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PERFORMANCE ANALYSIS OF TETHERED FLOAT BREAKWATER

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INTRODUCTION

Seymour and Isaacs (6) describe a floating breakwater in which the energy is removed from the waves through the drag created by the vigorous oscillations of tethered floats. This system has been under development at the Scripps Institution of Oceanography (SIO). As shown in Seymour and Isaacs (6), an effective predictive model for the breakwater was developed. As part of this effort, a "marina-scale" breakwater was built and installed in San Diego Bay. This unit was of a scale suitable for providing protection from waves in the 2-sec-4-sec period range, typical of the wave protection problems for marinas and anchorages in semiprotected waters.

Prior to the design of this marina-scale breakwater, an intensive laboratory modeling program was undertaken. This paper describes the laboratory and field experience and the comparison of predicted and measured breakwater performance.

THEORY OF PERFORMANCE PREDICTION

Laboratory measurements of breakwater performance, described in later sections, suggest that scattering and reflection are minor contributors to the reduction of wave energy. Therefore, the model for predicting performance considers only drag dissipation.

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Fluid drag, proportional to the velocity squared, is nonlinear even in steady flows. In the case of the floats oscillating in response to the wideband random flow produced by a wave field, the drag is proportional to the square of the relative velocity—itsself a wideband random variable. It is therefore very difficult to predict the drag in a deterministic sense from some measured parameter such as the surface elevation history. As in most random processes, it proves more convenient to work in the frequency domain and to deal with the statistics of float motion and drag.

Considering a single float, its average drag power may be defined as

$$\langle P_d \rangle = C \langle |V|^3 \rangle \dots \dots \dots (1)$$

in which P_d = drag power; $\langle \rangle$ indicates time averaging; C = a drag force coefficient, $(\rho/2) A C_d$; ρ = fluid density; A = the frontal area; C_d = the drag coefficient; and $|V|$ = the magnitude of the relative velocity. By definition, if x is a Gaussian variable, the average value of $f(x)$ can be calculated by

$$\langle f(x) \rangle = \frac{1}{\sqrt{2\pi}\sigma_x} \int_{-\infty}^{\infty} f(x) e^{-x^2/(2\sigma_x^2)} dx \dots \dots \dots (2)$$

in which σ_x = the standard deviation of x . Applying Eq. 2 to evaluate $\langle |V|^3 \rangle$ yields

$$\langle |V|^3 \rangle = \frac{2\sqrt{2}}{\sqrt{\pi}} \sigma_v^3 \dots \dots \dots (3)$$

Since the variance σ_v^2 , is given by half the sum of a properly scaled spectrum of the variable, Eq. 1 can be written

$$\langle P_d \rangle = C^* \sigma_v \frac{1}{2} \Sigma S_v(f) \dots \dots \dots (4)$$

in which $S_v(f)$ = the spectrum of relative velocity; and $C^* = (2\sqrt{2}/\sqrt{\pi}) C$. From Eq. 4, assuming that the process is linear in frequency, P_d can be expressed in terms of its spectral components

$$S_{p_i} = \langle P_{d_i}(f) \rangle = C^* \sigma_v \frac{1}{2} S_{v_i}(f) \dots \dots \dots (5)$$

in which S_p = the spectrum of float drag power.

It was shown by Seymour (4) that the spectrum of relative velocity for a single float can be estimated by

$$S_v(f) = S_u \gamma(f) \dots \dots \dots (6)$$

in which $\gamma(f) = 1 + |H|^2 - 2|H| \cos \theta \dots \dots \dots (7)$

in which $|H|$ and θ are defined from the complex transfer function of float position relative to water particle horizontal motion, $H(f)$

$$H(f) = |H| e^{-i\theta(f)} \dots \dots \dots (8)$$

and S_u = the energy spectrum of horizontal water particle velocity, which can be readily obtained from the spectrum of surface elevation by linear theory

$$S_u(f) = S_\eta(f) \beta(f) \dots \dots \dots (9)$$

in which S_η = the surface elevation spectrum; $\beta(f) = \cosh^2 k(h - d_s) \omega^2 / (\sinh^2 kh)$; k = the wave number; ω = the radian frequency, $2\pi f$; h = the water depth; and d_s = the depth of the float. Therefore, combining Eqs. 5, 6, and 9 provides an expression for the spectrum of average drag power of a single float in terms of the wave spectrum

$$S_p = S_\eta \gamma \beta \dots \dots \dots (10)$$

The power consumed in the drag of the float is at the expense of the spectrum of incident wave power, which can be expressed per unit of float spacing along the wave crest

$$S_w(f) = S_\eta(f) \alpha(f) \dots \dots \dots (11)$$

in which S_w : the spectrum of wave power; $\alpha(f) = (1/2) \rho g C_n(f) s$; C_n = the group velocity; and s = the float spacing. Thus the energy transmission ratio (ETR) which is the traditional parameter for describing breakwater performance, can be specified in terms of the three coefficients

$$\text{ETR}(f) = \frac{S_w - S_p}{S_w} = 1 - \frac{\gamma \beta(f)}{\alpha} \dots \dots \dots (12)$$

In Eq. 12, only γ has dependence on the float dynamics. Both α and β depend upon the wave field alone. Seymour (4) shows a method for linearizing drag so that the equation of motion for the float can be solved to yield $H(f)$. As a result of the linearizing technique, however, $H(f)$ is a function of σ_v ,

$$|H|(f) = \left[\frac{D^2 \omega^4 + (C^* U_0 \omega)^2}{(B - M \omega^2)^2 + (C^* U_0 \omega)^2} \right]^{1/2} \dots \dots \dots (13)$$

$$\theta(f) = \arctan \frac{\omega C^* U_0}{\beta - M \omega^2} - \arctan \frac{D \omega}{C^* U_0} \dots \dots \dots (14)$$

in which $U_0 = [8/(3 \sqrt{\pi})] \sigma_v$, = a characteristic velocity for linearizing drag; $D = M_w(1 + C_m)$; $B = g/L(M_w - M_s)$; $M = C_m M_w + M_s$; M_w = mass of water displaced by the float; M_s = mass of float; L = effective tether length; and C_m = added mass coefficient.

Seymour and Isaacs (6) describe a method for solving iteratively for σ_v . In this approach, a value is assumed for σ_v , and Eqs. 13, 14 and 7 are solved to yield values of γ for each frequency band. Eq. 6 can be summed over frequency to give an estimate of σ_v^2 . The assumed value of σ_v is then adjusted until there is reasonable agreement between the assumed value and the value calculated from summing the spectrum. The final values of $\gamma(f)$ obtained in this iteration are then used in Eq. 12 to calculate $\text{ETR}(f)$. By applying the ETR values as a spectral density function to the incident spectrum, a transmitted spectrum is obtained for the first row of floats in the breakwater. The process is repeated through each row to obtain the final exiting spectrum behind the array.

Thus it has been shown that, in principle, the performance of a tethered float breakwater can be estimated knowing only the incident wave field charac-

teristics, the breakwater geometry, and appropriate average values for two coefficients, C_d and C_m .

PHYSICAL ARRANGEMENT OF EXPERIMENTS

Laboratory Model at Half Scale.—A half scale section of the San Diego Bay Field Experiment Breakwater was installed in the 40-m long Wind Wave Channel at the Hydraulics Laboratory, SIO. The general characteristics of this

TABLE 1.—Laboratory Model Breakwater at Half Scale

Variables (1)	Data (2)
Float Diameter	15.8 cm
Effective Tether Length	83.8 cm
Float Spacing (beam)	31.6 cm
Float Spacing (length)	31.6 cm
Number of Rows	11
Float Density	0.04 gm/cc
Water Depth	178 cm
Breakwater Length	239 cm
Channel Width	244 cm
Freeboard	Each Row Separately Variable

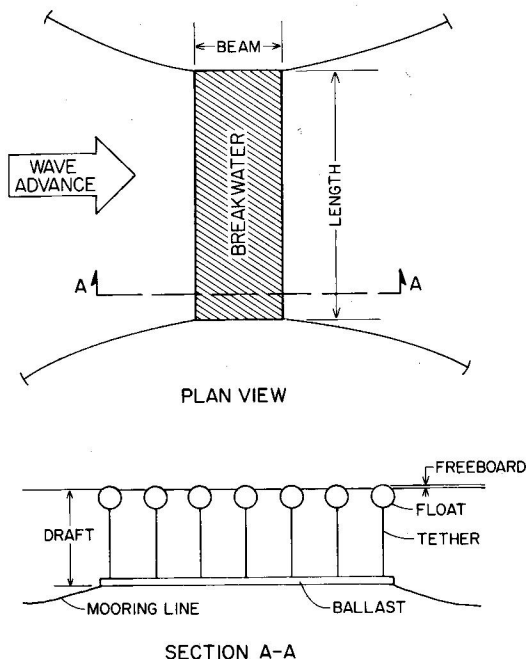


FIG. 1.—Definition Sketch: Tethered Float Breakwater

model are shown in Table 1. The nomenclature is defined in Fig. 1. Fig. 2 shows a model of similar scale in the wave channel.

The model was slack-moored by a single mooring line extending toward the wave generator. The slow currents set up by the generation of waves result in a net motion of the breakwater toward the beach. Thus, the mooring line might occasionally become taut for short periods of time.

Wave heights were measured with surface-piercing digital wave staffs having 5-mm resolution. The outputs of the wave staffs were sampled at 16 Hz and stored in core by an IBM 1130 computer. After storing 2,048 samples of each of two wave staffs, the records were transferred to magnetic tape.

San Diego Bay Field Experiment.—A 46-m length of breakwater, twice the scale of the laboratory section, was installed in San Diego near Point Loma. The breakwater was subjected to ship and boat wakes generated in the main entrance channel to San Diego Bay and to limited fetch wind waves when

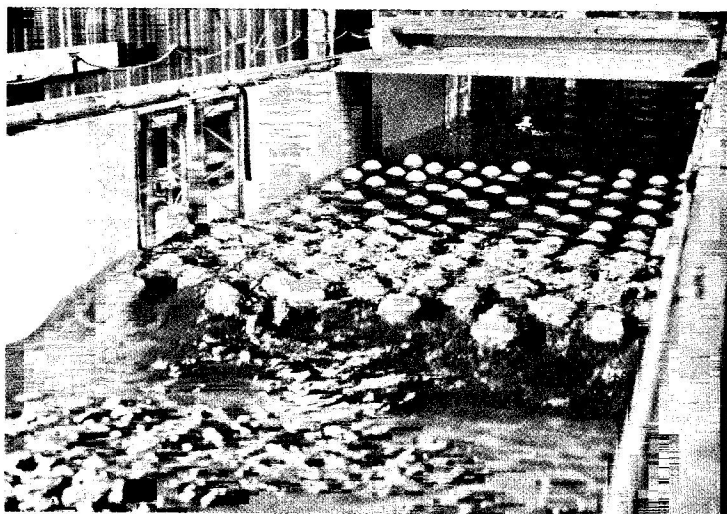


FIG. 2.—Model Tethered Float Breakwater in Wave Channel

winds from the south occurred. The breakwater was protected from ocean-generated waves because it was located on the lee side of Point Loma.

A detailed description of the configuration, construction, and installation of this breakwater is contained in Berkley and Johnson (1). The wind wave attenuation performance is shown in Fig. 3, and the physical arrangement is shown in Fig. 4.

Table 2 defines the basic characteristics of this installation. The breakwater was slack-moored with three lines forward and three lines aft at approx 12-m intervals. Lateral restraint was supplied by slack moors at each end of the system. The tide range is approx 2 m, and tidal currents reach a maximum value of about 1 m/sec.

Incident and transmitted wave heights were measured by dual wire resistance gages mounted on tilting spars pivoting on gravity anchors at the bottom. These

gages were connected by submerged cables to a van onshore. There, the signals were digitized, multiplexed, and transmitted over a leased telephone line on command from a dedicated minicomputer at Scripps Institution of Oceanography. The gages were located approximately equidistant from the ends of the breakwater and about 15 m away from the nominal breakwater position, one in front and one behind.

Extended Tether Laboratory Model.—A second laboratory breakwater model was evaluated in which all of the physical parameters were identical to the half-scale model described previously, except that the tether length was increased to 134.6 cm.

WAVE CLIMATE

Laboratory Experiments.—The laboratory breakwater experiments were conducted using simulated random seas generated in response to magnetic tape control. The methodology for producing these broad-band random wave spectra



FIG. 3.—Wind Wave Attenuation in San Diego Bay Field Experiment

is described in Seymour (7). A series of eight tapes was employed for these experiments. The statistics of each are shown in Table 3. These are derived from bare-channel measurements made with the breakwater removed. The significant wave height, H_s , is calculated from $H_s = 4 \sigma_\eta$ and H_m , the maximum wave height, is taken as the difference between the maximum and minimum excursions from the mean during the experiment.

For the shorter period wave trains, Tapes T1, T2, and T3, it was possible to maintain the H_m/H_s ratio close to the nearly constant oceanic value of 1.65 reported by Goda (2). For longer period wave trains the wave generator efficiency limited the attainable H_m/H_s ratios. The measured spectra of these wave trains are shown in Fig. 5.

The wave generator control voltages were provided by one track of a two-track tape deck. By means of a computer start signal on the second track, wave data were recorded at identical intervals in the time series. This ensured that incident waves characterized in a bare-channel experiment would be exactly

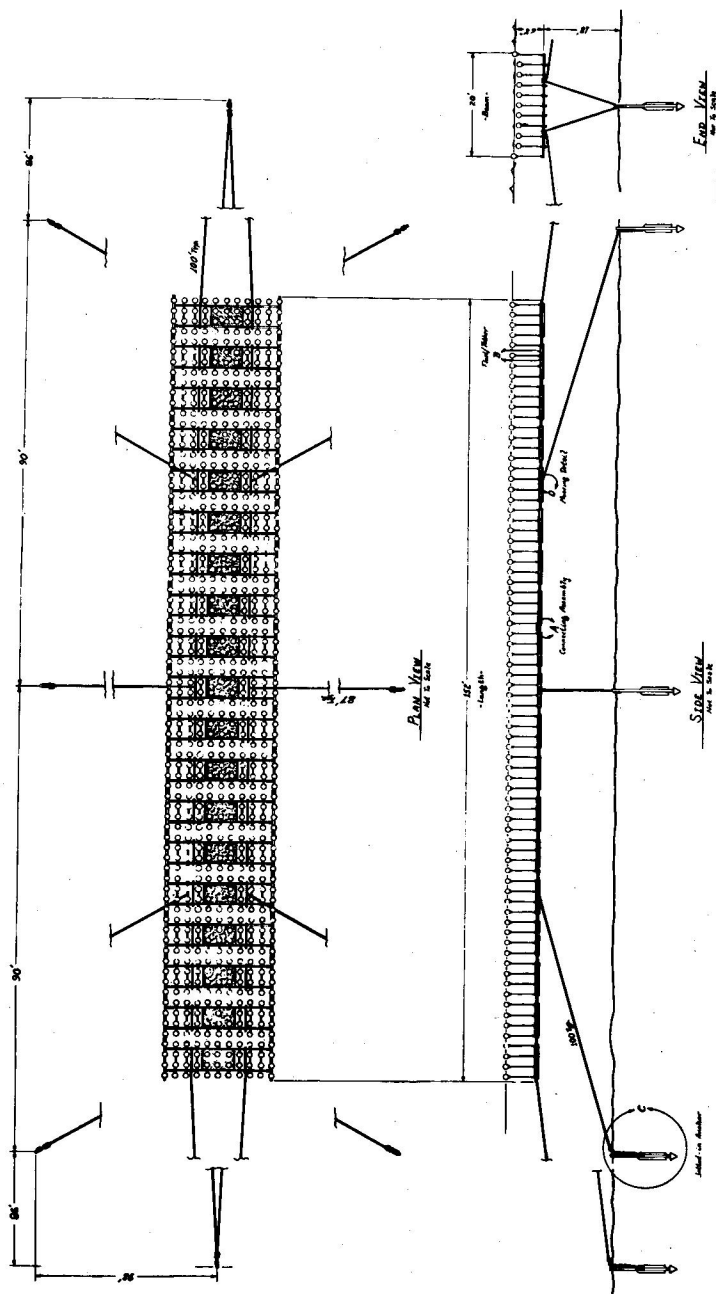


FIG. 4.—Arrangement of San Diego Bay Breakwater

reproduced with the breakwater in place.

San Diego Bay Experiments.—Significant south wind activity was observed at the Point Loma site only twice in the 8-month span of this experiment. The two storm periods that were recorded occurred on January 22 and February 9, 1976. On the January 22 occurrence, the wind rose from calm at 0945 a.m. PST to a maximum of 22 knots at 1015 a.m., varying between 12 knots and 16 knots from 1100 a.m.–1245 p.m. The direction was constant from 180°. On February 9, the wind direction varied from 180°–200°. The peak speed was 20 knots between 0930 a.m. and 1015 a.m. and continued to exceed 12 knots through 1700 p.m.

Ten experiments were obtained on January 22, each with 4,096 samples taken at approx 5.11 Hz, in the interval between 1024 a.m. and 1300 p.m. PST. These experiments were designated S1 through S10. The incident wave spectra for these runs are shown in Fig. 6(a).

A total of 16 experiments were recorded on February 9. Three were in the morning between 1000 a.m. and 1130 a.m. and 13 in the afternoon between

TABLE 2.—San Diego Bay Field Experiment

Variables (1)	Data (2)
Float Diameter	29.2 cm
Effective Tether Length	168 cm
Float Spacing (beam)	61 cm
Float Spacing (length)	61 cm
Number of Rows	11
Float Density	0.085 gm/cc
Water Depth	approx. 8 m
Breakwater Beam	6 m
Breakwater Length	46 m
Freeboard	positive 15 cm (front and rear rows); negative 7.5 cm (interior nine rows)
Positive Buoyancy	approx. 10% of float volume

1340 p.m. and 1700 p.m. These runs were designated S11 through S26. The incident wave spectra are shown in Fig. 6(b).

These spectra are quite broad, bearing little resemblance to the sharply peaked spectra characteristic of waves generated on the open ocean. This broadening is caused by the extreme degree of fetch width restriction as considered in Seymour (8). These broad spectra, however, are reasonably close to the longer period laboratory spectra.

SPECIFICATION OF RESISTANCE COEFFICIENTS

It was shown previously that values of the resistance coefficients, C_d and C_m , must be specified in the performance predictive model. It is theoretically possible to define deterministic time-varying values for these coefficients in oscillating flows. For example, the instantaneous value for C_d may be found, in concept, by comparing the instantaneous value of that component of resistance

which is in phase with the velocity with the value of the square of the instantaneous velocity. Since the flow conditions are changing radically through the oscillations in velocity, it is clear that the instantaneous values of the resistance coefficients must also change. Therefore, such a time-varying parameter is of no value for the statistical predictive model presently employed.

TABLE 3.—Laboratory Wave Climate Parameters

Tape designation (1)	Peak frequency, in hertz (2)	H_s , in centimeters (3)	H_m , in centimeters (4)	Ratio, H_m/H_s (5)
T1	0.883	6.89	11.51	1.67
T2	0.675	10.33	17.84	1.73
T3	0.510	11.80	18.58	1.58
T4	0.375	9.69	14.44	1.49
T5	0.375	17.16	28.05	1.63
T6	0.290	17.60	25.10	1.43
T7	0.250	16.16	24.62	1.52
T8	.190	15.28	21.17	1.39

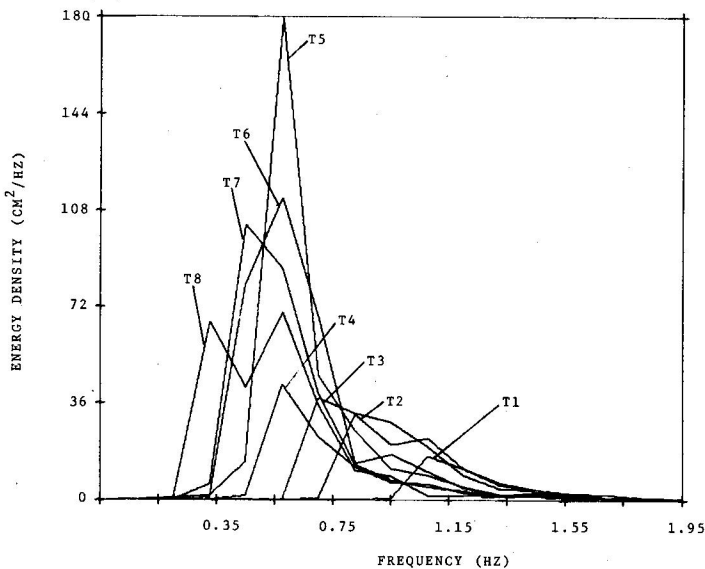


FIG. 5.—Spectra for Laboratory Experiments

In Seymour (4), the method was described for determining average constant values for the resistance coefficients for broad-band oscillatory flows. That resulted in minimum errors in predicting certain statistical properties of the resistance. This concept of utilizing constant coefficients to approximate the

resistance of a single float is embodied in the predictive model for breakwater performance described previously.

The concept is further extended in the model, however, to include the use of single-constant values for all floats within the breakwater, even though the

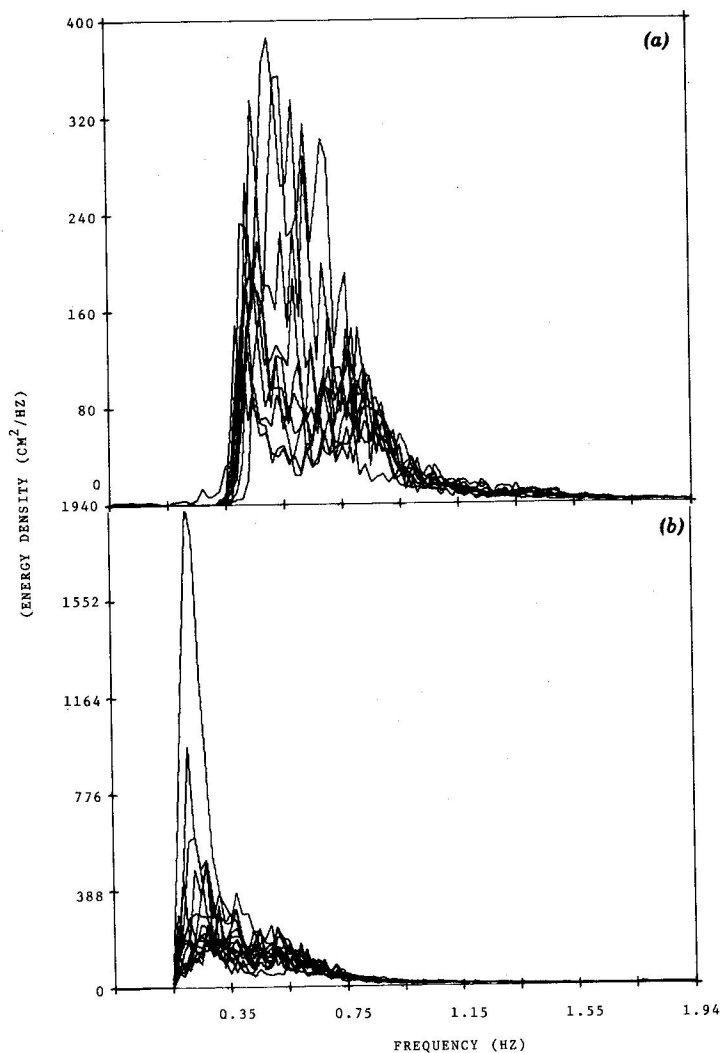


FIG. 6.—Incident Spectra: (a) Storm of January 22, 1976; (b) Storm of February 9, 1976

average flow conditions in a functional breakwater vary significantly between the front and the rear rows as the wave is attenuated. Thus, these coefficients are even further removed from the true, or instantaneous, values that they attempt to approximate.

As stated previously free surface effects such as scattering or reflection have been assumed to be small and are therefore not considered explicitly in the predictive model. However, these free surface effects do exist, particularly with floats whose diameter is an appreciable fraction of a wavelength and which are arranged near the surface. The net sum disturbance of the free surface can be considered as an increase in the resistance force. The increase in resistance that is in phase with the velocity would therefore result in an apparent increase in the drag coefficient. In the same manner, that portion of the resistance increase which is in phase with the acceleration would result in an apparent increase in the inertial coefficient.

The energy associated with the true drag of the float is lost to the wave field. The energy associated with the disturbance of the free surface may not necessarily be lost, but only phase shifted or changed in direction. In recognition of this, two drag coefficients have been defined. One, C_r , is used to define the apparent drag resistance (total of true drag and free surface disturbance). The value C_r is used in Eq. 6 to calculate the spectrum of relative velocity. The second, C_d , is used in Eq. 5 to estimate the drag power spectrum. In

TABLE 4.—Comparison of Incident Spectra with and without Breakwater

Experiment number (1)	Tape number (2)	H_s , in centimeters		Ratio, H_s^*/H_s (5)
		Bare channel (3)	With breakwater ^a (4)	
L1	T1	7.26	7.75	1.07
L2	T2	10.70	10.79	1.01
L3	T3	11.93	12.01	1.01
L4	T4	9.52	9.66	1.01

^aFreeboard on all floats was -3.8 cm.

practice, these two values vary only slightly (C_r must be larger than or equal to C_d) but they allow a slight additional flexibility in selecting coefficients to employ in the predictive model.

This procedure is in marked contrast to the traditional approach used by naval architects in which the frictional and wave-making components of resistance are separated and independently scaled. The present approximation, in which wave-making resistance is treated as an additional component of frictional resistance, appears to be feasible because of two considerations. First, the wave-making resistance, as demonstrated herein, is small compared to the frictional resistance. Secondly, as shown by Seymour (4), drag in random oscillatory flows has no Reynolds number dependence and scales approximately as Froude scaling, the same as the wave-making resistance.

The relative importance of the wave-making resistance can be deduced from the level of backscattered energy. In Table 4, four experiments using the half-scale model and different wave climates show the difference between the significant wave heights at the measurement station in front of the breakwater and at the same location with the breakwater removed. The measurement of the

backscatter of narrow band waves from fixed surfaces requires that the wave measuring device be moved to a number of locations to insure that reflected energy is not masked by the measurement point occurring at a node. In this system, however, a single location suffices because the signal is random and broad-band, and because the reflecting body has a large number of reflecting surfaces all of which move randomly during the sampling interval. It is readily apparent from Table 4 that the backscattered energy content is quite small. Since this is the only component of the free surface disturbance that can be measured easily, it is necessary to assume that the other components are also small.

SELECTING C_r , C_d AND C_m

Seymour (4) showed for spheres and Sarpkaya (3) for rough cylinders that drag and inertial coefficients are independent of Reynolds number and will

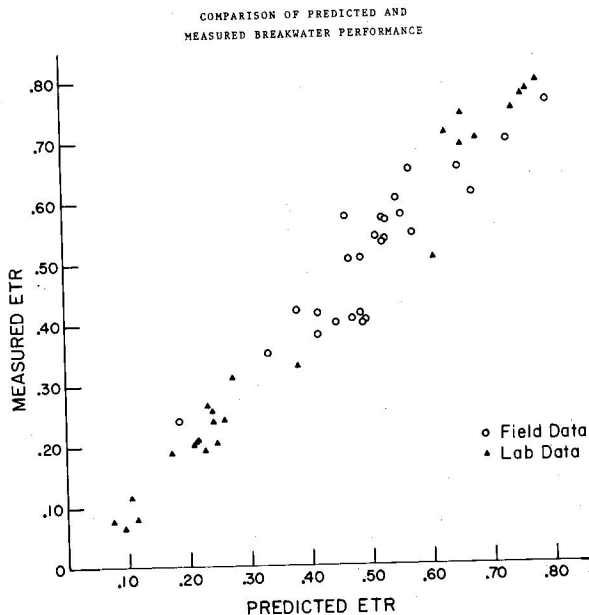


FIG. 7.—Comparison of Predicted and Measured Breakwater Performance

be constant with Froude scaling. This suggests that, for geometrically similar models above a limiting critical size, a single set of these coefficients should be sufficient to predict the performance of any scale breakwater.

Therefore, the entire body of laboratory and field data of similar geometry could be explored to determine the best values of the coefficients. This was accomplished by means of a computer program which predicted the ETR and the transmitted spectrum for a particular experiment and compared these with the measured values. A normalized error function was established to compare the predicted and measured transmitted spectra in which the rms error was

normalized by the standard deviation of the measured transmitted wave. The nondimensional ETR values could be compared directly. Values of C_r , C_d , and C_m spanning the range of possible values were examined using a large number of the field and laboratory experiments. These results were evaluated subjectively to yield a set of coefficients giving minimum errors over the full range of conditions. Because of the wave climates involved, these data necessarily included experiments in which the incident waves exceeded the design optimum. The coefficient set selected to model breakwaters with the geometry employed in these experiments is: $C_d = 0.282$; $C_r = 0.345$; and $C_m = 0.55$.

RESULTS OF LABORATORY MODELING

Fig. 7 shows the comparison between measured and predicted performance (i.e., energy transmission ratio) for both the field and the laboratory experiments

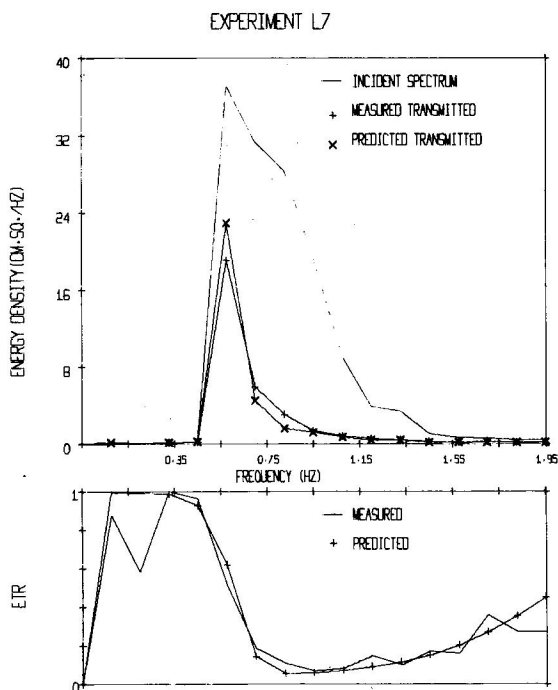


FIG. 8.—Experiment L7

described in this paper. The laboratory data are shown by triangles. The 25 laboratory experiments displayed ranged from an energy reduction of about 20% to a reduction of about 94%.

Fig. 8 shows the measured transmitted and incident spectra and the predicted transmitted spectrum for a typical laboratory experiment. A graphical comparison is also made of the measured and predicted ETR curves as functions of frequency. When comparing the two ETR curves, it is important to refer to the incident

wave spectrum in the plot mentioned previously. In general, the agreement between the ETR curves is quite good over the frequency range where a significant amount of incident energy is present. The ETR curves have little physical significance in frequency regimes with small energies and are subject to considerable measurement error.

The standard error in estimating ETR for the 25 laboratory experiments plotted in Fig. 7 is 0.0017. Since good agreement on an overall ETR is possible with very large, but offsetting, errors in estimating the transmitted spectrum, a second criterion was developed to evaluate the quality of the estimation. A normalized error function was defined as

$$\text{error} = \Sigma(f) = \frac{E \text{ transmitted}_{\text{measured}} - E \text{ transmitted}_{\text{estimated}}}{E \text{ incident}}$$

The standard deviation of this function was calculated over all frequency bands.

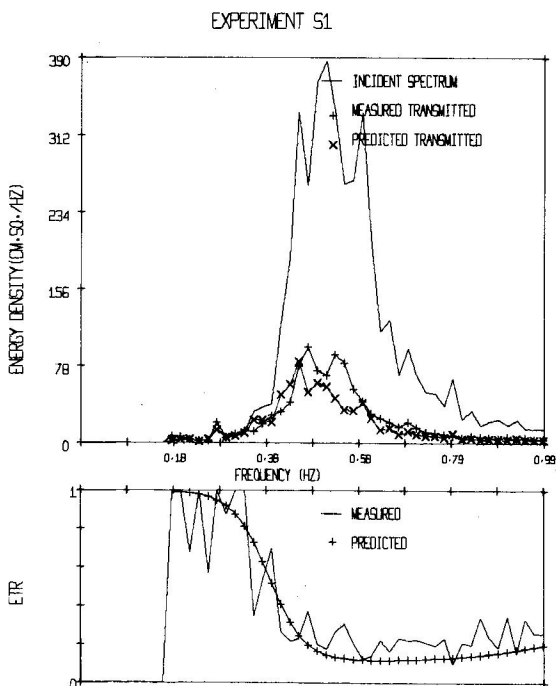


FIG. 9.—Experiment S1

The mean of all the standard deviations for the 25 laboratory experiments plotted was 0.066.

The 26 field experiments are shown as open circles in Fig. 7. These experiments cover a range of energy reductions from about 24% to about 76%. The spectra and ETR curve comparison on a typical field experiment are shown in Fig. 9. The corresponding curves for all laboratory and field experiments are reported in Seymour and Hanes (5). The standard error in estimating overall ETR for

the 26 field experiments was 0.0027. The mean standard deviation of the error function was 0.061.

CONCLUSIONS

The following conclusions may be drawn from this paper:

1. Lumped, single valued resistance coefficients applied to a linearized model for float motion can effectively predict the statistics of the response of the float to random wave excitation.

2. The values for the resistance coefficients, determined empirically by numerical curve fitting techniques for a particular freeboard ratio, apply over a broad range of both breakwater scales and wave climates.

3. The performance estimation technique predicted the transmitted spectrum, given the incident spectrum, with a mean rms normalized error of less than 0.07, and predicted total energy transmission within 3%.

4. The wave attenuation characteristics of the tethered float breakwater were satisfactorily demonstrated in a limited fetch application.

ACKNOWLEDGMENTS

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

- A = area;
- B = buoyant restoring force;
- C = drag force coefficient ($\rho/2$) AC_d ;
- C^* = force coefficient;
- C_d = drag coefficient;
- C_m = added mass coefficient;
- C_n = wave group velocity;
- C_r = resistance coefficient;
- D = apparent displaced mass;
- d_s = depth of float;
- E = wave energy;
- $|H|$ = response operator of float motion;
- $H(f)$ = transfer function between water velocity and float motion, $|H|e^{-i\theta}$;
- H_m = maximum wave height;
- H_s = significant wave height;
- h = water depth;
- k = wave number;
- L = effective tether length;
- M = apparent mass;
- M_s = mass of float;
- M_w = water mass displaced by float;
- P_d = drag power;
- S_p = spectrum of float drag power;
- S_u = spectrum of horizontal water;
- $S_v(f)$ = spectrum of V ;
- S_w = spectrum of wave power;
- S_η = spectrum of surface elevation;
- s = float spacing;
- U_0 = characteristic drag velocity;
- V = relative velocity;
- $\alpha(f)$ = spectral weighting function, S_w/S_η ;
- $\beta(f)$ = spectral weighting function, S_u/S_η ;
- $\gamma(f)$ = spectral weighting function, S_v/S_u ;
- θ = phase angle of float motion;
- ρ = density;
- σ_v = standard deviation of V ; and
- ω = radian frequency.

14755 PERFORMANCE OF TETHERED FLOAT BREAKWATER

KEY WORDS: Breakwaters; Coastal engineering; Harbor facilities; Marinas; Model studies; Ocean engineering; Waves

ABSTRACT: Describes laboratory experiments at one-half scale using simulated random seas and field tests at full scale of an installation of a dynamic floating breakwater system in a limited fetch situation. An analytical model is described which successfully predicted the performance of a tethered float breakwater configuration, given the incident wave spectrum. The methodology for selecting the arbitrary resistance coefficients in the predictive model is considered. Predicted and measured performance data for a total of 60 laboratory and field experiments are displayed, covering a very broad range of wave climates.

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