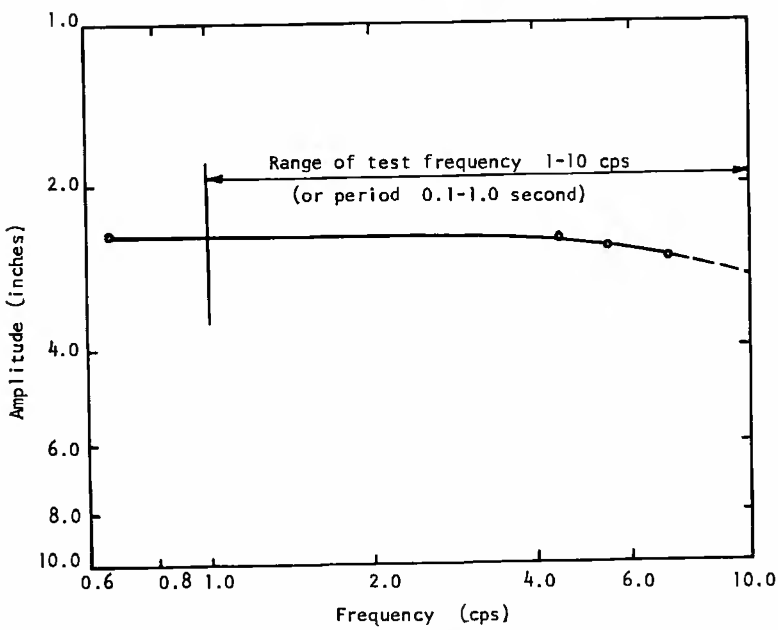


Fig. 12 Frequency response of the wire-resistance wave gage

ANALYSIS OF WAVE DATA BY THE DARBYSHIRE METHOD

The Darbyshire formula (Francis, 1959) suggested the relationship between wave height, wind speed, and fetch as follows.

$$H_{max} = 0.0076\ (1 - e^{-0.23F^{1/2}})\ U^2 \qquad (1) \qquad F^{1/2}$$

or

$$H_{max} = 0.0060\ (1 - e^{-0.003F_1^{1/2}})\ V^2 \qquad (2) \qquad F_1^{1/2}$$

where

- H = maximum wave height of 100 waves in feet
- F = fetch length in nautical miles, F_1 = fetch length in feet
- U = gradient wind speed in knots estimated to be 1 5 times the wind speed at 30 feet above the mean sea level
- V = average wind velocity in ft/sec measured over water surface in the wind-wave flume.

As shown in Fig 13, the use of the Darbyshire formula to predict the maximum height of wind-waves generated in the laboratory is feasible for high wind speeds but a significant correction factor may have to be applied for the cases of low wind speeds. Therefore, the discrepancy may have resulted from the use of 1.5 times the average wind speed at 30 feet above mean water level in the ocean. Further investigation of these aspects is necessary. Due consideration should be given the use of gradient wind speed which needs to be defined for laboratory wind waves.

In summary, the application of experimental results to field conditions should be done carefully to avoid any significant error in maximum wave prediction

FETCH GRAPH COMPARISON

The dimensionless relationships gF/U^2, gH/U^2, and $gT/2\pi U$ determined from the fetch (F), wind speed (U), and wave period (T) are referred to as "Fetch Graph." This is considered the most effective means for correlating the above variables The non-dimensional representation has facilitated the comparison of various wave data collected either in the field or in the laboratory.

The experimental results were compared with those developed theoretically by Hino (1966), and Ijima and Tang (1966) as presented at the 10th Conference on Coastal Engineering, Tokyo, Japan. Comparison was also made with the previous empirical formulae by Bretschneider (1951, 1957), Sverdrup and Munk (1947) and Wilson (1961, 1962). The data compared well with the Hino theory for both wave heights and wave periods, and fairly well with Bretschneider's fetch graph for wave heights The difference in the comparison of wave data with other investigators is shown in Figs. 14, 15, 16 and 17. The discrepancies

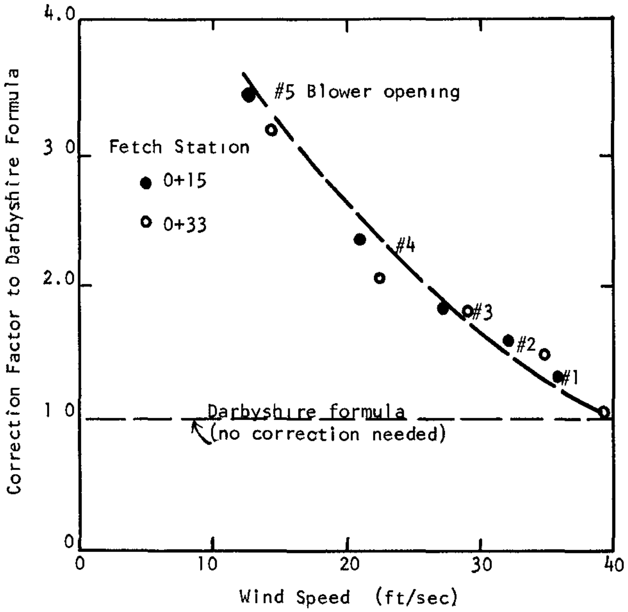


Fig. 13 Correction factor to the maximum wave height computed by Darbyshire's formula as a function of wind speed for simulated wind-waves

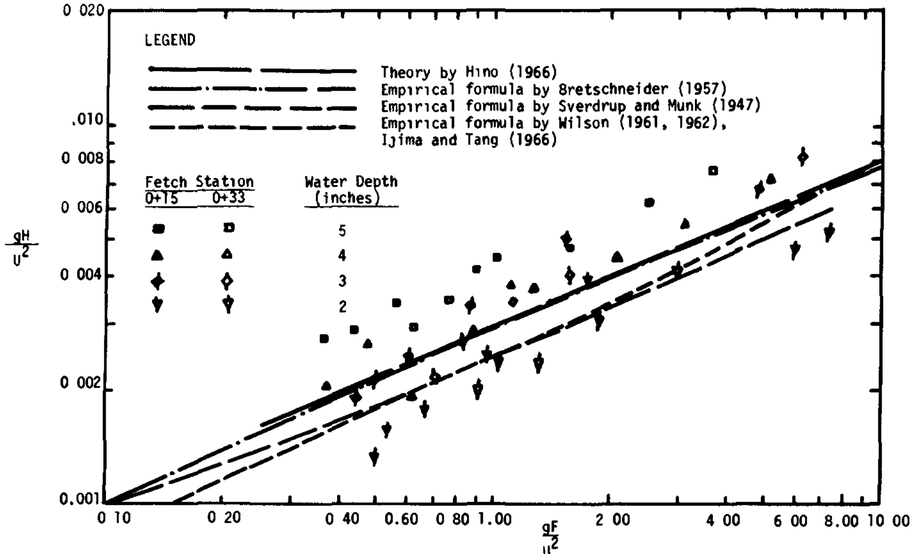


Fig. 14 FETCH GRAPH (1)

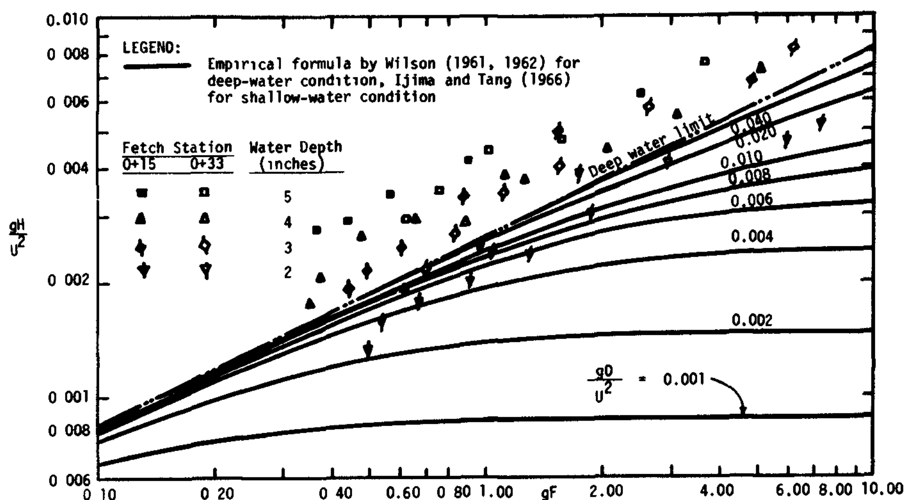


Fig. 15 FETCH GRAPH (2)

Deep Water Condition, Wilson (1961, 1962)

$$\frac{gH}{U^2} = \alpha \tanh\left[K_1\left(\frac{gF}{U^2}\right)^{1/2}\right]$$

where
$\alpha = 0.26$
$K_1 = 0.01$

Shallow Water Condition, Ijima and Tang (1966)

$$\frac{gH}{U^2} = \alpha \tanh\left[K_3\left(\frac{gd}{U^2}\right)^{3/4}\right] \tanh\left[\frac{K_1\left(\frac{gF}{U^2}\right)^{1/2}}{\tanh K_3\left(\frac{gd}{U^2}\right)^{3/4}}\right]$$

where
$K_1 = 0.578$
$K_3 = 0.01$
$\alpha = 0.26$

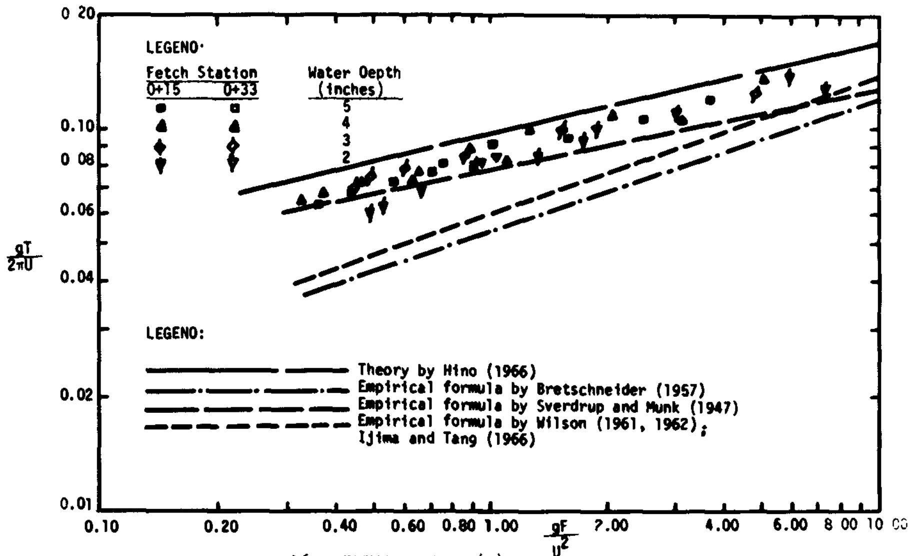


Fig. 16 FETCH GRAPH (3)

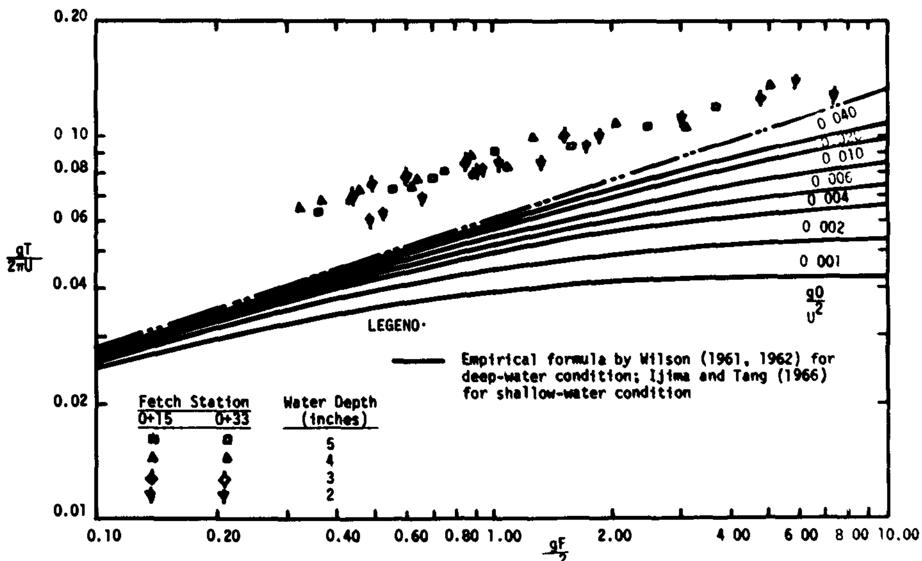


Fig. 17 FETCH GRAPH (4)

Deep Water Condition, Wilson (1961, 1962)

$$\frac{gT}{2\pi U} = \beta \tanh\left[K_2\left(\frac{gF}{U^2}\right)\right]^{1/3}$$

where:
β = 1.40
K_2 = 0.0436

Shallow Water Condtion, Ijima and Tang (1966)

$$\frac{gT}{2\pi U} = \beta \tanh\left[K_4\left(\frac{gd}{U^2}\right)\right]^{3/8} \tanh\left[\frac{K_2\left(\frac{gF}{U^2}\right)^{1/3}}{\tanh K_4\left(\frac{gd}{U^2}\right)^{1/8}}\right]$$

where
K_2 = 0.436
K_4 = 0.520
β = 1.4

are perhaps due to the fact that the wind waves generated in the laboratory were of narrow wave spectra distribution. Furthermore, the empirical coefficients as shown in Figs. 16 and 17 are being adjusted in the 1968 revision of wave forecasting (Bretschneider, 1968).

APPENDIX A

ANALYSIS OF WAVE DATA BY TUCKER AND DRAPER METHOD

The basic procedure of analysis is as follows (Draper, 1966)·

1. Select a section of wave record which covers at least 100 waves or more for the short fetch Station 0+15 during which period the waves are fully developed. The same period of time is used to analyze waves measured at the long fetch Station 0+33.

2. Wave height parameters are calculated from the sum of amplitudes measured from the mean water level to the highest crest (A) and to the lowest trough (C), regardless of whether or not the amplitudes are part of the same wave. The sum of (A) and (C) is defined as H_1. The mean water level is drawn by eye, although it could be determined more accurately by other methods such as the use of a planimeter However, experience indicated that the error introduced by determining wave periods from zero-crossing by eye is rather minor, and there will be no significant errors in the determination of wave heights and crest periods.

3 Count the number of zero crossings of the waves over the record period, (t), selected and then divide by two (2) to get N_z.

4. Compute the mean zero-crossing wave period, T_z, i.e, $T_z = \frac{t}{N_z}$.

5. Count the number of wave crests, N_c, including both those above and below mean water level.

6. Compute the mean wave period of the crests, T_c, i.e., $T_c = \frac{t}{N_c}$.

7. Compute the spectral width parameter, which is an indicator of the statistical distribution of wave periods This parameter shows that when the waves cover a wide range of frequencies or periods, the long waves will carry short waves on top of them and there will be many more wave crests, N_c, than zero-crossings N_z. Then, T_c will be much smaller than T_z and approaches unity, which indicates that the wave train has a wide wave-spectral distribution. On the other hand, if the range of frequencies is narrow, each wave crest will be associated with a zero crossing, then T_c and T_z will be approximately equal and will be close to zero (Draper, 1966).

8 Compute the significant wave height from the following relationship $H_s' = H_1$ factor The factor is determined from Fig 10, as plotted from Draper's data

9 Compare the values of significant wave heights obtained from item No 8 above with those determined from the frequency analysis described in the preceding section Fig. 17 shows the deviations; it is apparent that a correction factor of 1.21 should be entered According to Draper (1966), H_1 should be corrected for the response of the recording instrument and for the attenuation of waves with depth In this case, $H_s = H_1' \cdot$ factor and $H_s = (H_s \cdot \text{factor})\ 1.21$

10 Similarly, the zero-crossing and crest periods were compared with the average wave periods obtained from the frequency analysis described in the preceding section

11 Based on the new relationship of $H_s = (H_1 \cdot \text{factor})\ 1\ 21$, the significant wave heights were computed for the other runs under test conditions other than the 4-inch water depth in the flume

ACKNOWLEDGEMENTS

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