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Floating Breakwater Field Assessment Program, Friday Harbor, Washington

by

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A theoretical model for predicting the dynamic behavior of a floating breakwater is presented along with a report on a field experiment designed to provide basic data for verifying the model. Additional data were taken from the literature and from auxiliary laboratory experiments.

The dynamic behavior characteristics investigated were: (a) Total transmitted and reflected waves and their components; (b) wave forces on the breakwater; (c) motions of the breakwater; and (d) forces on the mooring lines. The

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) prediction model was developed from two-dimensional, linearized solutions of the hydrodynamical equations formulated in terms of a boundary value problem for the velocity potential. Some nonlinear effects are considered. Results for the predicted transmission coefficients were in good agreement with laboratory and field data, and they showed how the influence of fixed-body transmission, and of sway, heave, and roll motions on the transmission coefficient changed with increasing values of the parameter, beam (width) to wavelength ratio. The shape of the curves predicting the mooring line forces as a function of the beam (width) to wavelength ratio (or of wave frequency) followed those for the measured responses, but predicted magnitudes did not agree closely with measured values.

The floating breakwater at Friday Harbor, Washington, was used as the field experimental platform; it was instrumented to record the incident and transmitted waves, mooring line forces, and the acceleration components of sway, heave, and roll. Ninety-five 17-minute records were obtained during the period 30 December 1974 to 5 May 1975. Statistical summaries of all data are presented with analyses of selected transmitted waves, transmission coefficients, and acceleration components. The summaries and analyses constitute a performance report of a particular floating breakwater as well as an input to the development of the theoretical model.

PREFACE

This report is published to provide coastal engineers with a basic analytical procedure in the evaluation of certain floating breakwater types as structures for protecting particular sites against wind waves. The work was carried out under the coastal construction program of the U.S. Army Coastal Engineering Research Center (CERC).

This report was prepared by Dr. Bruce H. Adee, Assistant Professor of Mechanical Engineering, Mr. Derald R. Christensen, Research Engineer, and Dr. Eugene P. Richey, Professor of Civil Engineering, of the Ocean Engineering Research Laboratory, University of Washington, Seattle, Washington, under CERC Contract No. DACW72-74-C-0012.

Special appreciation is extended to the port of Friday Harbor, Washington, for the use of the floating breakwater for the field assessment part of the study. Mr. Robert Hovey, Port Engineer, and Mr. Jack Fairweather, Port Superintendent, provided generous assistance with the numerous logistics problems in the installation and maintenance of the measuring equipment. The sensor monitoring and recording package was adapted from a design developed in a contemporary project sponsored by the University of Washington Sea Grant Program for monitoring two other floating breakwaters of a different type. Data from these two sites were used for comparative purposes in the analyses of the Friday Harbor breakwater.

Dr. D. Lee Harris, Chief, Oceanography Branch, was the CERC contract monitor for the report under the general supervision of Mr. R.P. Savage, Chief, Research Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use forumla: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

A_1, A_2	Amplitudes of two incident waves
a_1	Amplitude of sway, heave, or roll motion for i = 1,2,3
B	Characteristic beam of breakwater
C_O	Body contour
C_T	Transmission coefficient
$F_j(t)$	Sway, heave, or roll exciting forces or moment for j = 1,2,3
KH_{ij}	Hydrostatic restoring-force coefficient for force in the jth direction due to motion in the ith direction
KM_{ij}	Similar to KH_{ij} but due to the mooring system
k_1, k_2	Wave numbers of two incident waves
L	Incident wavelength
m_{ij}	Mass or moment of inertial when i = j, 0 when $i \neq j$
$\vec{n}$	Unit interior normal to body surface
$P(x,y,t)$	Pressure
$\vec{r}$	Vector from center of gravity to a point on the body surface
$\alpha_i, \dot{\alpha}_i, \ddot{\alpha}_i$	Sway, heave, or roll motion; speed or acceleration
δ	Phase angle
δ_1, δ_2	Phase angles for two incident waves
$\eta(x,t)$	Free-surface elevation
$\eta_I(x,t)$	Wave surface elevation for incident wave
$\eta_T(x,t)$	Wave surface elevation for transmitted wave
λ_{ij}	Damping coefficient for force in the jth direction related to velocity in the ith direction
μ_{ij}	Added-mass or inertial-force coefficient for force in the jth direction related to acceleration in the ith direction
ρ	Fluid density
ϕ	Velocity potential
ω	Frequency
ω_1, ω_2	Frequencies for two incident waves

FLOATING BREAKWATER FIELD ASSESSMENT PROGRAM, FRIDAY HARBOR, WASHINGTON

by
B.H. Adee, E.P. Richey,
and *D.R. Christensen*

I. INTRODUCTION

Floating structures for use in the attenuation of water waves were introduced by Joly (1905). Little was done with the concept until the Bombardon floating breakwater was deployed to form a harbor during the Normandy invasion of World War II. The use of mobile harbors for potential military applications provided the incentive for extensive work during the postwar years. Representative articles from this period include those by Minikin (1948) who discussed floating breakwaters in general terms, Carr (1951) who used basic mechanics to predict transmission characteristics, and the review of the performance of the Bom-Bardon by Lochner, Faber, and Penny (1948). In 1957, the Naval Civil Engineering Laboratory, Port Hueneme, California, began a concerted exploration of the existing knowledge of transportable units that could serve as breakwaters or piers. Results of the study are summarized in Naval Civil Engineering Laboratory (1961), which was an invaluable state-of-the-art assessment with particular emphasis on military uses under the rather severe site criteria of an incident wave with a 15-foot height, 13-second period, minimum water depth of 40 feet, inshore transmitted wave height of 4 feet, and tidal range of 12 feet. A sequel to the earlier study (Naval Civil Engineering Laboratory, 1971) surveyed concepts for "transportable" breakwaters, including over 60 in the "floating" category. Although no breakwater system was disclosed which would meet the stringent military site criteria and transportability requirement, these state-of-the-art reviews sparked renewed interest in the floating breakwater for nonmilitary applications. A review of developments in floating breakwaters was summarized by Richey and Nece (1974); Seymour (1974) introduced a new and innovative concept for wave attenuation using a system of tethered floats which may have application over a wide range of wave conditions.

Continually increasing pleasure boat ownership has nearly exhausted the available supply of moorage space in many areas. The need for additional moorage space in conjunction with escalating construction costs and more stringent environmental restrictions require careful scrutiny of alternatives to the traditional fixed breakwater and excavation techniques employed in marina construction. Productive time in weather-dependent, waterborne activities such as construction, logging, and cargo handling could be increased if protective floating, transportable breakwaters were used. Other uses in the control of shoreline erosion and in the emerging mariculture industry may also be found.

The information on the performance of floating breakwaters, i.e., their wave attenuating characteristics, mooring line forces, and motions, is contained primarily in reports of laboratory scale-model tests with monochromatic incident waves; the few exceptions are the early analytical work by Carr (1951) and the occasional piece of information from a full-scale test like that performed by Harris (1974). There is a need for a fundamental analytical procedure to predict the performance characteristics of floating breakwaters with arbitrary cross section when exposed to a given incident wave. This procedure could be used to systematically compare performance information available in the literature, to examine new design proposals, and either eliminate or reduce and systematize auxiliary experimental studies.

The development of the predictive procedure was the primary thrust of the project with the concommitant field assessment of a full-scale floating breakwater in operation at Friday Harbor, Washington (Fig. 1). The analytical model developed from the two-dimensional, linearized solutions of the hydrodynamical equations formulated in terms of a boundary value problem for the velocity potential. The model was refined progressively by comparisons with results already reported in the literature, by auxiliary laboratory tests, and by the results from the Friday Harbor field program, where measurements of incident and transmitted waves, mooring line forces, and acceleration in sway, heave, and roll were measured over a 6-month period.

Figure 1.   Aerial view of Friday Harbor breakwater.

II. THEORETICAL ANALYSIS

In the analysis of complex systems such as floating breakwaters, there is a great need for model-scale experiments to predict their performance and provide data for the application of rational engineering design principles. Full-scale measurements are also extremely valuable in verifying scaling relationships and in providing confidence that the data obtained from smaller scale experiments are reasonable.

When one considers the myriad possible breakwater configurations which have been proposed to date and the different conditions which prevail at each potential breakwater site, the number of required model tests and the attendant expense are very large. To avoid this expense and also to permit parametric studies aimed at obtaining optimum breakwater configurations, a theoretical model was developed. The goal was to theoretically predict the performance which could be measured in laboratory studies or at prototype installations.

The initial restriction imposed on the theoretical model was to consider only two-dimensional conditions. Under this restriction the breakwater is assumed to be very long in one direction with long-crested waves approaching so that their crests are parallel to the long axis of the breakwater. At most breakwaters where the wave climate results from wind-generated waves, this condition would rarely be approached. However, experiments performed using a boat wake to generate incident waves on the beam and at an angle to a breakwater indicate larger breakwater motions and larger transmitted waves when the incident wave crests approach parallel to the long axis of the breakwater (Stramandi, 1975). As a design tool, a two-dimensional theory provides information on the worst conditions which might be expected to occur. In addition, the extensive two-dimensional wave-channel experiments provide the data needed to test the theoretical model.

Throughout the development of the theoretical model, every attempt was made to orient the model toward providing a useful tool applicable to realistic problems. To perform the calculations the user need only know the incident wave frequencies of interest, the contour of the breakwater cross section (catamaran- or trimaran-type cross sections are permitted), and the physical properties of the breakwater (these include mass, mass moment of inertia, and the static restoring-force coefficients).

The approach used here has been to employ the techniques which naval architects have developed to deal with ship motion problems. Mathematically, the hydrodynamic equations are formulated in terms of a boundary value problem for the velocity potential. Solution of this complete problem is presently impossible because the free-surface boundary condition is nonlinear. An approximate solution may be obtained if restrictions are imposed on the boundary value problem, and the procedure of linearization is applied. The restrictions limit the applicability of the solution to cases of small incident wave amplitude and small motion response of the breakwater.

When using the linearized theory which is presented here, one must be well aware of the limits of applicability which are imposed on the results in order to permit the formulation of a tractable mathematical problem. Care must also be exercised because these restrictions may exclude phenomena which occur in nature from appearing in the mathematical analysis. For instance, field observations clearly demonstrate the occurrence of mooring line force oscillations at periods greater than those which could be attributed directly to wind-generated wave excitation. Using a linearized approach, these long-period oscillations would not appear in the analysis. A theoretical model which includes nonlinear behavior of the system is required if these long-period oscillations are to be included.

A possible nonlinear mechanism for the transfer of wave energy to lower frequencies has been postulated and is presented to supplement the linear analysis.

1. Linear Theoretical Model.

The problems involved in theoretically predicting the performance of a two-dimensional floating breakwater are illustrated in Figure 2. Here an incident wave approaches the breakwater on the beam. A part of the energy contained in the incident wave is reflected, part passes beneath the breakwater, and some is lost through dissipation. Another part of the incident wave energy excites the motions of the breakwater. These motions are restrained by the mooring system. The oscillating breakwater in turn generates waves which travel away from the breakwater in the directions of the reflected and transmitted waves. The total transmitted wave is the sum of the component which passes beneath the breakwater and the components generated by the breakwater motions. The total reflected wave is composed similarly.

In completing the calculations, the information which is of most interest to the designer includes:

(a) Total transmitted and reflected waves including their components.

(b) Wave forces on the breakwater.

(c) Motions of the breakwater.

(d) Forces on the mooring lines.

For the two-dimensional breakwater, definitions for the motions are shown in Figure 2. Sway is defined as the oscillation perpendicular to the long axis, or along the x-coordinate axis. Heave is the vertical

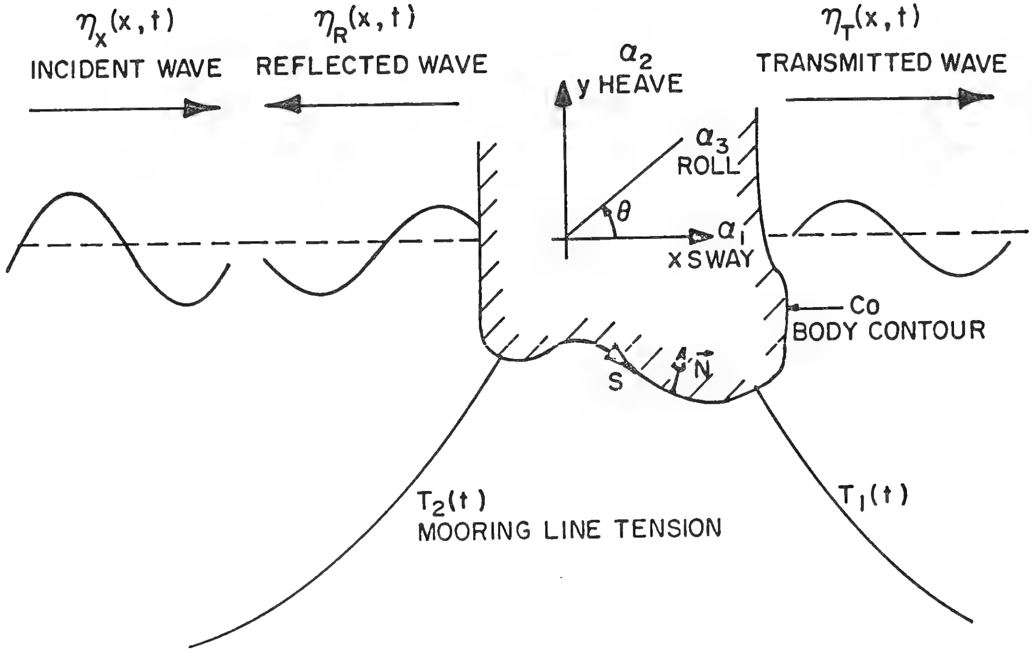

Figure 2. A two-dimensional floating breakwater.

motion of the breakwater along the y-coordinate axis, and roll is the rotation about the long axis or the z-coordinate direction.

As long as the problem is linear, computing the performance of a floating breakwater may be separated into three parts:

(a) Formulate equations of motion.

Calculate hydrostatic forces and moments.

Evaluate hydrodynamic coefficients in equations of motion.

Compute exciting forces on breakwater.

Solve for the motions and motion-generated waves.

Compute forces in the mooring lines.

(b) Solve for the waves diffracted by a rigidly restrained breakwater.

(c) Sum components to obtain total reflected and total transmitted waves.

When combined, these parts of the calculation provide complete performance data for a two-dimensional breakwater.

a. Breakwater Motions. In deriving the equations of motion, Newton's law is used.

$$m_{ij} \ddot{\alpha}_i = \Sigma \text{ forces}; \tag{1}$$

here:

α_i = motion of the breakwater in sway, heave, and roll for $i = 1,2,3$, respectively. The dot above indicates differentiation with respect to time.

m_{ij} = mass or mass moment of inertia when $i = j$ and zero when $i \neq j$.

Expanding this equation to include the various forces in the summation yields:

$$m_{ij} \ddot{\alpha}_i = F_j \text{ (inertial)} + F_j \text{ (wave damping)}$$
$$+ F_j \text{ (friction)} + F_j \text{ (hydrostatic)} + F_j \text{ (mooring)}$$
$$+ F_j \text{ (wave exciting)}$$

The inertial force (or added-mass force) arises when the breakwater accelerates, which also accelerates the fluid around it. The motion-generated waves are moving away from the breakwater and result in the wave-damping term. A term representing the forces due to viscosity is included, but these forces are neglected in the analysis. Experience in ship motion analysis (Salvesen, 1970) has shown this to be acceptable for all motions but roll, where damping may make a more significant contribution than for sway and heave motions. At present, the main reason for neglecting the frictional forces is that they lead to nonlinear terms in the equations of motion, which make their solution far more complex. Hydrostatic forces arise because of changes in the displaced volume of the breakwater when it moves. In this analysis the mooring forces are modeled as simple springs with their contribution to the damping and inertial forces considered small in comparison to similar terms resulting from the breakwater motion. The wave exciting force results from the incident waves striking the breakwater.

If we neglect the nonlinear terms and assume that the fluid is inviscid, then the equations of motion describing the coupled sway, heave, and roll motions of the breakwater are of the form:

$$\sum_{i=1}^{3} \{(m_{ij} + \mu_{ij}) \ddot{\alpha}_i + \lambda_{ij} \dot{\alpha}_i + (KH_{ij} + KM_{ij}) \alpha_i\} = F_j (t) \qquad (2)$$

$$\text{for } j = 1,2,3.$$

The symbols are defined as follows:

μ_{ij} = added-mass coefficient with the $\mu_{ij} \ddot{\alpha}_i$ representing the added-mass force or moment in the jth direction due to acceleration in the ith direction.

λ_{ij} = damping-force coefficient relating damping force or moment in the jth direction to velocity in the ith direction.

KH_{ij} = hydrostatic spring constant relating the restoring force or moment in the jth direction to displacement in the ith direction.

KM_{ij} = similar to KH_{ij} but due to the mooring system.

F_j = exciting force or moment in the jth direction.

In order to solve these equations, the physical mass and moment of inertia, added mass and damping coefficients, static spring constants, and the exciting forces must all be known. Mass and moment of inertia are computed directly from the specifications of the breakwater section. The KH_{ij} are derived directly from hydrostatic considerations in Appendix A, while approximate values for KM_{ij} are obtained by using a discretized approximation for the mooring line as described in Appendix B. Potential theory and the principle of linear superposition permit derivations for the hydrodynamic coefficients and forcing function μ_{ij}, λ_{ij} and $F_j(t)$.

Steady-state solutions of the form:

$$\alpha_i(t) = a_i \sin(\omega t + \delta_i) \text{ for } i = 1,2,3 \quad (3)$$

are assumed. Substitution of the assumed solution (eq. 3) into the equations of motion (eq. 2) yields a set of linear algebraic equations which may be solved for the unknown amplitudes and phase angles a_i and δ_i. Transfer functions, H_i, are then defined by the a_i and δ_i since the incident waves are assumed to be sinusoidal.

b. Hydrodynamic Coefficients and Waves. Potential theory is employed in computing the reflected and transmitted waves, hydrodynamic coefficients and the exciting forces. Under the assumptions of small incident waves, small breakwater motions and an inviscid fluid, the velocity potentials may be found and the problem subdivided using the principle of linear superposition. The total velocity potential:

$$\phi_{total} = \phi_{incident} + \phi_{diffracted} + \phi^{(i)}_{motion} \text{ for } i = 1,2,3 \quad (4)$$

is the sum of the incident wave potential, the diffracted wave potential and the potential resulting from forced sway, heave, and roll motions.

The incident wave potential is well known and may be expressed directly. Obtaining the diffracted wave and breakwater motion potentials requires the solution of boundary value problems. These problems and their solutions are described in Appendix C. Appendix D provides the computer program used to calculate breakwater performance.

When the velocity potentials have been obtained, the free-surface elevation at any position is found using the linearized free-surface boundary condition:

$$\eta(x,t) = -\frac{1}{g}\phi_t(x,0,t). \quad (5)$$

Here:

$\eta(x,t)$ = free-surface elevation measured from stillwater level ($y = 0$),

g = acceleration of gravity,

$\phi_t(x,0,t)$ = derivative of the velocity potential with respect to time evaluated at $y = 0$.

$$\eta_{total}(x,t) = -\frac{1}{g}\{\phi_{t\ incident}(x,0,t) + \phi_{t\ diffracted}(x,0,t)$$

$$+ \phi^{(i)}_{t\ motion}(x,0,t)\}. \qquad (6)$$

The fluctuating component of pressure in the fluid and on the breakwater hull surface may be computed using Bernoulli's equation:

$$P(x,y,t) = -\rho\, \phi_t\, (x,y,t). \qquad (7)$$

By computing pressures on the hull surface and integrating these around the contour, the forces on the breakwater may be computed. The force per unit length acting on the breakwater is then:

$$F(t) = \int_{C_o} P\, \vec{n}\, ds. \qquad (8)$$

In this case,

$F(t)$ = force on the breakwater,

$\vec{n}$ = unit interior normal vector on the hull surface,

C_o = contour of breakwater cross section.

The rolling moment is:

$$M(t) = \int_{C_o} P\, \vec{r} \times \vec{n}\, ds, \qquad (9)$$

where,

$\vec{r}$ = the vector from the center of gravity to a point on the surface.

To compute the exciting forces on the breakwater in linear theory, the pressure due to the incident and diffracted waves is integrated over the hull surface. These forces and moments become:

$$F_1(t) = \{-\rho \int_{C_o} [\phi_{t\ incident}(s,t) + \phi_{t\ diffracted}(s,t)]\, \vec{n}\, ds\} \cdot \vec{i},$$

$$F_2(t) = \{-\rho \int_{C_o} [\phi_{t\ incident}(s,t) + \phi_{t\ diffracted}(s,t)]\, \vec{n}\, ds\} \quad \vec{j},$$

$$F_3(t) = \{-\rho \int_{C_o} [\phi_{t\ incident}(s,t) + \phi_{t\ diffracted}(s,t)]\, \vec{r}\times\vec{n}\, ds\} \cdot k. \qquad (10)$$

Hydrodynamic coefficients are found using the potential resulting from forced oscillation of the breakwater. In this case the pressure integrated over the surface has a component in phase with acceleration and a component in phase with velocity. The component in phase with acceleration is normally referred to as the added mass, while the component in phase with velocity is the damping.

The hydrodynamic coefficients shown in this section are derived in greater detail in Appendix C.

c. Mooring Forces. At the time the spring constants for the mooring lines are computed, mooring force coefficients are also calculated. These are:

$\frac{\Delta F}{\Delta \alpha_i}$ = change in mooring line force per unit displacement in sway, heave, or roll when i = 1, 2, or 3, respectively.

The forces in the mooring lines may then be computed once the motions have been found.

$$\text{Mooring Force} = \sum_{i=1}^{3} \left(\frac{\Delta F}{\Delta \alpha_i}\right) \alpha_i(t)$$

The description of the linear system is now complete. The block diagram in Figure 3 shows the relationships among the calculations which are required.

2. Nonlinear Theoretical Model.

Measurements taken at the Tenakee, Alaska, floating breakwater before this research program was begun indicated the presence of a long-period oscillatory motion of the breakwater. These long-period motions were manifested most clearly in the measured mooring line forces. Looking at these, one can visually observe an oscillation with a period of about 60 seconds superimposed over the expected shorter period oscillations. Figure 4 shows the results of a spectral analysis of the seaward mooring line data after a low-pass filter has been applied (the technique for performing the spectral analysis is given in Section III of this report).

The linear theoretical model permits the system to respond only at the frequency of the incident wave. In order to explain the presence of these long-period oscillations, nonlinearities must be included in the analysis. To perform a mathematically complete analysis including all nonlinear effects is beyond the present state of the art. However, in the case of the floating breakwater, one can show that if two incident waves are considered and second-order terms are retained, then an exciting force is present at the difference between the frequencies of the incident waves. The complete derivation in Appendix E shows that the nonlinear pressure may be expressed as:

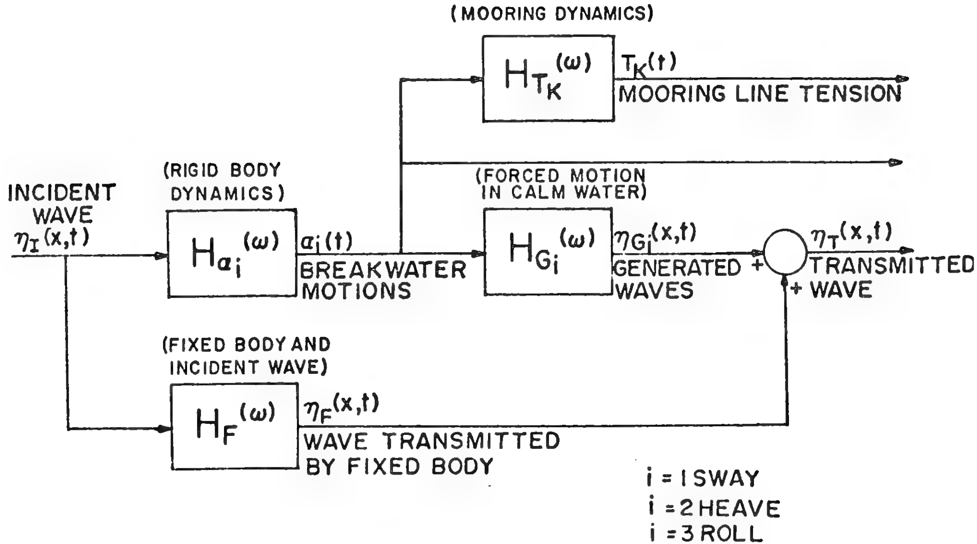

Figure 3. Linear system representative of a floating breakwater.

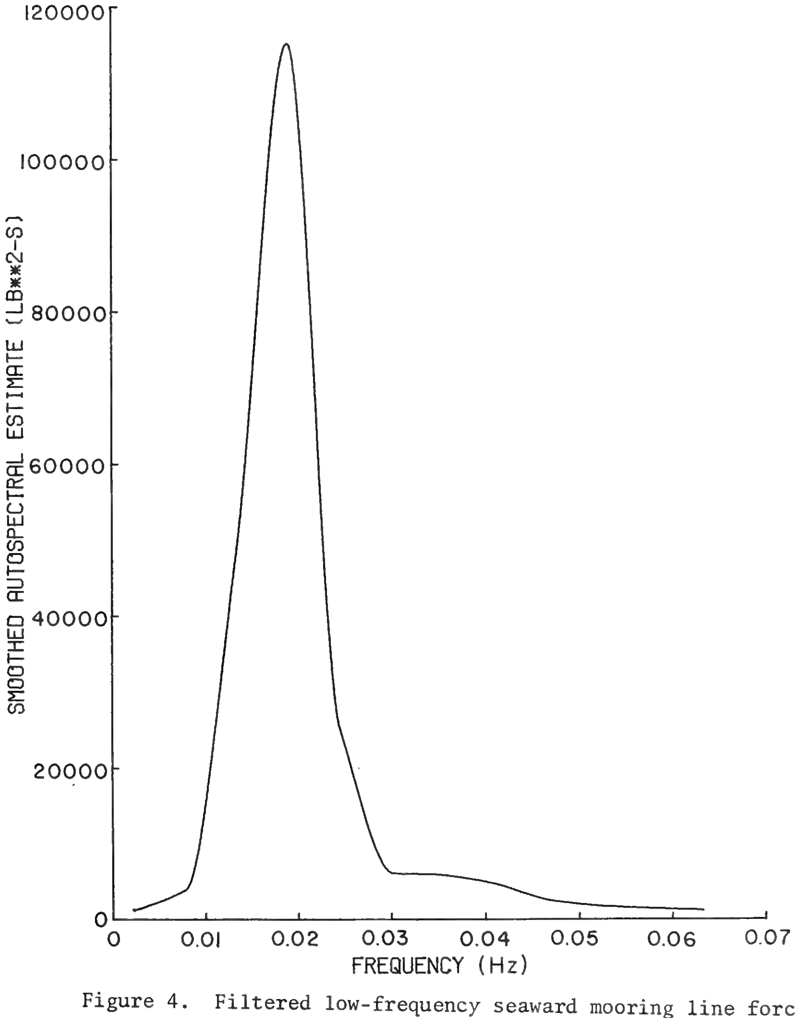

Figure 4. Filtered low-frequency seaward mooring line force, Tenakee, Alaska (record TK7-23).

$$P(t) = -\frac{\rho}{2}\{\omega_1^2 A_1^2 e^{2k_1 t} + \omega_2^2 A_2^2 e^{2k_2 y} - 2\omega_1\omega_2 A_1 A_2 e^{(k_1+k_2)y} \cos[(k_1 - k_2)x - (\omega_1 - \omega_2)t + \delta_1 - \delta_2]\}, \tag{11}$$

where,

ρ = fluid density,

ω_1, ω_2 = incident wave frequencies,

A_1, A_2 = incident wave amplitudes,

k_1, k_2 = incident wave numbers = $\frac{\omega_1^2}{g}, \frac{\omega_2^2}{g}$,

δ_1, δ_2 = incident wave phase angles.

Combining this pressure with the pressure obtained from the linear theory and integrating over the hull would provide additional exciting-force terms at zero frequency and at the difference frequency. Carrying the nonlinear exciting-force terms back through the linear response analysis should provide a quasi-linear approach. While there is no reason to expect this to provide exact correlation with measured data, the quasi-linear approach would at least permit the natural phenomena to enter into the mathematical analysis.

One would expect terms to appear in the second-order pressure (eq. 11) at twice the incident wave frequency and at the sum of the incident wave frequencies. Terms at twice each of the incident wave frequencies can be derived by applying the trigonometric relationships to the terms at zero frequency. While a term at the sum of the incident wave frequencies does not appear in the second-order incident wave potential, this term may result when the second-order potentials representing diffraction or forced oscillation in calm water are included.

A great deal more effort is required in this area to complete the analysis. There is also one other area where a nonlinear, or quasi-linear, analysis should be investigated. This is in the roll-damping coefficient. Here, viscous effects seem to be important, and while the problem has not been dealt with within the present study, investigators have included a term proportional to velocity squared in the equation for roll motion.

3. Results.

The computer program given in Appendix D has been developed to calculate the values of hydrodynamic coefficients, breakwater motions, and the wave field. Input variables include:

(a) The body contour, C_o, represented by a series of points on the contour.

(b) The physical properties of the body: mass, mass moment of inertia, and position of the center of gravity.

(c) The mooring system spring constants.

(d) The hydrostatic restoring spring constants.

(e) The incident wave frequency, ω.

In this program the exciting forces and moments appearing in the equations of motion and the fixed-body parts of the transmitted and reflected waves are found by computing the forces, moments, and waves which result when a rigidly fixed body is struck by a sinusoidal incident wave of frequency ω. Motions are found by computing the steady-state solution to the three equations of motion. The hydrodynamic coefficients and the waves generated by the body motions are found by computing the forces, moments, and waves which result when the body is forced to oscillate in stillwater in pure sway, pure heave, or pure roll.

The physical properties used in the performance calculations for the various breakwaters are collected in Appendix F.

a. Wave Transmission. To assess the performance of a floating breakwater, one quantity which is commonly used is the transmission coefficient. This is simply the transmitted wave amplitude divided by the incident wave amplitude, $|\eta_T(x,t)|/|\eta_I(x,t)|$ for monochromatic incident waves.

(1) Proposed Oak Harbor Breakwater. At one time the Corps of Engineers was considering a marina and floating breakwater at Oak Harbor, Washington. Model experiments were carried out by Davidson (1971) to determine transmission characteristics and mooring forces. The breakwater itself had a catamaran-type cross section. A comparison between the theoretically predicted and experimentally measured transmission coefficient is shown in Figure 5. This figure as well as the others plotted in this section and Section IV were drawn using a CALCOMP plotter. The plotting program uses a parabolic fit to determine additional points between the given data. Varying numbers of data points were used to describe each curve depending on its behavior. Data points were closely spaced in regions where the theoretical predictions indicated large changes in curvature. Wavelength is calculated in all the figures using the relationship between wavelength and period for waves in deep water.

In this case, the results compare reasonably well except for the

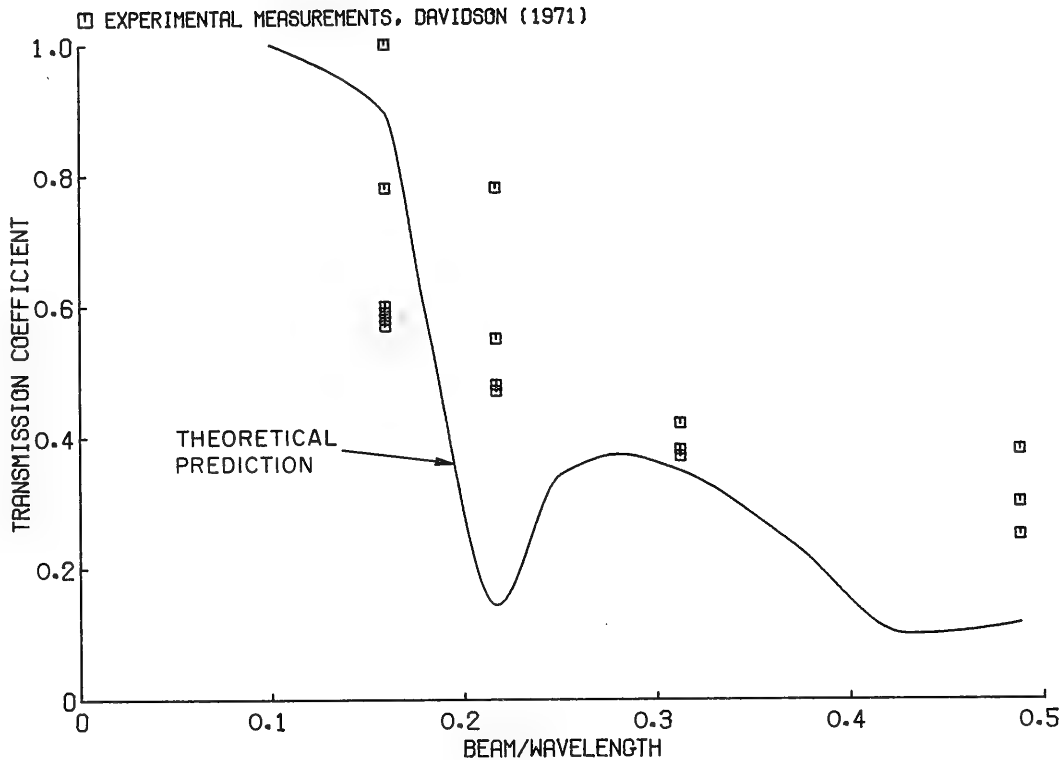

Figure 5. Transmission coefficient for proposed Oak Harbor breakwater.

predicted dip in transmission just above a B/L (beam/wavelength) of 0.2. There is also some difference at higher B/L ratios.

The theory predicts that the part of the transmitted wave which would result where the body is rigidly fixed is almost 1 for a B/L less than 0.1 and drops rapidly at higher B/L ratios to the point where it is of little consequence beyond 0.2. Waves generated by the breakwater motions play an increasing role for B/L ratios above 0.15. Heave motion is the major contributor to the transmitted wave in the very narrow band of B/L between 0.15 and 0.18 with a predicted heave resonance at a B/L of about 0.18. The dip occurs because the waves generated by heave and sway motions are almost 180° out of phase and cancel each other out. At B/L ratios above 0.25, sway motion assumes an increasingly dominant role. Roll motions are small throughout and generate only very small waves.

(2) Rectangular Breakwater. A breakwater of rectangular cross section with the same beam and draft as the proposed Oak Harbor breakwater was tested at the University of Washington by Nece and Richey (1972). Results for the water depth of 29.5 feet are shown in Figure 6.

Again the agreement is reasonable. Further experiments with this model have confirmed the existence of the trough at a B/L of 0.2. However, this phenomenon can be observed only for very small wave heights. For practical purposes, the dip may be smoothed over considerably. The major discrepancy is at the high B/L ratios where the theory shows considerably greater transmission than is actually measured in the model tests. Since the transmitted wave is almost totally a result of sway motion, the problem must lie in the wave predicted by this motion.

Over the entire range of wavelengths of interest, the predicted results follow the pattern previously discussed for the proposed Oak Harbor breakwater. The transmitted wave is almost completely a result of fixed-body transmission followed by regions of heave resonance, heave and sway cancellation, and finally, sway wave generation as the B/L increases.

It is interesting to note that there is very little difference between the open-well breakwater and the closed rectangle of the same overall dimensions.

(3) Rectangular Breakwater Tested by Sutko and Haden. In some recent experiments Sutko and Haden (1974) have examined the effect that restricting breakwater motions has on the transmission coefficient. They used a rectangular breakwater model with a beam-to-draft ratio of 1.5. Plexiglas end assemblies were used to restrict the breakwater motions.

Figure 7 shows the transmission coefficient when the breakwater is restricted to sway motions only. Here, the transmitted wave contains a component resulting from the fixed-body transmission and a component

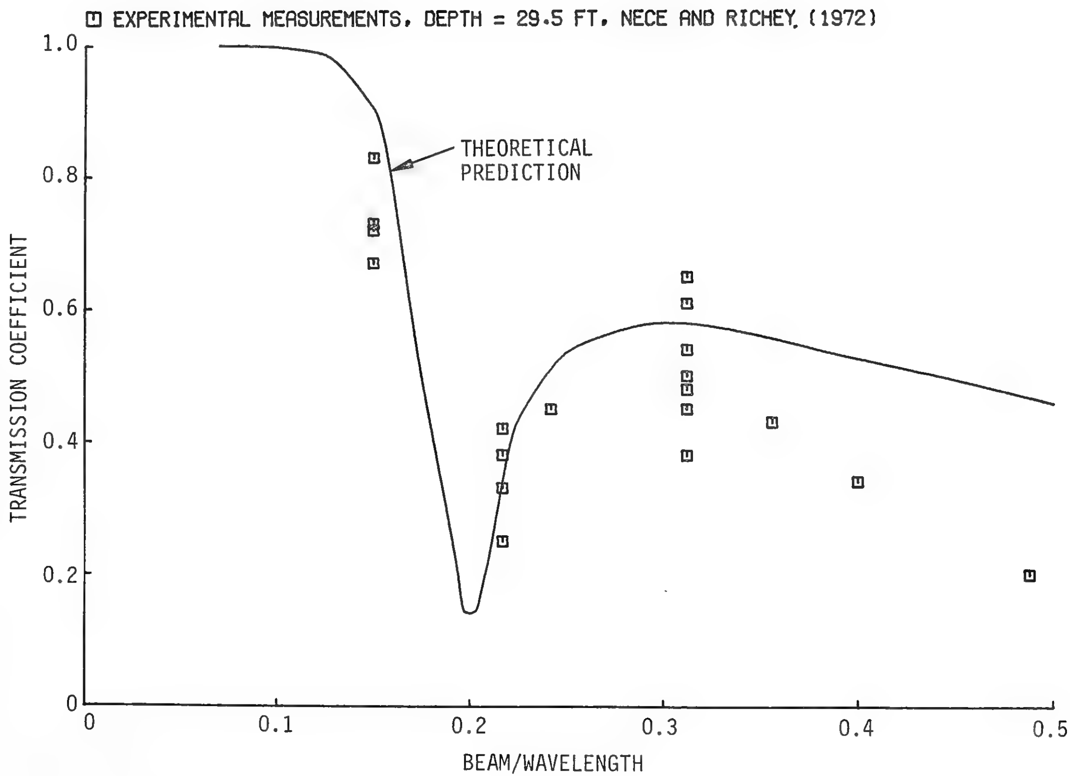

Figure 6. Transmission coefficient for a rectangular breakwater.

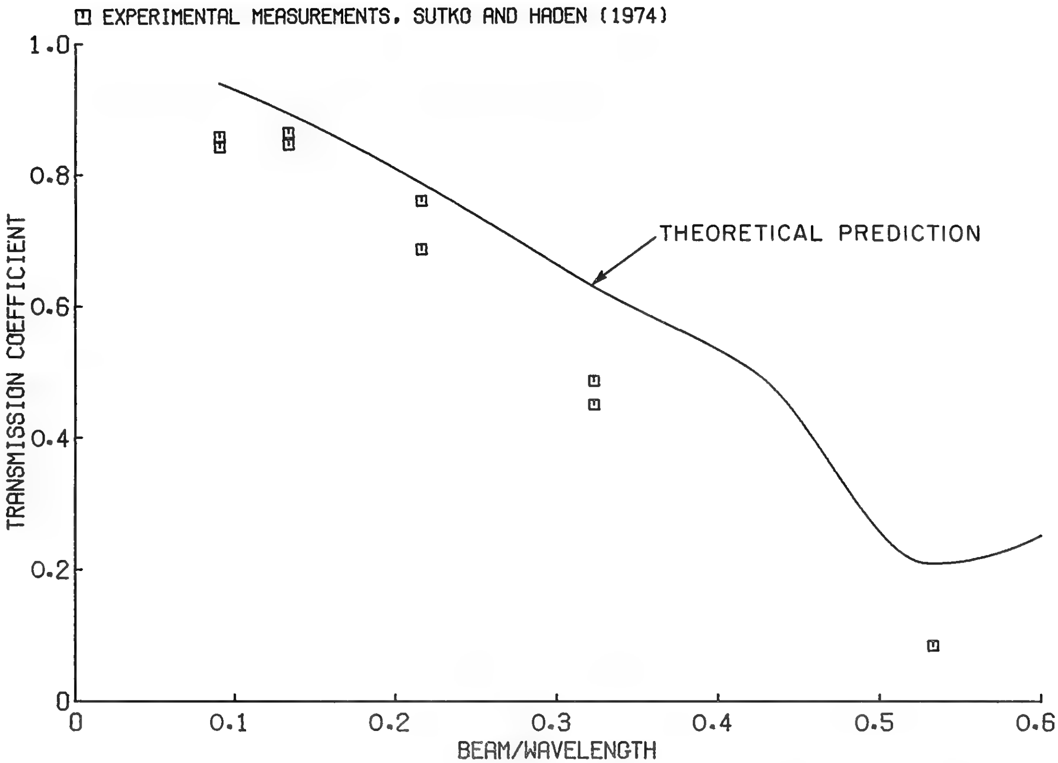

Figure 7. Transmission coefficient for a rectangular breakwater restricted to sway motion only.

resulting from the wave generated by the sway motion. At very low B/L ratios the fixed-body transmission is the more important component. At a B/L of about 0.1 both the fixed-body transmission and the sway-generated wave are of equal importance. At B/L ratios higher than 0.215, the wave generated by sway motion dominates. The agreement between theory and experiment is quite reasonable for this case.

A comparison when the breakwater is restricted to heave motion only is shown in Figure 8. There is clearly a discrepancy in this case between measured and theoretically predicted transmission coefficient near the B/L ratio of 0.13. As a matter of fact, the theory predicts a heave resonance in this region which does not seem to be supported by the measured data.

In examining the mechanism used to restrain the breakwater motion, it seemed possible that this apparatus was introducing damping into the system. To test this supposition, transmission coefficients were computed with the calculated hydrodynamic damping increased by an arbitrary amount. The major effect of increasing the damping was to decrease the transmission near the heave resonance region. With damping at three times the hydrodynamic value, the results were quite close to the experimental measurements. Increasing the damping beyond this had very little additional effect on the predicted transmission coefficient. The scatter which appears in the experimental data in this region is a further indication that some nonrepeatable effect may be influencing the experimental results. So long as the additional damping is included in the theoretical calculations, the results compare well with experimental measurements.

Figure 9 shows a comparison between model measurements when the model is unrestrained except by a horizontal mooring cable and the theoretically predicted results without mooring restraints. The theoretical results are characteristic of the rectangular breakwater with the dip in transmission near a B/L equal to 0.2. The pattern of interactions between motion-generated waves and fixed-body transmission is similar to the previous description. The agreement between these results indicates that the theoretical model may also yield the correct results when the model is free to heave only. At least further experimental investigation is warranted.

(4) Alaska-Type Breakwater. The State of Alaska has embarked on an ambitious program for constructing moorages using floating breakwaters. As part of a Sea Grant project the University of Washington has been studying the performance of this type breakwater. A theoretically predicted transmission coefficient and the transmission coefficient measured in model tests are shown in Figure 10. The model tests were conducted using very small incident waves (wave heights on the order of 0.2 to 0.3 feet at prototype scale). Results for larger wave slopes were not included in the figure but do show the same trends with lower values of transmission coefficient. Theoretical predictions without added damping and with double the hydrodynamic damping are shown in Figure 10.

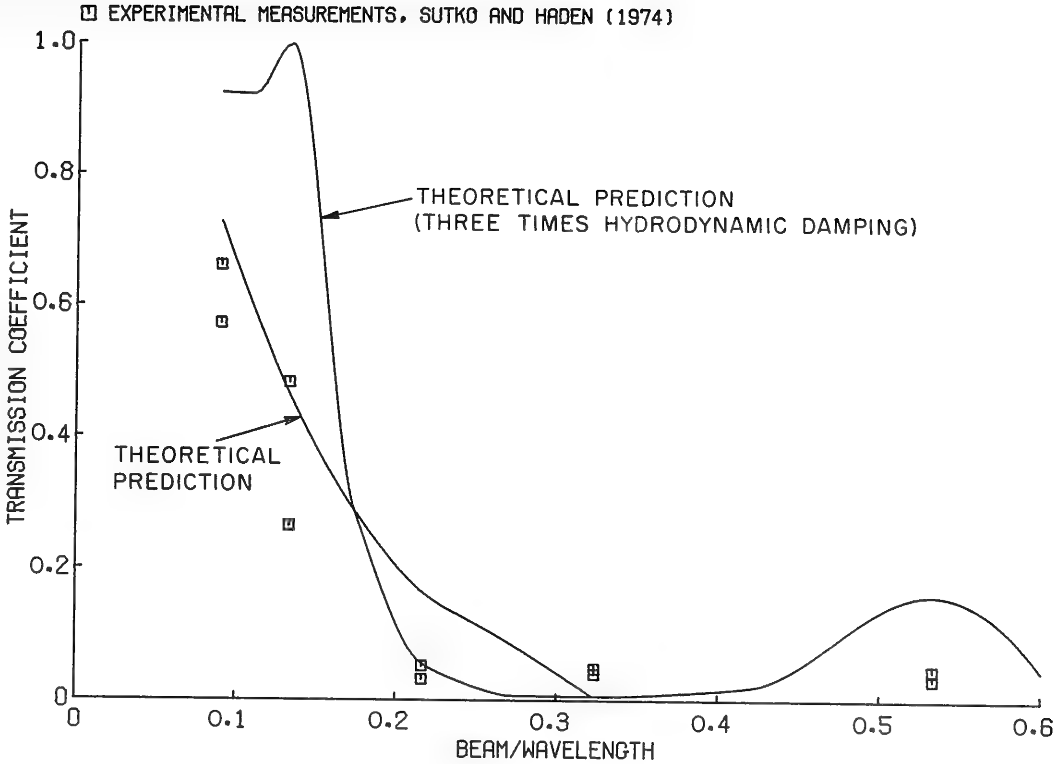

Figure 8. Transmission coefficient for a rectangular breakwater restricted to heave motion only.

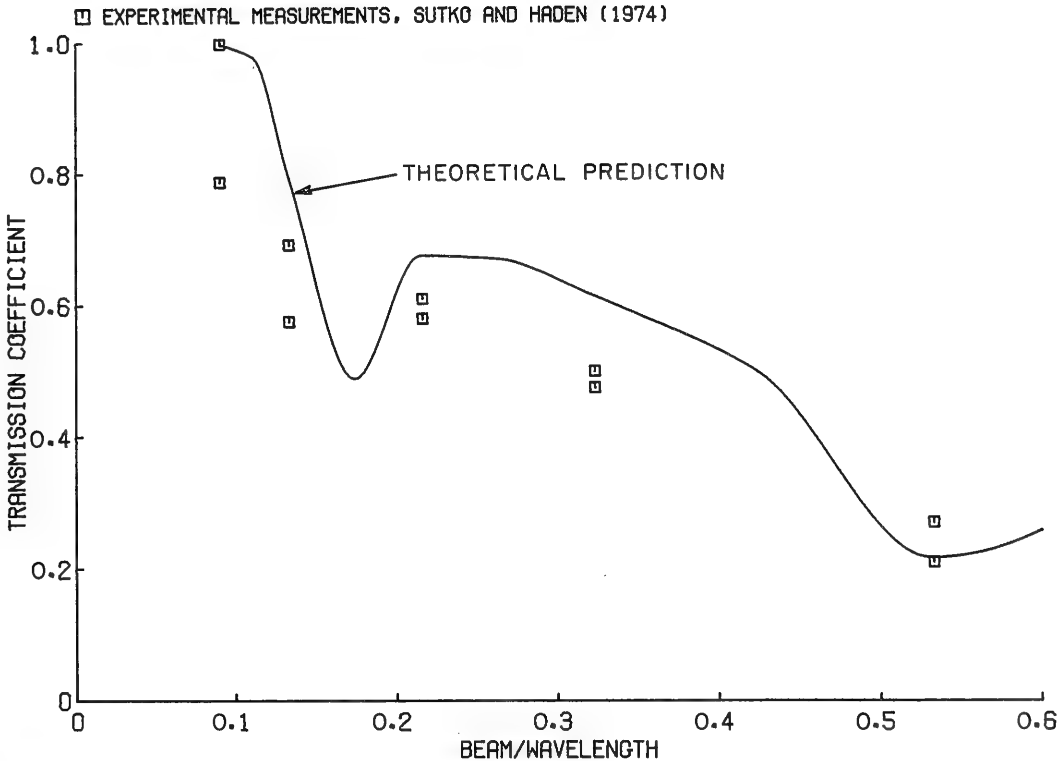

Figure 9. Transmission coefficient for a rectangular breakwater.

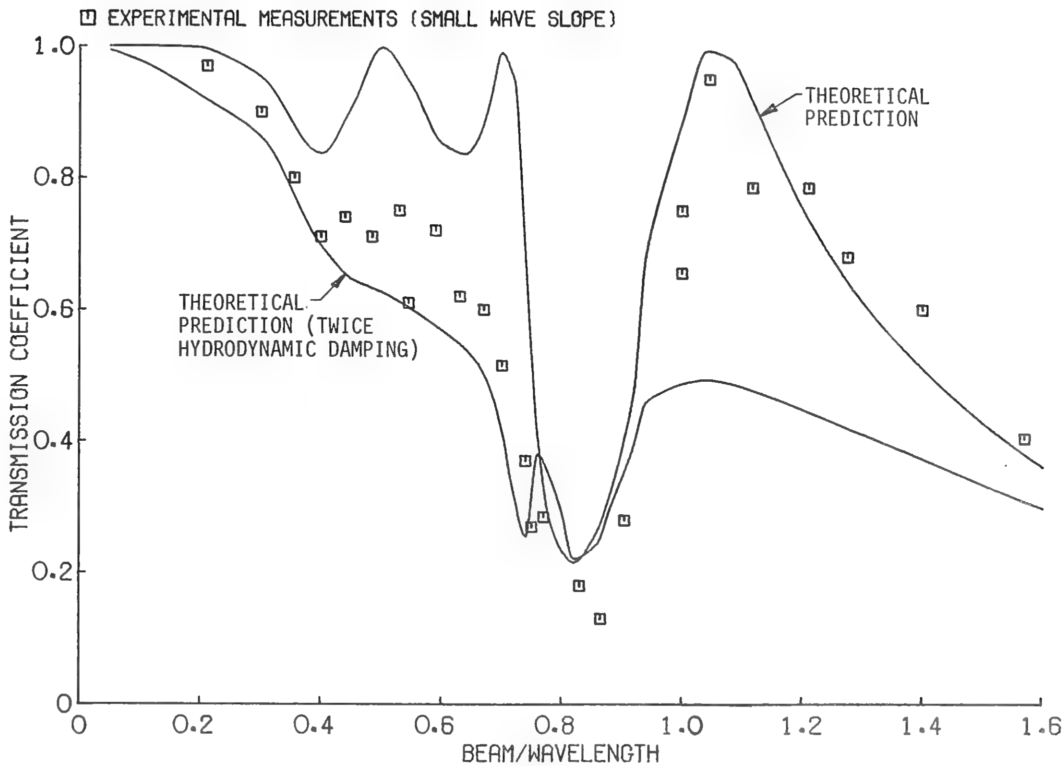

Figure 10. Transmission coefficient for Alaska-type breakwater model.

Clearly the increased damping makes a significant difference in the results.

Some insight into the performance of this breakwater may be gained by following the theoretical results as a function of B/L. At very low B/L the fixed-body transmission dominates. The trough at a B/L of 0.4 comes mainly from the interaction of the roll-generated wave and the fixed-body transmission. For the next peak at B/L of 0.5 the roll-generated wave dominates as the roll resonant frequency is encountered. The next trough at B/L of 0.65 is a result of all three motion-generated waves interacting with the fixed-body transmission making only a relatively small contribution to the transmitted wave. The following peak at B/L of 0.7 results from interactions among the motion-generated waves which are of about equal magnitude. At a B/L of 0.86 the heave-generated wave dominates again, but as B/L increases beyond this the effect of heave and roll are rapidly decreasing while sway motion is becoming the dominant wave-generating mechanism. In the region of B/L between 0.4 and 1.0, changing the physical properties of the breakwater can have a marked effect in shifting the peaks and troughs by altering the heave and roll resonant frequencies.

Experience with linear ship motion theory has shown that the worst agreement between predicted and measured motions occurs when rolling motions are considered (Salvesen, 1970). This discrepancy is often overcome by arbitrarily increasing the computed roll damping to compensate for the viscous damping which is neglected. As indicated in Figure 10, when damping is added the theory gives a better prediction where roll motion plays a significant role. This places a significant restriction on the theory requiring careful monitoring of predicted roll motion. Where the theory predicts large roll motion, additional damping will be required to obtain results comparable to measurements.

Figure 11 shows the predicted fixed-body transmission coefficient and the results of model tests. Agreement is quite close except at B/L of 0.78. The peak in predicted transmission may be due to a resonance of the waves within the well of the catamaran breakwater. There is another peak near B/L of 1.4 indicating the presence of higher harmonic resonances as well. Model tests show at least a slight hump in this region suggesting that the theoretical prediction clearly overestimates the effect of this phenomena, but that this probably is occurring in real life.

For the data measured in the field, the transmission coefficient is defined as the square root of the transmitted wave spectral density divided by the incident wave spectral density. Figure 12 shows the transmission coefficient derived from the data obtained at the Tenakee, Alaska breakwater. The theoretically predicted transmission coefficient with the computed hydrodynamic damping doubled is also shown for comparison. Details of the technique used in the spectral analysis of the field data may be found in Section III.

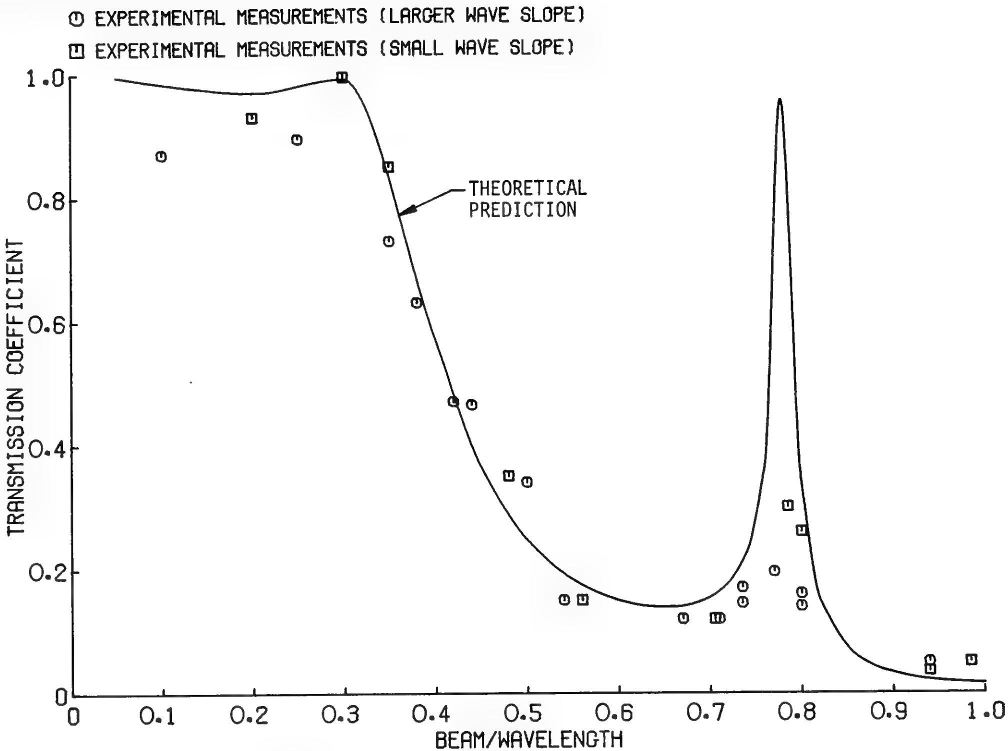

Figure 11. Transmission coefficient for a rigidly fixed Alaska-type breakwater model.

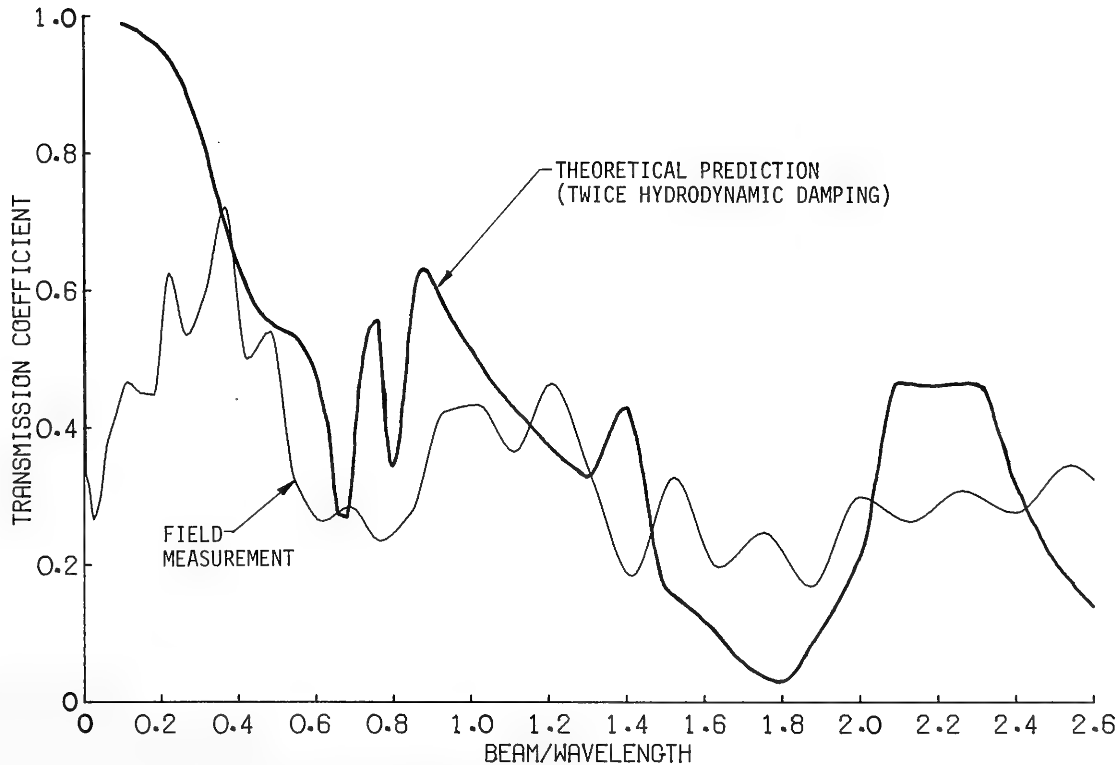

Figure 12. Transmission coefficient for Alaska-type breakwater, Tenakee, Alaska (record TK7-23).

It should be noted that the model for the Alaska-type breakwater was not built to the correct scale to represent the prototype. Further investigation of the physical properties of the prototype after the model tests were complete revealed that it was heavier than originally predicted. The physical properties used in making the theoretical calculations are correct for all the comparisons made in this report. However, care must be exercised in comparing the model test results and the field measurements directly. The physical properties for all the breakwaters discussed in this section are in Appendix F.

The first trough in the transmission coefficient curve results because the wave generated by roll tends to cancel the fixed-body transmission. The sway-generated wave is small but cancels a little bit of the heave-generated wave. The total transmitted wave is then almost in phase with the heave-generated wave at a slightly reduced amplitude. Complex interactions among the components of the transmitted wave continue to result in oscillations of the transmission coefficient up through a B/L of 0.9. At values of B/L above this, the transmitted wave is primarily a result of sway motion except for the peak at B/L equal to 1.4 which results from an increase in the fixed-body transmission. Considering the complexity of the breakwater response, the agreement should be considered to be reasonably good.

(5) Friday Harbor Breakwater. The computed transmission coefficient for the Friday Harbor breakwater is shown in Figure 13. As in the case of the Alaska breakwater calculations, the computations of wave-damping coefficients have been arbitrarily doubled to reduce the excessive calculated motions in the region of resonant motions. In this figure the spacing of data points varies. More points are used to specify the curve in regions of rapid change so that the plotted result accurately represents the theoretical prediction.

In Figure 13, the first trough in transmission coefficient at about B/L = 0.5 results from heave- and roll-generated waves canceling the fixed-body wave transmission. This transmission coefficient is well below the transmission coefficient which would be obtained with the breakwater rigidly restrained and only fixed-body transmission waves passing through. As B/L increases, there is a peak at about 0.7. At this point the heave-generated wave has almost vanished, and the fixed-body transmission is also small. The larger transmission coefficient is primarily the result of a roll-generated wave with a smaller component resulting from sway motion. The next trough at a B/L of 0.9 occurs as the heave motion-generated wave increases and cancels the roll and sway motion-generated components. The fixed-body transmission is very small at B/L of 0.9. As B/L increases beyond 0.9 the transmitted wave is almost totally the result of sway motion of the breakwater.

At larger B/L ratios there are several oscillations in the

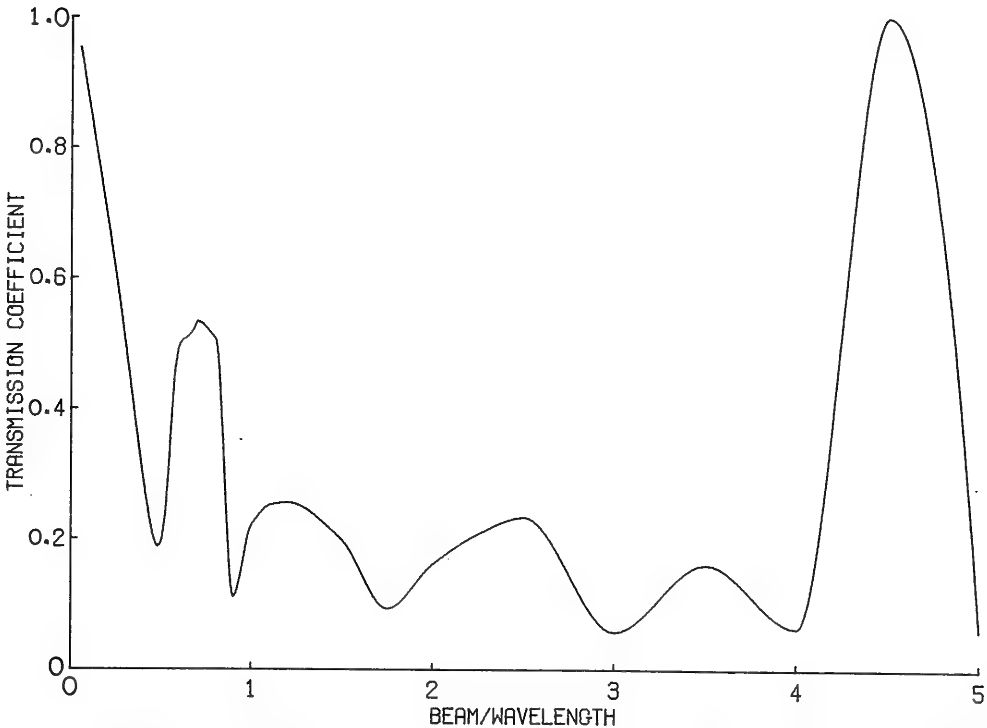

Figure 13. Theoretically predicted (twice hydrodynamic damping) transmission coefficient, Friday Harbor breakwater.

transmission coefficient curve. In this region one must be careful of the analysis because there are certain "irregular frequencies" or "John" frequencies where the approach adopted here breaks down mathematically (John, 1950). These are described with reference to the integral equation technique by Frank (1967). It is extremely difficult to predict where the first of these irregular frequencies will occur when the breakwater cross section is as complicated as the Friday Harbor breakwater. If this cross section were rectangular with the same exterior dimensions as the Friday Harbor breakwater, then the first irregular frequency would occur at $B/L \simeq 1.7$. In practice, one may watch for this mathematical phenomenon by checking the determinant of the matrix inverted to solve the system of equations. In fact, this does decrease in the region of B/L of 1.7 but does not indicate a singular matrix for the calculation in this region of B/L. Since this is beyond the frequency range of primary interest, it is best to simply view the results at B/L greater than 1.7 with extreme caution. The oscillations in the transmission coefficient in this region of B/L are probably the result of these irregular frequencies.

b. Breakwater Motions. In the wave channel experiments performed to date, there has been no attempt to compute the breakwater motions. While the transmission coefficient is the primary measure of breakwater performance, the motions may be very important to the designer, particularly if boats are to be tied to the breakwater. For the theoretical analysis, this is a critical intermediate step where extensive experimental measurements used for comparison would be invaluable.

Friday Harbor Breakwater. The theoretically predicted motions of the Friday Harbor breakwater are shown in Figures 14, 15, and 16. The motion response is almost the same as one would expect from an uncoupled spring, mass, dashpot linear system. The only unusual behavior is the null response in heave at B/L of about 0.75. This null occurs at a point where there is a phase shift in the "added-mass" force, a phenomenon which has been observed in experiments with catamaran-type cross sections (Lee, Jones, and Bedel, 1971), and is a result of resonant wave conditions within the open well of the catamaran.

c. Mooring Line Forces. In recent years a great deal of effort has been expended in understanding and predicting mooring line performance, particularly for moored ships and drilling rigs (e.g., American Society of Civil Engineers, 1971). While many of these analysis techniques could be applied to the moorings of floating breakwaters, this has not been done to date. There are also very few model-scale experiments in which mooring forces have been measured and only a few cases where good field data are available.

Two techniques for calculating the spring constants for mooring lines have been used. At first the catenary equations were applied to find the change in force per unit displacement. While this approach leads to a fairly simple algorithm for the calculation, there are a few problems. In several cases spring constants were needed when the mooring

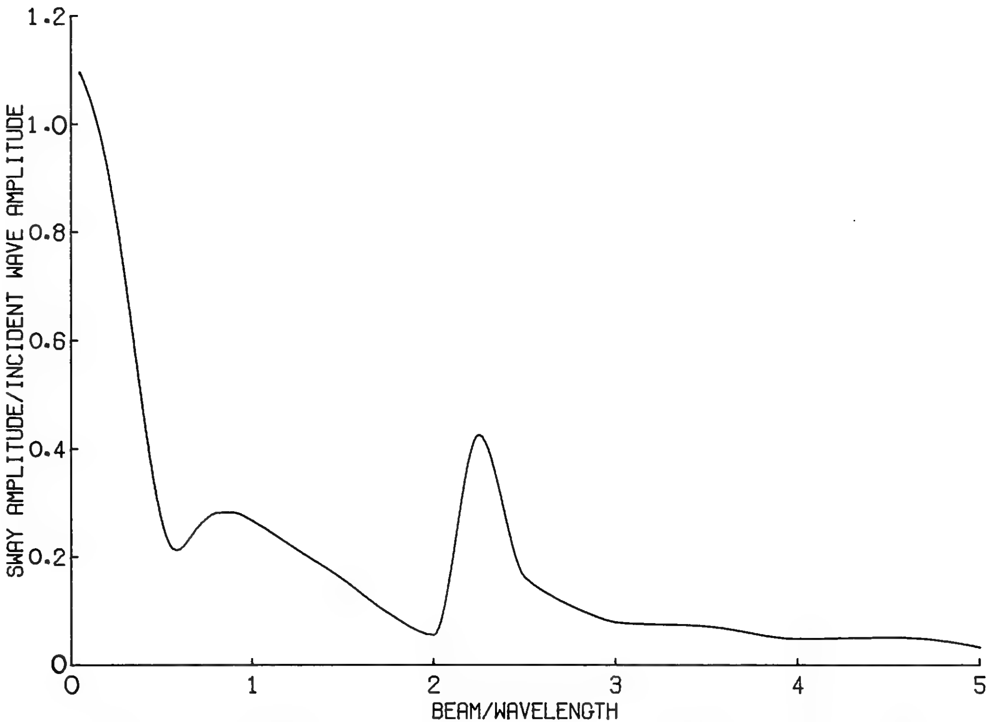

Figure 14. Theoretically predicted (twice hydrodynamic damping) sway motion response, Friday Harbor breakwater.

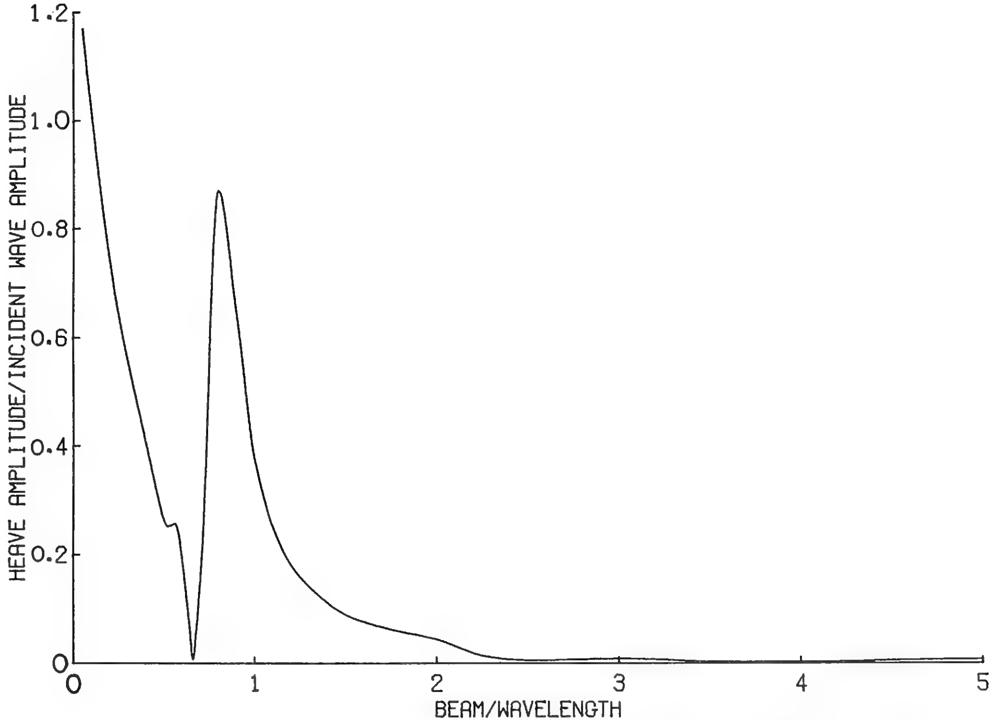

Figure 15. Theoretically predicted (twice hydrodynamic damping) heave motion response, Friday Harbor breakwater.

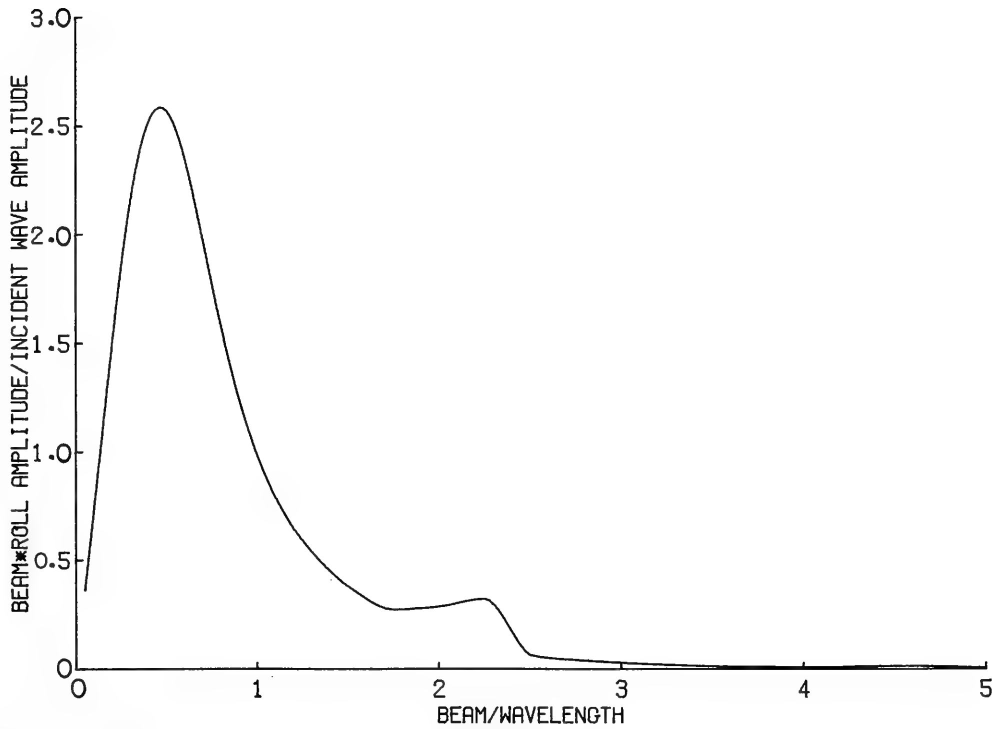

Figure 16. Theoretically predicted (twice hydrodynamic damping) roll motion response, Friday Harbor breakwater.

line was too taut to allow it to become tangent to the bottom at the anchor. If this condition occurs, or as it is approached, the catenary equations no longer apply. For many full-scale installations, a combination chain and synthetic line anchor cable is used. This combination anchor cable presents problems in attempting to use the catenary equations.

Comparisons between the mooring line forces calculated using the catenary equations to predict spring constants showed poor agreement with measured results (Adee, 1975). While the general trends were reproduced, an increase in the predicted spring constants of about a factor of 4 would have been required to bring the theoretical prediction into agreement with the measured results.

To overcome the problems encountered in using the catenary equations, a system based on discretization of the mooring line and static equilibrium was developed. This method is described in Appendix B.

(1) Proposed Oak Harbor Breakwater. One of the few model tests in which mooring line forces were measured was performed by Davidson (1971) for the floating breakwater proposed for Oak Harbor, Washington. The model configuration with properties scaled to the prototype is included in Appendix F. The shape of this breakwater is basically an inverted bathtub with foam flotation.

Applying the theory to predict the mooring line force in the seaward anchor line at a water depth of 29.5 feet, one obtains the results shown in Figure 17. The mooring-force coefficient is defined as the amplitude of the force oscillation divided by incident wave amplitude times the weight per unit length of the breakwater. In this figure, the large range of the experimental results is directly related to incident wave amplitude. The smaller incident wave amplitudes generally produce lower measured mooring line forces per unit amplitude except at the beam to wavelength ratio of 0.49. Since the linear theory is mathematically correct only in the limit as wave amplitude tends to zero, one would expect the best correlation between theoretically predicted and measured results for small amplitude incident waves. The results shown in Figure 17 are consistent with this expectation. However, the very large difference in mooring line forces as incident wave amplitude increases indicates a highly nonlinear response.

A potential explanation for the nonlinear response observed in these experiments results from the condition of the mooring lines at the 29.5-foot water depth used for the model tests. Under these conditions, the mooring lines no longer maintain a catenary shape. When the initial tension in the mooring lines is increased to this level, they respond with very large changes in mooring line force for very small displacements of the breakwater. Consequently, small deviations in the planned positioning of the anchors will lead to large changes in forces in the mooring line. This condition clearly should be avoided in prototype installations where very large mooring line forces are to be avoided.

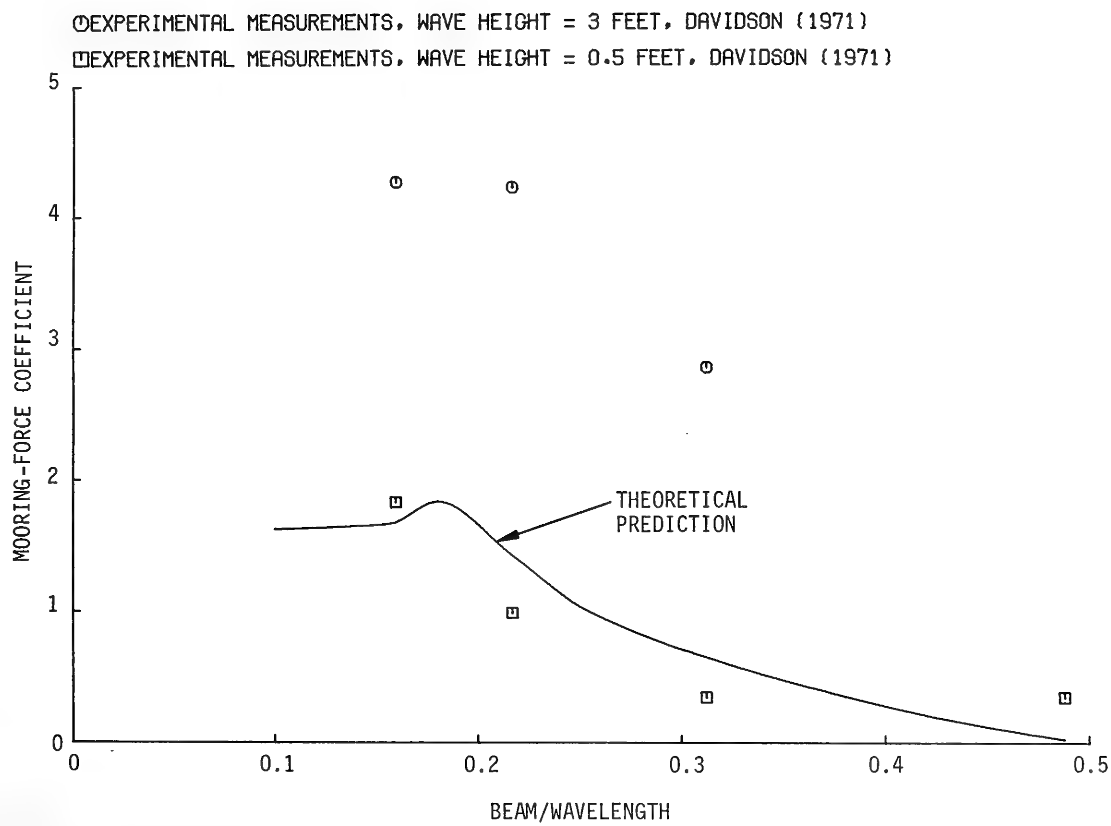

Figure 17. Seaward mooring line force for proposed Oak Harbor breakwater.

A second possible explanation of the nonlinearity results when the "drift force" on the breakwater is considered. If one carries the hydrodynamic analysis to second order, there are terms at zero frequency which yield a force on the breakwater in the direction in which the incident waves are traveling. This force has the same effect as increasing the initial tension in the mooring line and is proportional to wave amplitude squared. Increasing the initial tension tends to increase the spring constants of the mooring lines leading to larger oscillating forces as well.

(2) Alaska-Type Breakwater. Mooring-force coefficients theoretically predicted and measured for the Tenakee, Alaska, breakwater are shown in Figure 18. For the field data the mooring-force coefficient is obtained by taking the square root of the mooring-force spectral density divided by the incident wave spectral density and then dividing by the weight per unit length of the breakwater. Again, as with the Oak Harbor model experiments, there is good agreement, especially in predicting the peak in the curve near B/L of 0.65.

One important aspect of the mooring line problem which should not be overlooked is a comparison between the model-scale results and the field measurements. For the Alaska-type breakwater, all the measured results indicate the amplitude of oscillation in mooring line force is in the order of hundreds of pounds, not thousands of pounds, as was predicted for the Oak Harbor breakwater in the model-scale tests.

When the mooring line tension data recorded at Tenakee are plotted as a function of time as in Figure 19, one observes that there clearly are oscillations associated with the incident waves. However, there are also low-frequency oscillations which are of greater magnitude. A complete explanation of the origin of these low-frequency forces has not been developed. However, one possible explanation is that these forces are a result of breakwater oscillation at the sway resonant frequency. Since the spring constant for sway motion is very small, one would expect a long natural period. Theoretically predicted sway motion response for the breakwater is plotted in Figure 20. Predicted natural periods are 64, 37, and 29 seconds for tidal conditions of mean lower low water (MLLW), +10 and +20 feet, respectively. By applying a high-pass filter to the field data, one obtains the spectrum of force oscillation shown in Figure 4. Here, a peak is at a period of about 53 seconds (tide height = +7 feet). The predicted sway natural frequency is at 45 seconds when the tide height is +7 feet, which indicates that this explanation is plausible.

(3) Friday Harbor Breakwater. The predicted performance of a seaward mooring line on the Friday Harbor breakwater is shown in Figure 21 for a tide height of +5.33 feet. The Friday Harbor mooring lines are different than those at the other breakwaters. They are composed of a section of chain attached to the breakwater, followed by a length of nylon rope and, finally, another section of chains at the bottom. This particular tidal condition was chosen because it is the condition during record FH 7-8 used later for comparison.

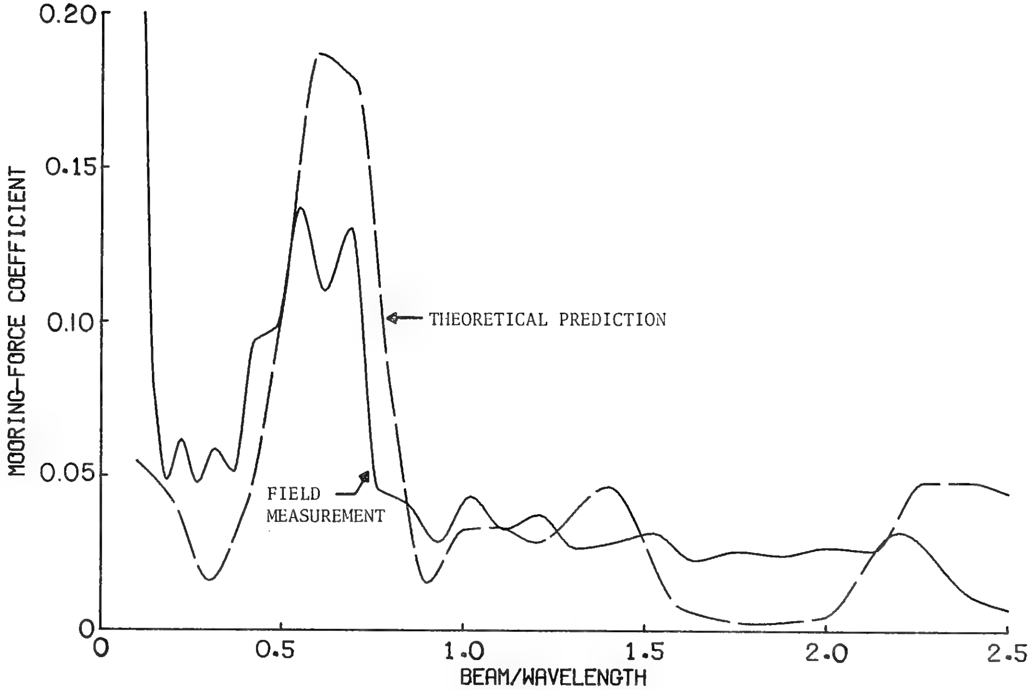

Figure 18. Seaward mooring line mooring-force coefficient, Tenakee, Alaska (record TK7-23).

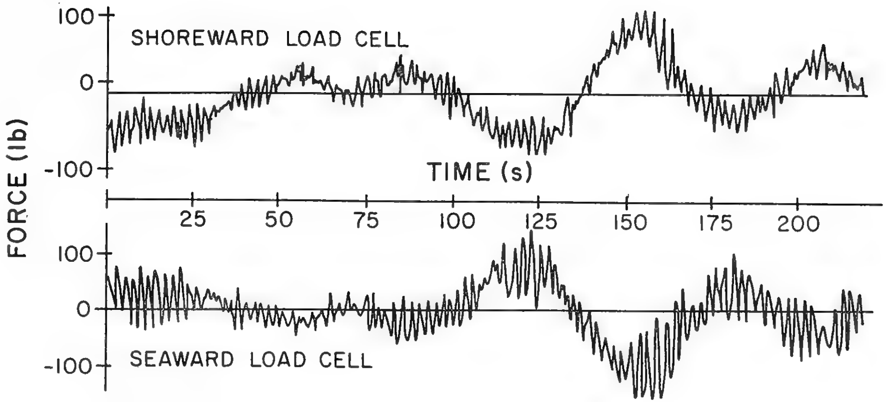

Figure 19. Recorded time series, Tenakee, Alaska (record TK7-23).

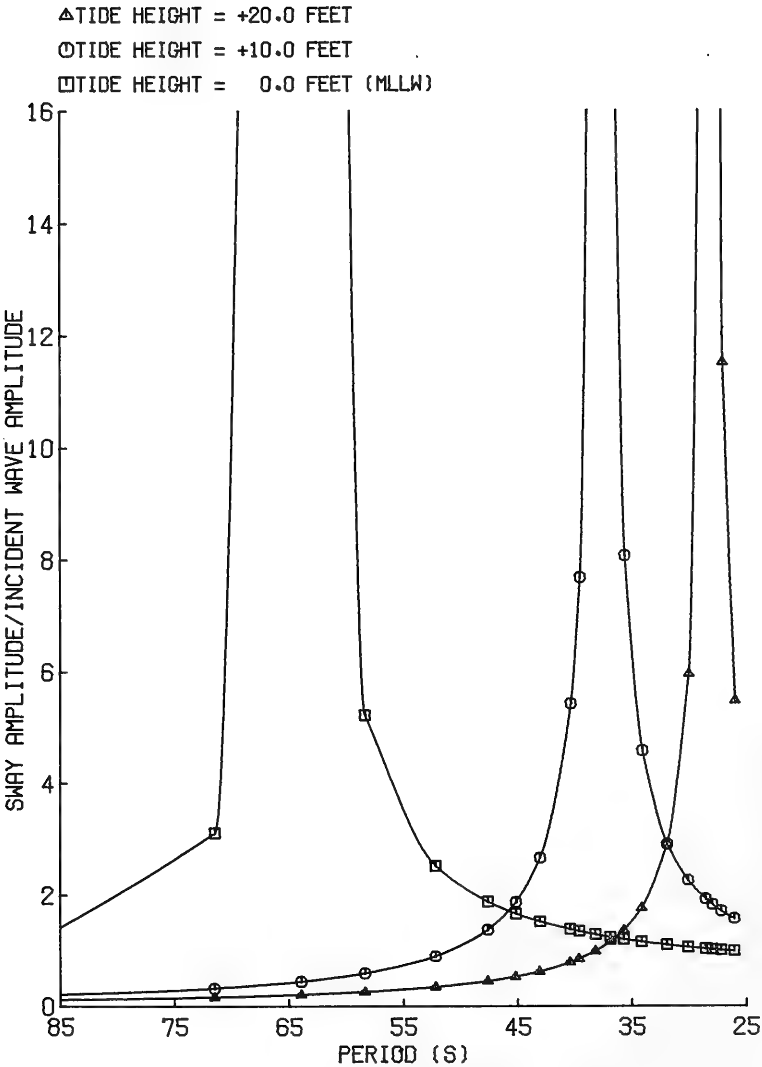

Figure 20. Theoretically predicted long-period sway response of Alaska-type breakwater, Tenakee, Alaska.

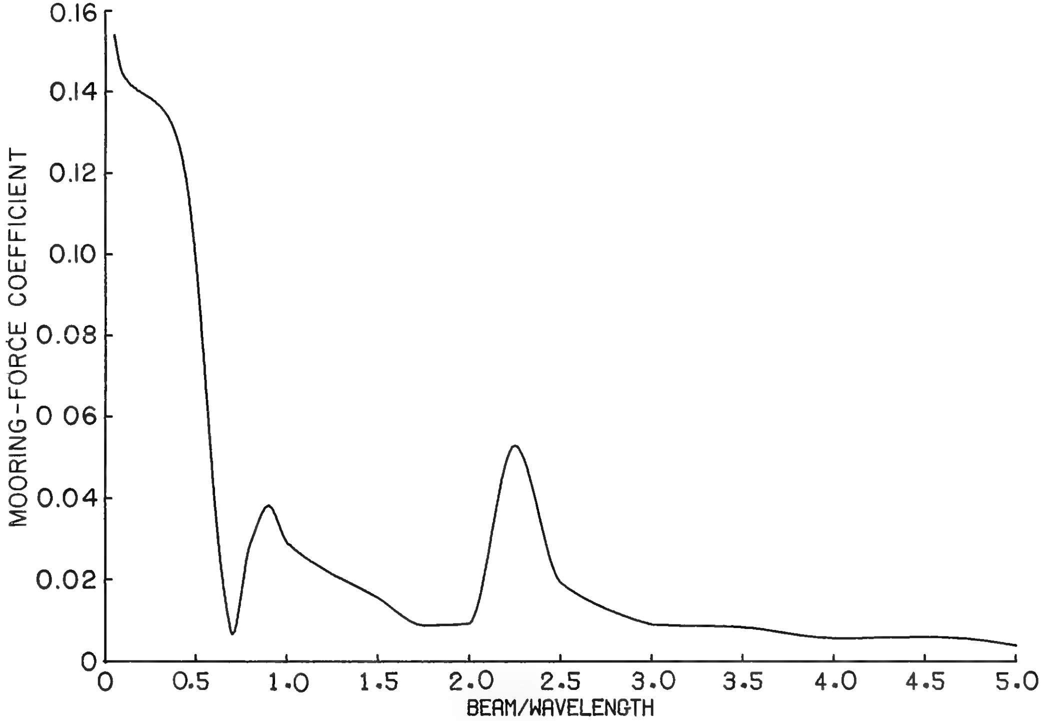

Figure 21. Theoretically predicted seaward mooring line mooring-force coefficient, Friday Harbor breakwater.

Low-frequency predicted sway motion and resonance are shown in Figure 22 for MLLW, +5.33 feet, +10 feet, and +15 feet tide heights.

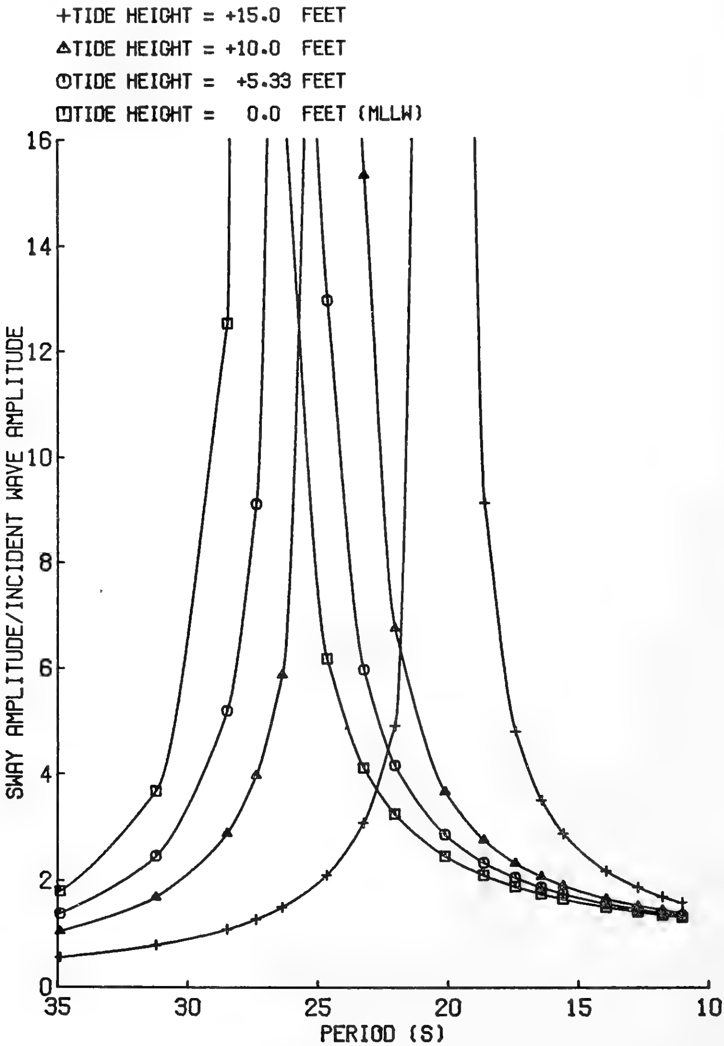

Figure 22. Theoretically predicted long-period sway response, Friday Harbor breakwater.

III. FIELD DATA

1. Layout.

The site of the floating breakwater instrumented in this study is located at Friday Harbor, Washington, on San Juan Island, just east of Victoria, British Columbia (Fig. 23). The breakwater is 25 feet wide, 904 feet long, anchored in approximately 40 feet of water, and was installed in October 1972. The structure is made of Polyolefin flotation tanks linked together by a matrix of large wooden timbers. It is laid out in an expanded L-shape, the inside angle being 115°, with the shorter leg (227 ft.) directed toward shore and the longer leg (627 ft.) toward magnetic north. The site itself is protected on three sides by San Juan and Brown Islands off the harbor entrance. This leaves an 0.25-mile-wide channel into the harbor with a northeasterly fetch of about 1.7 nautical miles. Southeasterly winds can also generate waves of importance parallel to the shorter leg where the fetch is about 1 nautical mile.

2. Instrumentation.

The shorter leg was instrumented in this study for two reasons: (a) the most frequent winds are out of the southeast, and (b) barges were to be tied to the longer leg during the winter months for added protection. However, the wave gages are positioned to give the proper incident and transmitted wave data for all relative wind directions (Figs. 24 and 25).

Four types of time-dependent data which are basic to describing the response of the breakwater were collected: (a) wind velocity and direction; (b) wave heights at key locations; (c) anchor cable forces; and (d) directional acceleration and angular motions of the breakwater. The locations of the measuring sensors are shown on Figure 25. Signals from the sensors were carried by underwater cable to the recording system which was located in a small building mounted near the center of the short leg.

3. Wind Data.

Windspeed and direction were measured by Weather Measure Corporation's W121 sensor. Some additional circuitry was required to record the windspeed, and the sensor was recalibrated to this circuit. The sensor was mounted on the breakwater at the intersection of the two legs at 20 feet above the water surface.

4. Waves.

Wave characteristics were measured at four locations with the second

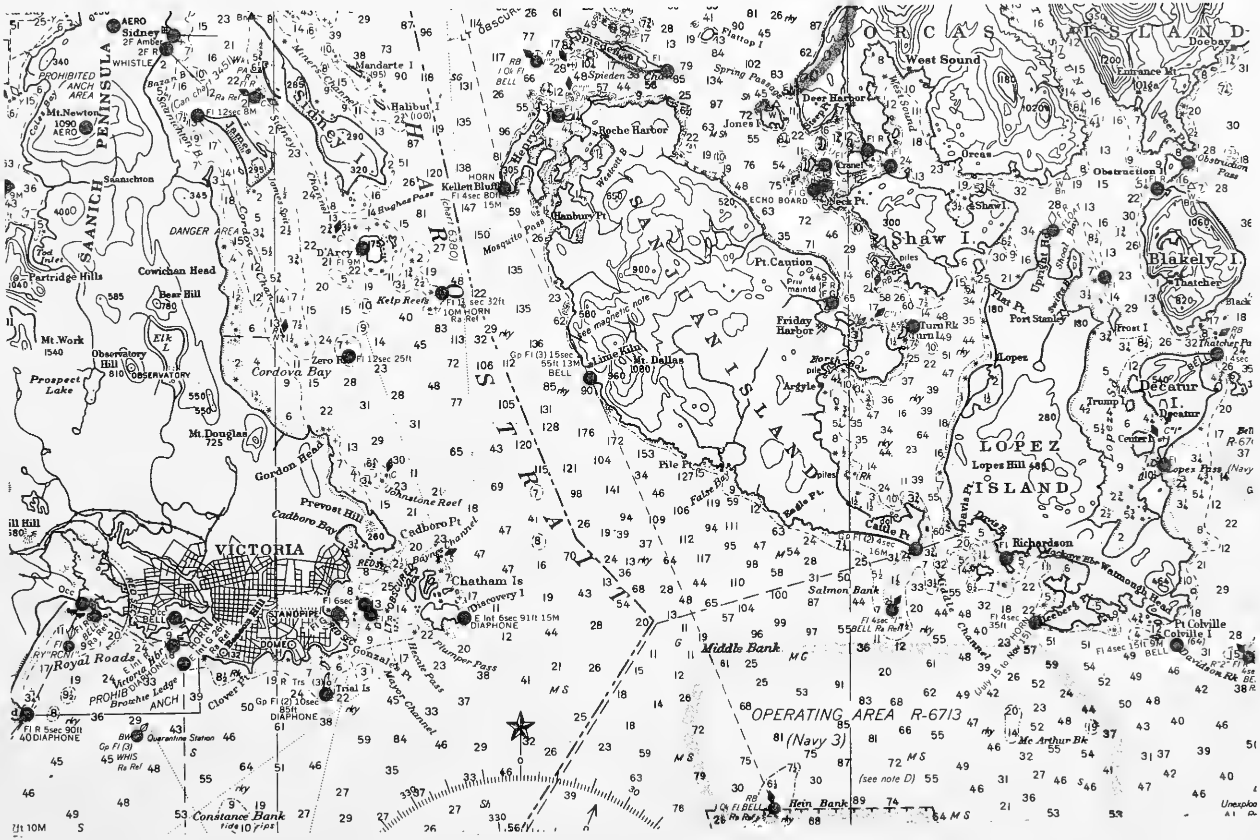

Figure 23. General Location Map

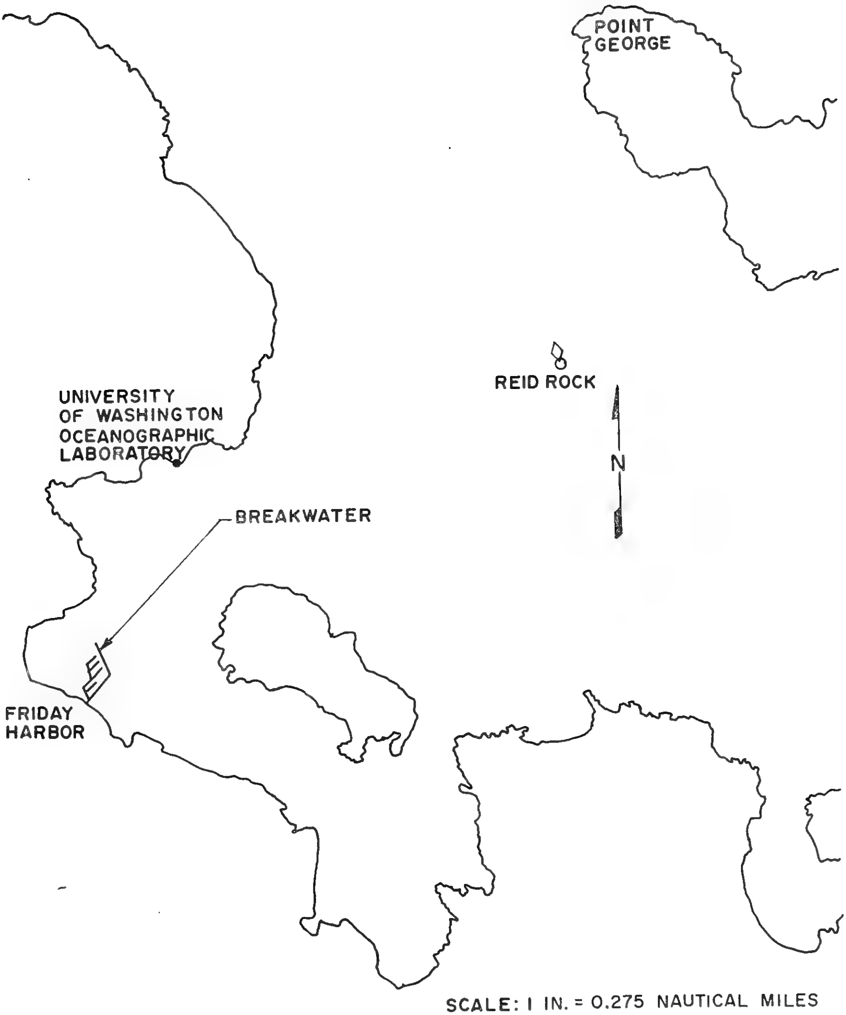

Figure 24. Field experiment site location map.

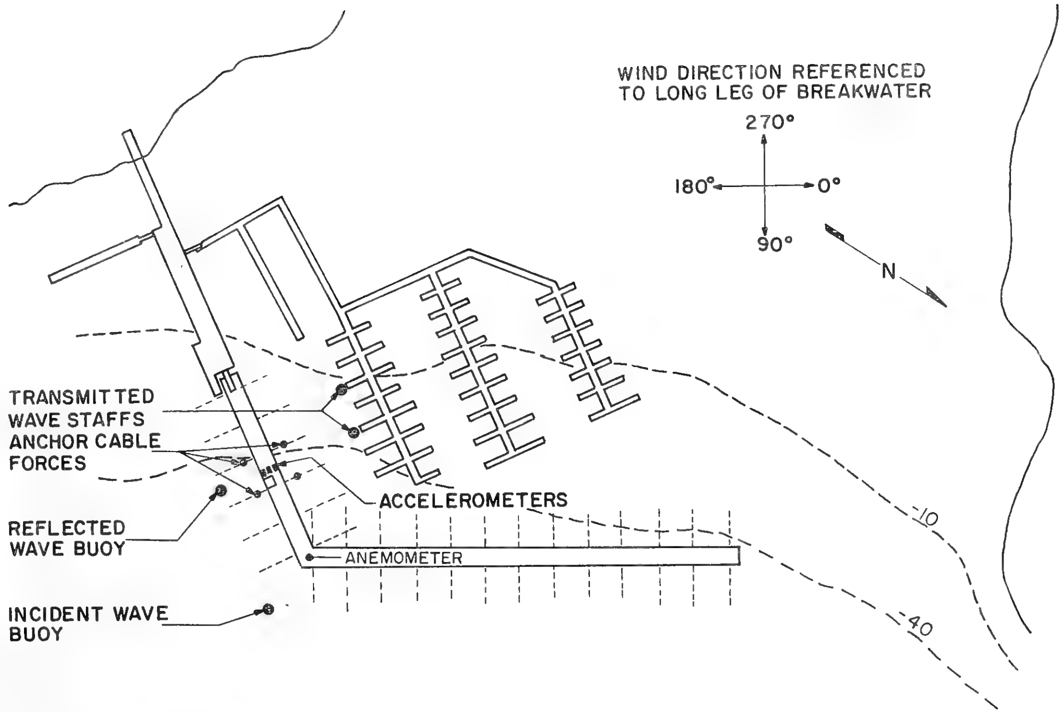

Figure 25. Instrumentation location plan, Friday Harbor breakwater.

transmitted gage being used as a backup. Two spar buoys instrumented to measure wave elevation were located outboard of the breakwater and positioned so that one measured the incident wave field, and the other measured the incident plus reflected wave field. Two stationary gages were attached to pilings behind the breakwater to measure transmitted wave height. All four gages were of the resistance type. The spar buoys were used outside the breakwater to help reduce navigation hazards and because of the costs and logistics of placing stationary piling at these locations.

The buoys were made of two sections of PVC pipe, the lower section being 6 inches in diameter and 15 feet long, and the upper section of 3-inch diameter and 12 feet in length with the upper 8 feet wound with a resistance wire. Four feet were exposed above the water surface, and a 2.5-foot-diameter disc was attached to the bottom to damp vertical motions. The natural periods in heave and roll, respectively, are 18 and 14 seconds, well above the anticipated maximum wave period of about 4 seconds. See Appendix J for a complete description of the wave staff and buoy designs.

5. Cable Forces.

Anchor cable forces were measured using a bonded strain gage-type load cell that was placed in the anchor chains beneath the water surface. These cells and the associated electronics were designed and built for this project. They have an overall system accuracy of 0.75 percent of the designed or rated total load cell capacity over a temperature range of 10° Celsius (design load 12,500 pounds). These load cells employ a four-arm wheatstone bridge circuit which has two strain gages in each leg of the bridge and are self-temperature compensating. The units are O-ring sealed and wired directly to the bridge amplifier circuitry mounted in the recording package.

6. Motion Package.

Breakwater accelerations were measured using three Kistler servo-accelerometers (Model 303T). One accelerometer, oriented horizontally, was mounted at the center of the breakwater to measure the sway acceleration. The other two were oriented vertically and mounted at opposite outboard edges of the breakwater to measure the vertical accelerations. The heave acceleration was obtained by taking the average of the signals from the two outboard accelerometers; the roll acceleration was obtained by taking the difference of these two signals and dividing by the distance between them. The accelerometer locations are indicated in Figure 25.

7. Data Acquisition System.

The data recording and electronic package was built around the Sea

Data Corporation's Series 610 four-track incremental digital cassette tape recorder. The complete package, which included all the electronic circuitry for the individual transducers plus the tape recorder, was housed in a watertight, 6-inch-diameter PVC cylinder 5 feet in length. The system was designed to be operated manually or in a completely automated mode, thus requiring only periodic tape changes (Fig. 26).

In its automatic mode, the system was activated when the windspeed reached or exceeded a preset value and stayed there for at least 1 minute. At this point, a single 17-minute sample of all the inputs was taken. Each 68 minutes following this, another 17-minute sample was recorded if the wind was still above its preset value; if not, the system was shutdown until the windspeed increased. Each 17-minute record consisted of 2,048 samples, taken at 0.5-second intervals, of all 13 channels plus a clock channel. Twenty-five of these records could be recorded on a single cassette tape.

8. Data Processing and Analysis.

The initial step in the data handling was to transfer the data from the individual cassettes to seven-track magnetic tape by means of the Sea Data reader. These tapes were then converted to a computer compatible format on the University of Washington's CDC 6400 computer. The histograms for all records plus the basic statistics, i.e., the minimum, maximum, mean values and standard deviations as well as the transmission coefficients based on these standard deviations, were then computed and tabulated (App. G). A digital filter, with a cutoff frequency of 0.05 hertz (Gold and Radar, 1969) was applied to the transmitted wave data prior to these tabulations to remove tidal drift. The transmission coefficients given in these summary sheets are a ratio of the standard deviations for the transmitted and the incident wave gages.

In the initial conversion, the data were checked for reader errors. These points were smoothed using a linear interpolation between the preceding and the following good data points. Following this, the data were checked for extreme values. Data points departing from the mean by more than five standard deviations were smoothed in the same manner as were the reader errors. In no case did the number of errors warrant elimination of a complete record (greater than six bad points). Record FH 11-1, however, had bad data for channels 3, 4, 5, 7, and 8. This record was run manually while calibrations were being made, and the affected channels were not connected properly at this time. The final edited data were then stored on magnetic tape.

The autospectra for all the wave data for all records were computed with a more complete analysis of the force and acceleration data applied to the more desirable events.

Digital filtering techniques were used prior to spectral analysis on all the wave and force data. The procedures used follow those given

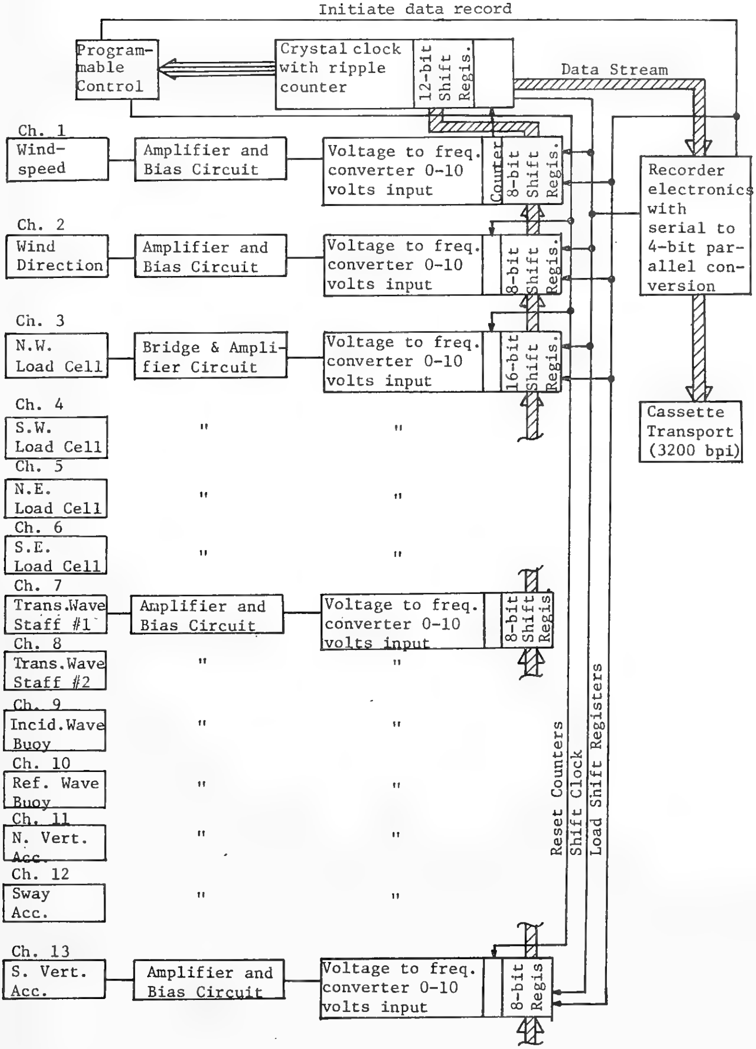

Figure 26. Instrumentation and recording package layout.

by Gold and Radar (1969). The first step in the development of this filter function is to assume an ideal filter response function.

$$F_\ell(f) = \begin{cases} 1, & 0 \le |f| \le f_c \\ 0, & f_c < |f| \le f_n \end{cases}$$
$$F_h(f) = \begin{cases} 0, & 0 \le |f| < f_c \\ 1, & f_c \le |f| \le f_n \end{cases} \qquad (12)$$

where f_c is the cutoff frequency, f_n the Nyquist frequency, and $F_\ell(f)$ and $F_h(f)$ are the ideal low-pass and high-pass filter response functions.

The ideal filter response function is then Fourier-transformed to the time domain, giving the impulse response function, which is truncated by using an appropriate window function and transformed back to the frequency domain giving a complex frequency response function. The number of points used in representing the filter function is allowed to vary and the resulting convolution with the original time series is accomplished by using the overlap-add method of convolving smaller series with larger ones. This allows for more economical filtering procedures.

This gives three variables to choose from in the final filter function design: the length or number of points used in the filter, the type of window used to truncate the impulse response function, and the number of points to be truncated.

This procedure is analogous to spectral estimation techniques except for the truncation of the impulse response function. The larger the number of points used in the filter function, the better the estimate. The smoother the window function, the broader the transition band. In addition, the ripple or Gibb's phenomena is reduced. Generally speaking, the more points that are truncated (set to zero) the better the resulting approximation. In practice, the actual number is determined experimentally by comparing results for different truncation values. This results in setting approximately 20 percent of the impulse response function to zero. The hanning window function was used with 128 points in the filter response function and 38 points being set to zero in the impulse response function. That is:

$$h(n\Delta t) = w(n\Delta t)\, h(n\Delta t)$$

and

$$w(n\Delta t) = \begin{cases} \frac{1}{2}\left(1 + \cos \pi \frac{n-1}{45}\right), & 1 \le n \le 45 \\ 0, & 45 < n < 83 \\ \frac{1}{2}\left(1 - \cos \pi \frac{128-n}{45}\right), & 83 \le n \le 128, \end{cases} \qquad (13)$$

where $h(n\Delta t)$ is the impulse response function and $w(n\Delta t)$ is the hanning window function. The final filter response function is defined as:

$$F(f_n) = \sum_n \beta(n\Delta t) e^{-j2\pi n f_n \Delta t},$$

where $j = \sqrt{-1}$ and Δt is the constant time interval between samples.

The transition band or the frequency increment traversed by the cutoff of the filter function can be approximated by:

$$\lambda = \frac{10}{128} = 0.078$$

and the maximum stopband attenuation for the hanning window is 55 decibels. These values can only be achieved through proper filter design. The actual values for the filters used are $\lambda = 0.08$ and a maximum attenuation of greater than 55 decibels. The ripples in the passband for each filter used were below 0.01 percent. These values could be improved on by increasing the number of points used for the filter response function estimate. Also the stopband attenuation could be improved, at the expense of a wider transition band for a given size filter function by using the Blackman window function. However, the accuracy of the filter response functions used exceeds that of the measurements and is sufficient for this application.

After initial processing and prior to all spectral calculations a tapered cosine data window was applied to the first and last 10 percent of the data to reduce spillover of spectral energy to adjacent frequency points. For data stretching from n = 1 to n = N, the formulas for the data window are:

$$w(n\Delta t) \begin{cases} \frac{1}{2}\left(1 - \cos \pi \frac{n-1}{0.1N}\right) & \text{for } 1 \le n \le 0.1N \\ 1 & \text{for } 0.1N < n < 0.9N \\ \frac{1}{2}\left(1 - \cos \pi \frac{N-n}{0.1N}\right) & \text{for } 0.9N \le n \le N. \end{cases} \tag{14}$$

The data were then transformed directly using fast Fourier transformation procedures and smoothed by averaging adjacent raw spectral components. Initial sampling was performed at 0.5-second intervals with 2,048 samples per record, and 20 adjacent points averaged together in the autospectral calculations to get the final smoothed spectral estimates. This gives a frequency resolution of 0.0195 hertz with 40 degrees of freedom per spectral estimate.

All of the wave data was high-pass filtered, using the filtering techniques previously outlined with a cutoff frequency of 0.05 hertz. This was done to remove the tidal influence on the transmit5ed wave staffs and to eliminate any possilbe buoy motion in the incident wave records. Also the anchor cable force data were separated into a low-and high frequency signal using the same filtering procedures. For the high-frequency case this was done to remove the influence of the large low-frequency spikes in the spectra. A high-pass filter with a cutoff frequency of 0.1 hertz was used.

For a closer look at the low-frequency information in the anchor cable force data, a new time series was generated from the original record by sampling every eighth data point. To reduce aliasing of the higher frequency energy in the original signal, each record was low-pass filtered prior to this sampling using the filtering techniques previously outlined with a cutoff frequency of 0.2 hertz. The sampling of every eighth point of the original time series gives a sampling interval of 4 seconds, a Nyquist frequency of 0.125 hertz and a record length of 256 points or 1,024 seconds. Five raw spectral points were averaged together to give the final smoothed spectral estimates. This results in a frequency resolution of 0.0049 hertz with 10 degrees of freedom per spectral estimate.

A total of 95 records was recorded at the site from 1330 hours on 30 December to 3 May 1975. There were no known equipment failures or breakdowns except for one of the load cells going off scale at low tide on the first tape (FH 7, NW load cell channel 3). A complete summary of these events is given in Appendix G. Also, Figure 25 gives the relative locations of the individual transducers.

The wind direction in all cases is referred to the long leg, which has a north-south compass bearing (magnetic declination in this area is 23° east). There are two wind-direction windows of interest. For the long leg, the directions are approximately 50° to 95°; for the short leg, 130° to 160° (Figs. 24 and 25).

Two storm events were chosen for presentation and further analysis. These events cover records FH 7-6 through FH 7-12 and FH 11-8 through FH 11-14 (Apps. G and H). They were chosen because of their directions relative to the short and long legs, respectively, and because of their duration and magnitude. Both events lasted for over 7 hours with maximum windspeeds in excess of 35 miles per hour, with all the mean wind direction within or close to the desired wind-direction windows. Appendix H gives the pertinent wave spectra and transmission curves for the above two events.

The average overall response or transmission curves for the events within each wind-direction window and for all the recorded data, are given in Figure 27. These plots were obtained by averaging the square root of the ratio of the transmitted to the incident wave spectras for the records indicated for each curve. Therefore, they have the same frequency resolution of 0.0195 hertz.

A puzzling feature in all the transmission response curves calculated from field data is the rise at lower frequency to a value near one and then dropping off again. This can partially be attributed to a lack of

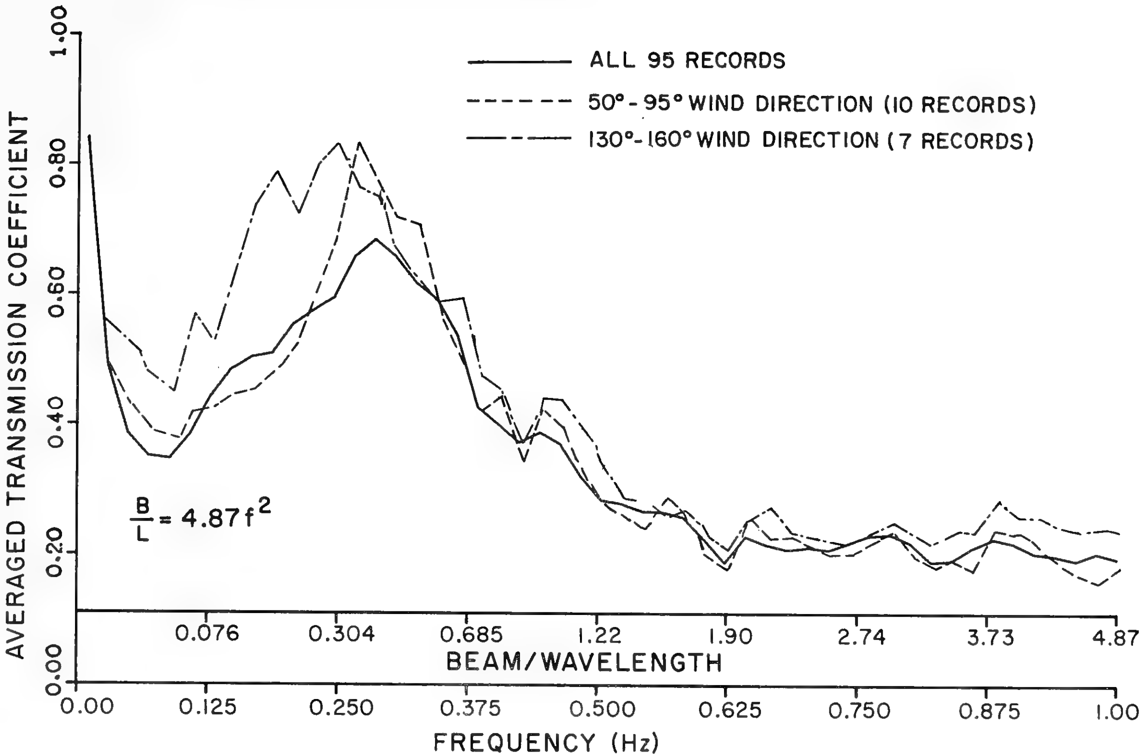

Figure 27. Average transmission curves for Friday Harbor breakwater.

energy in the incident wave spectra at lower frequencies. This possibility can be backed up in part by data from two similar projects undertaken in the past 2 years on a styrofoam-filled concrete-type breakwater (Christensen and Richey, 1974). The first is located in relatively sheltered water while the second breakwater is located near the open ocean where swell becomes an influence and results in a much broader spread of spectral energy over the frequency band in question. The first breakwater showed similar response curves to Friday Harbor while the second tended to approach one near the lower frequencies and stay there (see App. H., Figs. H-10 and H-11).

All of the anchor cable data showed a very dominant amount of energy at lower frequencies. Appendix I shows the results of the low-frequency analysis for three of the anchor cable force signals for record FH 7-8. The autospectra for the force gages show several large peaks in this lower frequency band (App. I, Figs. I-1, I-2, and I-3). The exact location of these peaks varies for different records, but in all records analyzed, the dominant amount of energy in the force spectra was contained in this lower frequency band of approximately 0.015 to 0.05 hertz. In most cases, however, a relatively dominant peak appeared in the 56- to 63-second-period range. The anchor forces measured were all quite low; the largest range was only 628 pounds. The cables are spaced at 50-foot intervals.

The phase and coherency spectra for three of the force gages for record FH 7-8 are given in Appendix I (Figs. I-4 through I-7). They show a strong linear relationship between the gages on the same side of the breakwater and for the opposing gages. The forces in the two anchor lines on the same side were in phase; the two opposing were 180° out of phase. This indicates that the sway or roll motions are dominant in this frequency range. The accelerations at these lower frequencies were too small to be recorded and could not be used to help confirm which motion was involved. However, in the overall frequency range (0 to 1.0 hertz) the variances for sway and heave were two orders of magnitude greater than roll, which indicates that sway would have to be the dominant motion involved here.

The analysis of the complete frequency range for the force data for FH 7-8 is shown in Appendix J (Figs. J-2 through J-8). The data were high-pass filtered (f_c = 0.1) for these spectra. A comparison of the variances computed for the high- and low-frequency sections of the force spectra showed that over 90 percent of the energy in all cases analyzed was contained in the lower frequencies. A summary of the force data, without any filtering, for all the data collected in this experiment is given in a table.

The autospectra for the force gages (FH 7-8) are relatively spread out (see App. J, Figs. J-2, J-3, and J-4), with the outside force gages showing a greater response to the lower frequency incident wave energy than the inside gages. However, the outside and the opposing gages show relatively high coherency, with the outside gages being in phase and the

Table. Summary of anchor cable force statistics.

	Standard deviations (pounds)				Maximum values (pounds)				Variations, max. to min. (pounds)			
	NW	SW	NE	SE	NW	SW	NE	SE	NW	SW	NE	SE
FH7 - 1	9.155	9.811	7.016	6.077	39.096	30.896	31.920	17.545	60.000	64.000	48.000	36.340
FH7 - 2	24.055	51.877	14.026	30.339	57.895	161.549	42.344	96.340	136.000	272.000	80.000	176.960
FH7 - 3	16.689	65.078	13.839	38.205	75.580	325.976	66.357	193.091	88.000	500.000	120.000	278.080
FH7 - 4	.000	89.072	14.051	55.777	75.580	445.255	43.045	278.098	88.000	628.000	84.000	390.260
FH7 - 5	2.057	97.282	16.930	61.033	15.646	333.143	47.802	221.935	16.000	560.000	108.000	350.760
FH7 - 6	18.688	50.922	11.194	27.538	40.508	156.487	23.366	90.272	76.000	252.000	60.000	137.460
FH7 - 7	10.657	82.997	14.872	46.791	51.649	259.791	50.953	162.782	56.000	472.000	100.000	274.920
FH7 - 8	1.003	86.332	13.652	48.214	7.844	291.235	37.668	173.786	8.000	496.000	80.000	290.720
FH7 - 9	1.128	80.256	12.471	47.411	7.793	362.348	34.456	197.821	8.000	540.000	68.000	304.940
FH7 -10	5.188	131.584	19.011	82.184	26.399	397.524	48.775	283.358	28.000	636.000	96.000	410.800
FH7 -11	20.866	86.769	15.340	52.033	88.545	305.942	43.058	195.538	108.000	520.000	88.000	306.520
FH7 -12	34.384	62.609	19.570	38.895	72.790	306.050	41.584	191.569	172.000	424.000	128.000	262.280
FH7 -13	20.978	39.646	14.441	26.267	46.319	199.034	39.261	130.431	148.000	304.000	100.000	257.540
FH7 -14	21.201	40.827	12.534	24.107	66.110	173.650	37.349	116.288	144.000	260.000	88.000	172.220
FH7 -15	24.710	54.314	14.292	31.875	108.727	195.614	57.304	109.471	176.000	344.000	96.000	188.020
FH7 -16	6.606	82.334	15.615	49.404	33.703	328.021	44.489	193.378	36.000	516.000	92.000	300.200
FH7 -17	.000	71.200	9.615	36.055	33.703	224.199	38.805	118.011	36.000	372.000	64.000	192.760
FH7 -18	.000	47.441	7.594	21.849	33.703	162.227	20.866	93.127	36.000	280.000	48.000	137.460
FH7 -19	21.840	41.588	14.847	20.752	54.065	157.809	35.505	78.933	104.000	340.000	104.000	145.360
FH7 -20	2.534	16.865	20.600	11.112	23.655	216.094	98.244	69.665	24.000	232.000	116.000	105.860
FH8 - 1	23.966	10.425	16.246	10.748	24.963	49.370	80.237	8.724	132.000	64.000	96.000	58.460
FH8 - 2	24.306	66.479	9.749	31.996	55.198	300.522	24.714	154.788	132.000	420.000	52.000	211.720
FH8 - 3	19.813	99.539	11.028	53.237	50.882	322.562	29.327	172.246	108.000	524.000	60.000	267.020
FH8 - 4	22.521	141.836	13.626	76.751	48.645	660.252	26.833	382.881	120.000	860.000	72.000	477.160
FH8 - 5	17.970	67.053	8.112	32.891	44.309	223.880	20.041	119.696	100.000	348.000	44.000	175.380
FH8 - 6	22.001	53.054	11.192	24.474	67.313	231.713	33.520	121.875	124.000	336.000	68.000	164.320
FH9 - 1	18.110	50.773	9.177	27.526	51.008	187.160	28.923	99.722	124.000	292.000	60.000	153.260
FH9 - 2	13.179	23.756	10.432	15.784	36.082	72.692	35.365	47.053	76.000	136.000	64.000	88.480
FH9 - 3	14.533	36.725	8.396	19.000	36.962	132.153	25.851	81.354	88.000	216.000	56.000	121.660
FH9 - 4	19.735	50.283	7.926	23.144	48.880	159.877	21.541	79.507	108.000	272.000	44.000	131.140
FH9 - 5	17.808	45.376	7.724	22.556	55.144	142.958	18.757	70.823	112.000	284.000	40.000	116.920
FH9 - 6	21.681	51.506	10.536	27.655	54.692	173.777	28.025	91.162	124.000	292.000	56.000	150.100
FH9 - 7	19.174	38.806	10.916	20.378	45.004	99.019	29.555	52.121	96.000	188.000	60.000	101.120
FH9 - 8	19.020	40.774	13.595	25.726	45.430	141.364	32.545	92.043	108.000	224.000	76.000	150.100
FH9 - 9	13.796	30.255	8.942	17.901	38.755	111.779	26.357	73.252	80.000	180.000	60.000	112.180
FH9 -10	16.768	42.001	10.086	24.075	57.927	142.372	29.720	82.578	108.000	256.000	60.000	135.880
FH9 -11	21.662	56.483	9.620	32.725	55.551	198.810	27.283	105.899	120.000	340.000	52.000	176.960
FH9 -12	18.393	73.711	8.438	38.399	61.489	242.349	20.758	129.846	124.000	436.000	52.000	214.880
FH9 -13	16.287	62.127	7.077	29.598	41.474	222.018	16.948	119.112	96.000	336.000	44.000	173.800
FH9 -14	17.753	76.333	8.323	38.727	41.791	292.927	23.927	142.024	108.000	456.000	52.000	232.260
FH9 -15	26.975	68.463	11.023	33.782	65.956	212.446	22.988	114.642	124.000	352.000	52.000	176.960
FH9 -16	18.338	31.378	16.039	21.074	38.091	98.716	35.680	64.331	96.000	164.000	80.000	107.440
FH9 -17	20.233	38.920	16.823	25.271	49.889	121.439	43.842	76.554	112.000	200.000	96.000	129.560
FH9 -18	21.148	55.706	11.080	32.035	47.555	240.434	27.454	148.562	136.000	340.000	64.000	202.240
FH9 -19	21.472	50.908	8.997	26.494	62.454	164.064	26.247	94.187	120.000	288.000	48.000	156.420
FH9 -20	16.001	33.948	6.131	14.763	40.317	130.442	14.502	61.505	100.000	200.000	36.000	68.480
FH9 -21	14.684	32.971	6.941	15.069	39.140	92.387	21.002	37.499	84.000	176.000	40.000	69.520

Table. Summary of anchor cable force statistics (continued).

	Standard deviations (pounds)				Maximum values (pounds)				Variations, max. to min. (pounds)			
	NW	SW	NE	SE	NW	SW	NE	SE	NW	SW	NE	SE
FH9 -22	14.200	32.860	8.144	17.977	43.288	109.508	22.458	57.980	88.000	220.000	48.000	110.600
FH9 -23	24.902	62.139	14.784	36.615	59.439	237.321	45.548	150.064	148.000	384.000	92.000	230.680
FH9 -24	21.917	54.967	13.017	32.035	56.463	222.087	32.201	136.193	144.000	356.000	76.000	200.660
FH9 -25	18.545	46.342	10.659	27.186	61.652	135.638	36.108	80.267	108.000	268.000	64.000	151.680
FH10- 1	3.957	5.271	3.182	3.632	10.237	10.746	9.290	9.151	34.166	30.532	24.797	26.861
FH10- 2	24.742	50.725	15.561	22.265	94.834	168.742	67.476	73.974	186.000	280.000	115.555	124.820
FH10- 3	21.037	61.374	11.987	36.717	52.322	197.755	54.176	129.148	120.000	404.000	88.000	279.660
FH10- 4	27.303	78.380	11.272	42.955	93.124	389.259	43.285	208.183	200.000	560.000	84.000	292.300
FH11- 2	22.494	65.805	13.598	37.841	56.107	202.384	37.065	123.866	124.000	360.000	74.000	212.000
FH11- 3	22.328	56.817	7.509	28.550	48.012	189.991	17.951	109.744	108.000	304.000	42.000	160.000
FH11- 4	24.406	53.350	14.372	33.448	63.307	182.538	40.743	122.528	142.000	294.000	86.000	190.000
FH11- 5	22.882	59.094	10.775	32.883	58.274	271.120	28.511	134.525	150.000	404.000	60.000	202.000
FH11- 6	24.054	63.906	8.467	30.352	54.022	246.449	27.250	117.612	122.000	386.000	56.000	186.000
FH11- 7	23.151	66.432	8.436	29.896	69.535	201.553	21.213	82.841	134.000	366.000	44.000	146.000
FH11- 8	28.009	68.262	13.612	37.728	63.996	254.244	33.133	124.014	164.000	396.000	74.000	196.000
FH11- 9	34.270	93.910	16.206	53.663	75.529	333.183	40.172	205.589	176.000	526.000	86.000	304.000
FH11-10	28.525	77.068	14.429	46.228	76.095	254.254	45.259	156.353	162.000	430.000	84.000	262.000
FH11-11	30.270	77.342	17.305	48.061	79.208	236.058	53.389	147.266	168.000	424.000	96.000	262.000
FH11-12	35.451	87.205	20.977	53.710	114.203	290.567	72.657	187.479	228.000	490.000	136.000	310.000
FH11-13	34.954	68.446	22.771	44.982	109.038	235.470	80.708	163.276	214.000	430.000	148.000	282.000
FH11-14	39.062	84.688	22.362	50.437	110.991	309.132	59.975	153.687	232.000	522.000	118.000	274.000
FH12- 1	13.971	21.354	9.562	11.443	62.201	99.147	44.326	48.563	102.000	148.000	64.000	72.000
FH12- 2	9.098	19.909	5.368	11.137	21.490	64.585	14.199	34.845	46.000	108.000	30.000	56.000
FH12- 3	18.660	35.685	10.805	22.129	40.248	138.962	34.395	85.847	106.000	208.000	74.000	128.000
FH12- 4	22.653	43.195	14.695	26.162	58.226	178.015	45.467	103.876	142.000	296.000	94.000	170.000
FH12- 5	19.137	39.018	11.795	25.009	50.916	153.139	31.666	87.406	126.000	248.000	68.000	146.000
FH12- 6	14.011	26.324	7.753	15.326	46.851	107.505	27.827	55.024	100.000	180.000	50.000	100.000
FH12- 7	19.667	36.519	11.697	22.201	50.547	150.864	35.346	98.391	128.000	236.000	82.000	158.000
FH12- 8	26.255	53.094	14.696	32.887	72.426	196.275	40.011	129.161	156.000	326.000	94.000	204.000
FH12- 9	23.462	44.187	13.576	29.269	49.645	143.406	32.260	100.631	122.000	226.000	72.000	154.000
FH12-10	36.376	77.993	19.146	45.590	100.799	296.819	54.695	170.487	224.000	472.000	114.000	262.000
FH12-11	29.763	83.770	17.150	48.104	95.243	256.215	57.197	145.447	196.000	504.000	104.000	278.000
FH12-12	25.076	69.811	12.488	41.639	67.139	250.153	38.582	168.483	150.000	440.000	78.000	276.000
FH12-13	24.012	66.572	9.373	36.446	55.361	183.384	20.981	102.581	120.000	308.000	50.000	166.000
FH12-14	21.781	54.227	7.195	24.182	58.399	184.949	21.444	88.238	124.000	294.000	44.000	140.000
FH12-15	40.126	51.751	39.879	20.837	136.208	110.201	139.250	49.158	216.000	268.000	206.000	108.000
FH12-16	51.112	54.756	26.527	16.088	233.839	218.919	109.241	80.787	346.000	356.000	166.000	124.000
FH12-17	22.067	52.260	11.290	26.120	49.497	161.298	29.337	83.695	110.000	258.000	66.000	136.000
FH12-18	19.434	47.133	9.794	23.689	43.586	186.820	25.805	82.684	112.000	278.000	56.000	132.000
FH13- 1	28.223	74.717	9.644	29.630	107.602	340.358	31.808	133.561	208.945	474.000	70.000	200.000
FH13- 2	25.606	73.194	10.994	30.246	57.596	307.876	24.964	132.105	134.000	444.000	62.000	182.000
FH13- 3	30.135	78.112	13.818	37.252	79.256	289.342	36.656	134.101	170.000	458.000	76.000	212.000
FH13- 4	35.103	96.943	17.090	53.806	71.049	306.891	41.425	199.855	166.000	478.000	92.000	296.000
FH13- 5	24.136	47.125	12.540	27.668	76.648	186.446	36.807	107.207	158.000	310.000	78.000	176.000
FH13- 6	24.240	40.460	13.459	24.938	56.828	142.378	36.660	77.077	124.000	240.000	72.000	140.000
FH13- 7	40.252	111.057	17.216	58.518	91.917	346.205	48.480	198.638	210.000	578.000	98.000	316.000
FH13- 8	38.769	114.883	16.219	61.259	83.843	460.616	42.063	207.326	198.000	684.000	86.000	338.000

outside leading the inside gage by approximately 180° over the frequency range of 0.25 to 0.37 hertz. This indicates that the forces are relatively uninfluenced by waves above approximately 0.37 hertz. This frequency range is also where the transmission curves rise to near unity. This agrees with the low-frequency analysis and suggests that the response is similar over the complete frequency range below 0.37 hertz.

The acceleration force, autospectral and cross-spectral analysis results, are also given in Appendix J for the higher frequency range for record FH 7-8. No dominant features were observed in the motion spectra. Their peak values and spread of energy with frequency appear to follow the general character of the incident wave spectra in all records analyzed. This implies that any natural frequencies in each of the motions is outside the range of significant incident wave energy. The cross-spectral analysis shows a high coherency and zero phase shift between the heave and roll accelerations. In both the sway and roll, and the sway and heave accelerations, the sway acceleration leads by approximately 180° over the range of significant incident wave energy and then tapers to near-zero phase shift at higher frequencies. Also, the coherency is high enough over the incident wave energy band to imply near linearity between all three motions.

These conclusions are based on positive sway being outward from the short leg (south), heave positive up, and the positive roll to be clockwise around a positive axis pointing westerly toward shore.

IV. COMPARISON OF THEORY WITH FIELD DATA FOR FRIDAY HARBOR BREAKWATER

Although the Friday Harbor breakwater has a very complex geometry and does not respond as a rigid body to the incident wave excitation, it is important to draw some comparisons between the theoretical prediction of performance and the field measurements. In seeking a "typical event" from the enormous quantity of data gathered, the goal was to find a case where the wind was reasonably close to being on the beam of the short leg of the breakwater.

The one striking item which emerges from the data is the similarity of all the transmission coefficients examined. These curves seem identical no matter what the wind direction. This was not expected because there were barges tied to the breakwater along the entire long leg, while there were none along the shorter leg. A further investigation of the reasons for the similarity is certainly warranted.

The record selected for comparison with the theory was FH 7-8. Figure G-3 in Appendix G shows the incident and transmitted wave spectra and transmission coefficient. This record is also listed in the statistical summaries of Appendix F. The spectral analysis using a high-pass filter was performed as described in Section III.

A comparison of the theoretically predicted and measured transmission coefficient is shown in Figure 28. So long as the calculated hydrodynamic damping is doubled in the theoretical analysis, the results are quite good. As described in Section II, the peak in the transmission curve at a frequency of 0.95 hertz probably results from the "irregular frequency" phenomenon which occurs in this mathematical formulation.

Comparisons of sway, heave, and roll acceleration predictions with measurements are shown in Figures 29, 30, and 31, respectively. Here, the acceleration response has been nondimensionalized by multiplying by the beam or beam squared, as appropriate, and dividing by the acceleration of gravity times the incident wave amplitude.

In the case of sway acceleration, the theory overpredicts the values throughout the entire frequency range. The peak at 0.5 hertz appears in the correct location, but the measured values would need to be doubled to bring the curves into better agreement.

For heave acceleration the curves appear to be in closer agreement, at least above the frequency of 0.4 hertz. Below 0.4 hertz there seems to be little correlation.

Roll acceleration seems to show the worst agreement of all. Here again, the predicted accelerations are considerably higher than the measured values.

There are several possible explanations for the discrepancy between predicted and measured accelerations. In the field, even if the wind

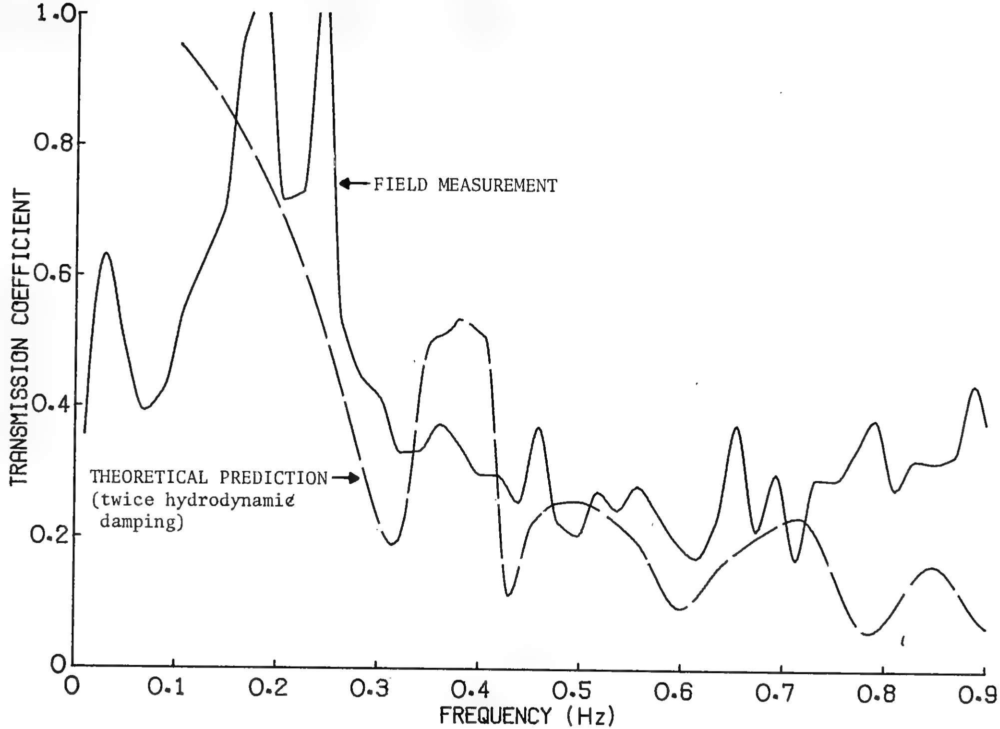

Figure 28. Transmission coefficient for Friday Harbor breakwater (record FH7-8).

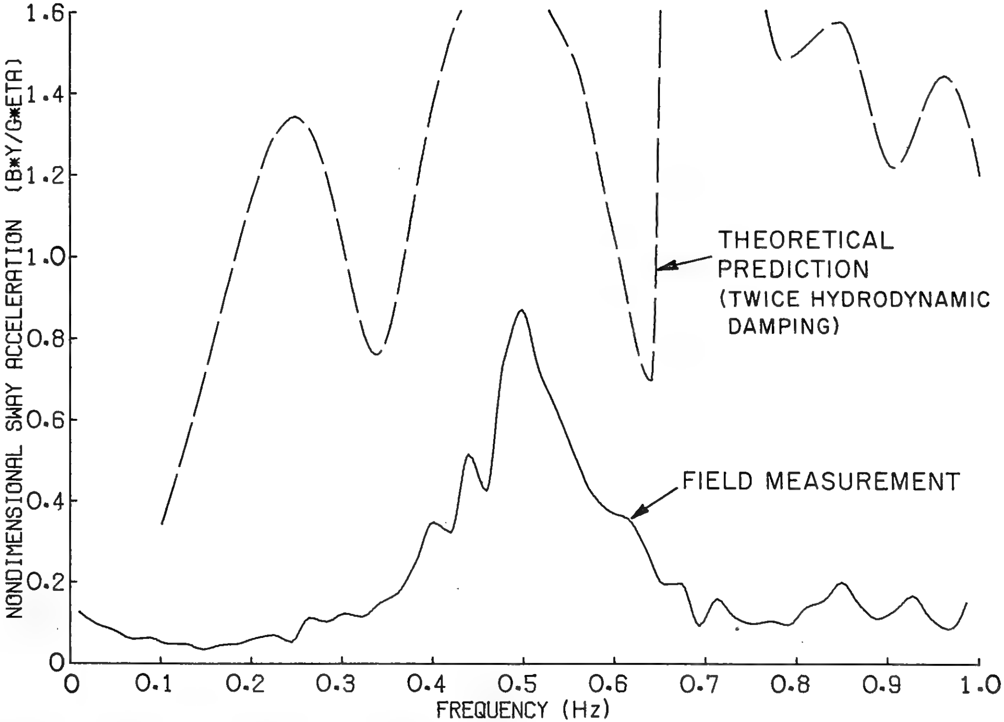

Figure 29. Sway acceleration response for Friday Harbor breakwater (record FH7-8).

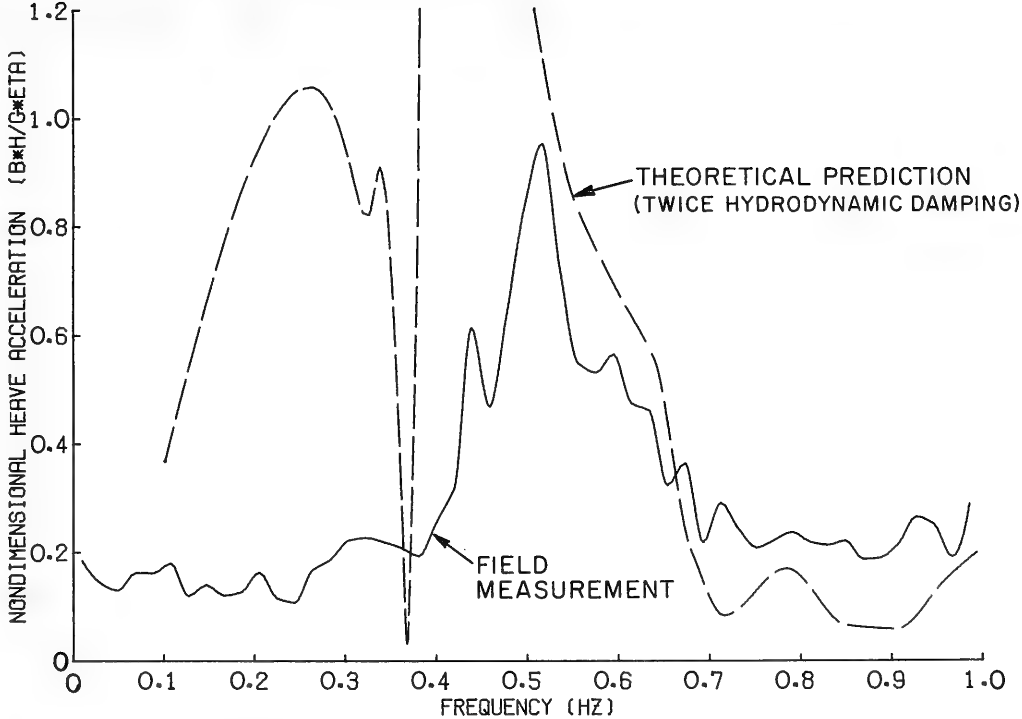

Figure 30. Heave acceleration response for Friday Harbor breakwater (record FH7-8).

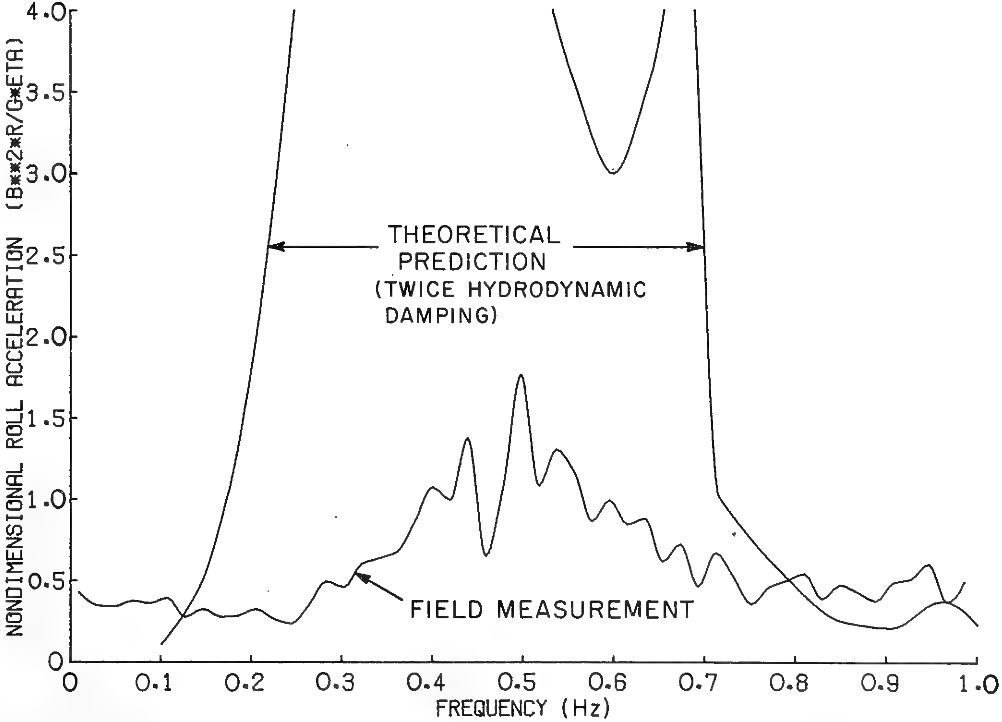

Figure 31. Roll acceleration response for Friday Harbor breakwater (record FH7-8).

were blowing directly on the beam of the breakwater, one would not find the condition of long-crested waves impinging directly on the beam of the breakwater. As a result, the breakwater is not excited uniformly along its entire length. Therefore, the breakwater itself provides restraint against motions which are excited in a local area. The construction of this particular breakwater is also quite flexible, which allows for considerable internal damping of the wave-excited motions. The barges tied to the long leg also serve to restrain the motion and provide additional damping.

There is a strong need, in this case, to provide laboratory data on the breakwater motions, which could be further correlated with the theory and the measured motions.

If one looks at the measured accelerations by themselves, a considerable resemblance in all three degrees of freedom appears. Further, if these accelerations are viewed along with the incident wave spectrum, considerable similarity appears again, suggesting that further investigation of the measurement scheme would also be welcome.

The final comparison to be made is between the theoretically predicted and measured mooring-force coefficient. The theoretical prediction and measured data for the seaward mooring line is shown in Figure 32. The correlation appears to be quite good in this case.

In looking at the time series of force on the mooring lines and the windspeed, one can observe a definite correlation between the wind gusts and increases in the mooring force. This is probably a result of the large barges tied to the structure which act almost as sails. If this is the case, the increase in tension caused by the mean wind on the barges needs to be accounted for. No attempt has been made to do this.

The most common method of presenting the spectral data obtained in the field uses a frequency scale rather than the nondimensional beam/wavelength scale used in Section II. In this section the comparisons are made using a frequency scale. For the Friday Harbor breakwater (beam = 25 feet) the conversion is:

$$\frac{B}{L} = \frac{2\pi B f^2}{g} = 4.87 f^2$$

assuming deepwater waves.

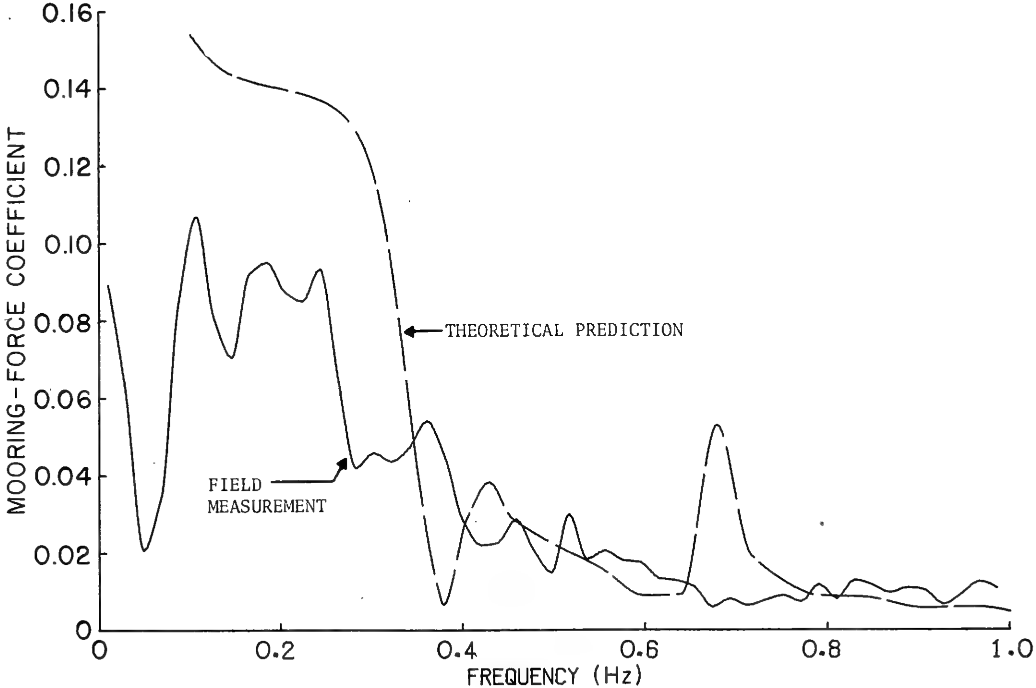

Figure 32. Seaward mooring line mooring-force coefficient, Friday Harbor breakwater (record FH7-8).

V. CONCLUSIONS

Results for the predicted transmission coefficients were in good agreement with laboratory and field data, and they showed how the influence of fixed-body transmission, and of sway, heave, and roll motions on the transmission coefficient changed with increasing values of the beam to wavelength ratio.

The curves predicting the mooring line forces as a function of the beam to wavelength ratio (or of incident wave frequency) followed those for the measured responses. Care must be exercised in the analysis of mooring line forces because there is strong evidence of nonlinear behavior.

An extreme storm event did not occur during the sampling season at Friday Harbor, nor during two winter sampling periods on the Alaskan breakwaters; however, the anchor forces measured were about an order of magnitude less than anticipated.

The barges tied to the long leg of the breakwater did not noticeably affect the transmission coefficients above a frequency of about 0.3 hertz, since the curves for all incident directions were approximately coincident above that mean frequency. Below the frequency of 0.3 hertz, it appears that the barges may have reduced the transmitted energy somewhat.

The extension of the theoretical model to include second-order terms showed the presence of additional exciting-force terms at zero frequency and at the difference frequency of the incident waves. Additional work on the basic theoretical model is needed to incorporate these terms into the calculations for mooring forces. The most appropriate means of verifying the role of the second-order terms may be in a model basin, where breakwaters of simple cross section and incident wave spectra having only two or three components could be employed under controlled conditions.

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APPENDIX A

HYDROSTATIC RESTORING FORCES AND SPRING CONSTANTS

Hydrostatic restoring forces and spring constants are computed for the two-dimensional analysis under the following assumptions:

(a) The body rotates about the origin of the coordinate system and all forces and moments are computed about that point.

(b) The body has vertical sides in the region of its waterplane.

(c) All motions are small.

1. Sway Motion.

In the horizontal plane the body is in neutral equilibrium. Therefore, there are no hydrostatic restoring forces and

$$KH_{11} = KH_{12} = KH_{13} = 0. \tag{A-1}$$

2. Heave Motion.

Vertical displacement of the body results in a change in the buoyant volume of the body and consequently a change in the buoyant force on the body. Since this force must be perpendicular to the waterline, there is no change in the horizontal force as a result of vertical displacement and

$$KH_{21} = 0. \tag{A-2}$$

If one considers a small vertical displacement, δy, there is a resulting change in volume:

$$\delta V = - \delta y A_w \quad \text{(for } \delta y + \text{ upwards)}.$$

Here, A_w is the waterplane area. The vertical force then is:

$$F = KH_{22}\delta y = - \rho g A_w \delta y,$$

or

$$KH_{22} = \rho g A_w = \rho g[x_b - x_a]. \tag{A-3}$$

In this equation x_a and x_b denote the sides of the body as shown in the Figure in this appendix. Since the vertical force may be regarded as acting at the centroid of the waterplane area, x_c, the moment may be expressed.

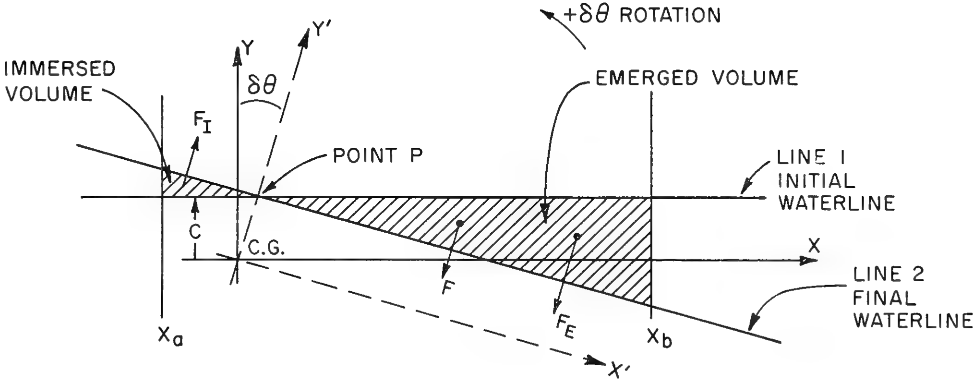

Figure. A-1 Schematic of floating breakwater near the waterplane.

$$M = K_{23}\delta y = -\rho g A_w x_c \delta y.$$

Substituting for x_c and A_w yields:

$$KH_{23} = -\rho g A_w x_c = -\rho g A_w \frac{1}{2}[x_a + x_b] = \frac{1}{2}\rho g[x_a^2 - x_b^2]. \qquad \text{(A-4)}$$

3. Roll Motion.

The analysis of roll motion-induced forces and moments is complicated by the fact that the body is assumed to rotate about the origin of the coordinate system and not the centroid of the waterplane.

The problem is illustrated in the figure. Here, line 2, the waterline after rotation through and angle $\delta\theta$ must pass through the intersection of the y' coordinate axis and the initial waterline. Equations for lines 1 and 2 may then be obtained.

Line 1: $y = c.$

Line 2: $y = mx + b.$

The slope of line 2 is:

$$m = \frac{\Delta y}{\Delta x} = -\tan\delta\theta.$$

Line 2 must also pass through the point P so that:

$$x_p = +c\tan\delta\theta$$

and

$$y_p = c.$$

These equations yield the relationship:

$$b = c(1 + \tan^2\delta\theta).$$

To find the force acting on the body as a result of the rotation, the net lost or gained volume is needed.

$$\delta V = \int_{x_a}^{x_b} (mx + b - c)\,dx$$

$$= \int_{x_a}^{x_b} [(-x\tan\delta\theta + c(1 + \tan^2\delta\theta) - c]\,dx$$

$$= - \frac{1}{2} [x_b^2 - x_a^2] \tan \delta\theta + c[x_b - x_a] \tan^2 \delta\theta.$$

By applying the "small angle" approximation and neglecting terms of the order of $\delta\theta^2$. Then,

$$\delta V \approx \frac{1}{2} [x_a^2 - x_b^2] \delta\theta$$

and the force is:

$$F \approx \frac{1}{2} \rho g [x_a^2 - x_b^2] \delta\theta.$$

The x and y components of the force are:

$$F_x = F \cos \delta\theta \approx \frac{1}{2} \rho g [x_a^2 - x_b^2] \delta\theta \cos \delta\theta$$

and

$$F_y = F \sin \delta\theta \approx \frac{1}{2} \rho g [x_a^2 - x_b^2] \delta\theta \sin \delta\theta.$$

Again applying the small angle approximation one finds:

$$F_x \approx \frac{1}{2} \rho g [x_a^2 - x_b^2] \delta\theta$$

and

$$F_y \approx 0.$$

The hydrostatic spring constants coupling roll to sway and heave are then:

$$KH_{31} = 0 \qquad \text{(A-5)}$$

and

$$KH_{32} = \frac{1}{2} \rho g [x_a^2 - x_b^2]. \qquad \text{(A-6)}$$

To obtain the moment induced by roll motion compute:

$$\text{Moment of Gained Volume} = - (\frac{1}{2} x_a^2 \tan \delta\theta)(\frac{2}{3} x_a) \approx \frac{1}{3} x_a^3 \delta\theta,$$

$$\text{Moment of Lost Volume} \approx \frac{1}{3} x_b^3 \delta\theta$$

and

$$\text{Moment of Original Volume} = W y_b \delta\theta.$$

In this formula,

W = weight per unit length

and

y_b = distance the center of buoyancy is below the center of gravity.

The total moment then is:

$$M = \frac{\rho g}{3} (x_b^3 - x_a^3) \delta\theta + W y_b \ \delta\theta,$$

and the spring constant becomes:

$$KH_{33} = \frac{\rho g}{3} (x_b^3 - x_a^3) + W y_b . \qquad \text{(A-7)}$$

Expressed in traditional naval architecture terminology, this reduces to:

$$KH_{33} = WGM, \qquad \text{(A-8)}$$

where

GM = metacentric height.

4. Collected Results.

$$KH_{11} = KH_{12} = KH_{13} = KH_{21} = KH_{31} = 0$$

$$KH_{22} = \rho g [x_b - x_a]$$

$$KH_{23} = KH_{32} = \frac{1}{2} \rho g [x_a^2 - x_b^2] \qquad \text{(A-9)}$$

$$KH_{33} = \frac{\rho g}{3} [x_b^3 - x_a^2] + W y_b \ .$$

APPENDIX B

MOORING ANALYSIS

1. Purpose of the Program.

Computer program BRKMOOR computes the forces and moments imparted by a pair of mooring cables on a floating breakwater section. BRKMOOR also computes the changes in the mooring cable tensions and the spring-constant values for the moorings as the breakwater moves in sway, heave, or roll.

2. Program Description.

Program BRKMOOR is written primarily in FORTRAN IV although FORTRAN II print statements are used.

The program consists of the main program BRKMOOR and the subroutines LINE2, CHAIN, NYLON, EQULIB, SPRING, and LTERPS.

BRKMOOR calculates the forces in a mooring cable by using a discretized approximation to the cable. The cable is divided into the number of segments specified in the input data. Each segment may be of a different material or size. Each segment is in turn divided into a specified number of sections. The cable is considered to be made of these sections with the weight of each section concentrated at the node at the bottom of the section. Connecting each node is a straight but elastic section.

The main part of the program specifies 15 different angles at the attachment, ranging from nearly vertical to nearly straight to the farthest reasonable anchor position. A first guess at a top tension is made.

LINE2 then sums down the cable computing forces and coordinates of each node starting with the initial angle and initial tension. The position of the end of the cable is compared with the specified water depth at the anchor. The initial tension is adjusted and the summation repeated until the cable ends at the proper depth. Control then returns to the main program.

LINE2 calls the subroutines NYLON or CHAIN to compute the strain of the cable section of the appropriate material. If other materials are used new subroutines should be written for strain computation, along with the appropriate calling expression in LINE2.

At each angle the cable forces at the attachment and the anchor position are stored in arrays. EQULIB then computes the breakwater equilibrium position for the specified conditions.

SPRING is called by EQULIB. SPRING computes the change in mooring cable tensions with breakwater displacement in sway, heave, and roll and the spring constants of the moorings on the breakwater.

LTERPS is a linear interpolation subroutine which computes the slop, $\frac{\Delta Y}{\Delta X}$, and the interpolated value of Y for a given X and an array of X vs. Y values. LTERPS is called by EQULIB and SPRING.

3. Type of Computer and Peripherals.

BRKMOOR was written for use on the CDC 6400 computer. It uses about $40{,}000_8$ words of memory. No peripherals other than the card reader and line printer are required.

4. Input Data.

The input to BRKMOOR is as follows:

Card #1 - Title card, Format (8A10).
80 alphanumeric characters max.

Card #2 - Breakwater geometry card, Format (5F10.0).
YCG = Vertical location of breakwater CG relative to water surface.
XCAB(1) = x coordinate of cable #1 attachment to breakwater (the CG is at X = 0 and cable #1 is defined as the cable with its anchor in the +x direction).
YCAB(1) = y coordinate of cable #1 attachment to breakwater.
XCAB(2) = x coordinate of cable #2 attachment to breakwater.
YCAB(2) = y coordinate of cable #1 attachment to breakwater.

Card #3 - Number of desired conditions Format (I2).
(Also number of condition cards to follow)

Card #4 - Condition cards, Format (4F10.0).
(One card for each condition)
FEXT = Force applied to the breakwater not due to moorings in x direction (could be due to wave action, tide, wind, etc. force in pounds).
SEP = Anchor separation in horizontal direction (feet).
TENS1 = Nominal tension in cable #1 (lb.).
TENS2 = Nominal tension in cable #2 (lb.).

It should be noted that only the following condition combinations are possible:

SEP
SEP+FEXT
TENS1
TENS1+FEXT
TENS2
TENS2+FEXT
TENS1+TENS2

Card #5 - Tide Card, Format (I1,9X,5F10.0).
NTIDE = Number of tide values to follow (max = 5).
TIDE = Tide position in feet relative to that at which the anchor depths are given.

Card #6 - Cable #1 Parameters, Format (I2,8X,2F10.0).
NSEG = Number of different segments (types of cable materials) from which the cable is constructed.
DEPTH = Depth of water at the anchor (feet).
BSLOPE = Slope of bottom in region of anchor (feet/feet).

Card #7 - Cable segment properties Format (I5,5X,2F10.0,A10,F10.0). One card for each of the number of segments listed in card 6 parameter NSEG.
NSECT = Number of sections into which it is desired to divide the cable segment.
ALSEG = The length of this cable segment.
WPF = Weight per foot in water of the cable material in this segment.
MATL = Material name (as the program now stands this must be CHAIN or NYLON (Name must begin in column 31).
DIAM = Diameter of the nylon rope or of the chain link in inches.

Card #8 and #9 - Same as cards #6 and #7 only as applies to cable #2.

Table B-1 illustrates the input cards for a test case. All the read statements for the program are in the main program along with comments and explanations of input requirements.

5. Mathematical Procedures and Program Limitations.

The basic cable computations which take place in LINE2 require some explanation. As was stated previously, the weight of each cable section is considered to be concentrated at the bottom of the section. In order to find the shape of the cable, summations of forces are computed for static equilibrium at each node. At each node we know the tension in the cable section above the node as well as the angle of that section with the horizontal. Figure B-1 illustrates the cable about the ith node.

If the angle ϕ_i is taken to be the angle from the horizontal, then the angle ϕ_{i+1} can be computed as follows:

$$\phi_{i+1} = \tan^{-1} \left[\frac{T_i \sin\phi_i + W_i}{T_i \cos \phi_i}\right] , \qquad \text{(B-1)}$$

where T_i = tension in section i,

W_i = weight of section i concentrated at node i.

```
 TEST CASE -- MEASURED CHAIN TEST 3/11/76
0.          1.          0.          -1.          0.
06
0.          58.02
            58.21
                        36.
                        42.
            54.
                        36.         30.
1
01          7.167
00030       29.33       .722        CHAIN        .25
01          7.167
00030       29.33       .722        CHAIN        .25
```

Table B-1. Example input for program BRKMOOR.

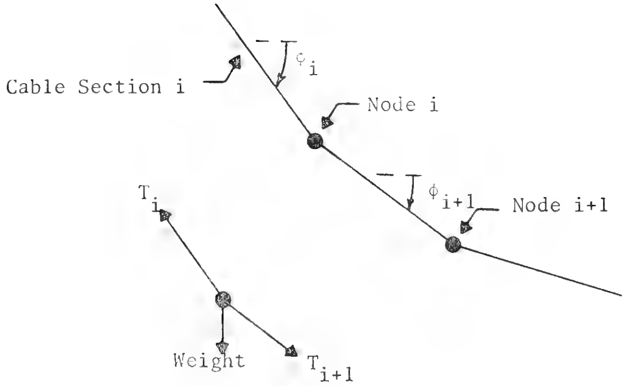

Figure B-1. Cable sections about node i and free body diagram of node i.

This new angle is then used to compute the tension in the next section:

$$T_{i+1} = \frac{T_i \cos \phi_i}{\cos \phi_{i+1}} \quad . \tag{B-2}$$

LINE2 computes the angle and tension of each **section** starting from the top. At each section the angle is compared with the slope of the bottom. When the angle ϕ is parallel or more positive than the bottom then ϕ is set to the slope of the bottom.

The x and y coordinates of each node are computed.

$$X_{i+1} = X_i + L_{EXT_{i+1}} \cos\phi_{i+1} \tag{B-3}$$

$$Y_{i+1} = Y_i + L_{EXT_{i+1}} \sin\phi_{i+1} \ , \tag{B-4}$$

where X_i = x coordinate of node i

Y_i = y coordinate of node i

L_{EXT} = length of section when under tension.

At the last node the y-coordinate is compared with the depth of the anchor. If there is a difference the initial tension value is adjusted. Guesses at the first and second tensions are made. From then on a secant (discrete form of Newton Raphson) iteration method is used to compute the subsequent initial tension values. An error of 0.0001*depth is allowed. In most cases 4 or 5 iterations yield the desired accuracy. Some important values are printed for each iteration to aid in troubleshooting.

Within EQULIB and SPRING interpolation is required to find the values of tension forces and x coordinates which are between the points computed by BRKMOOR and LINE2. The linear interpolation routing LTERPS was chosen over higher-order interpolation schemes because of the asymptotic nature of the tension versus λ values. If values are requested beyond the ends of the computer arrays, they can be extrapolated, but a warning message will be printed by EQUILIB.

An iterative procedure is required within EQULIB if the anchor separation condition is selected. Again the secant iteration method is used. EQULIB prints out values at each interation which can aid in troubleshooting but which can normally be ignored.

Subroutine CHAIN computes the strain in a chain using the basic elastic properties of a steel bar with a total area equal to the area of both parts of the links, and a factor of 6 to allow for the deformation characteristics of the links. This factor of 6 came from a finite element computation.

Subroutine NYLON computes the strain in a nylon rope using a power-function fit of the form:

$$\varepsilon = AX^{\beta},$$

where ε = Strain,
A = 0.02052,
β = 0.2237,

$$X = \frac{T}{D^2},$$

T = Tension (pound),
D = Diameter of rope (inches).

This function was determined using a least-squares power-function fit of experimental data provided by Sampson Cordage Works for their 2-in-1 nylon braided rope.

An experimental verification test was conducted as a check of the program. A chain was suspended from a spring scale. Measurements were made of the length of the chain, its weight and the tension in two geometrical configurations. The program gave computed values of the tension very close to those measured.

6. Flow Chart.

Figure B-2 illustrates the flow chart of BRKMOOR and its subroutines.

7. Program Comments and Glossary of Terms.

The program listing contains many comments which aid in following the logic of the program. The important variable names are explained as well as the input requirements.

8. Run Time and Memory Size.

BRKMOOR requires about 40 seconds on the CDC 6400 to compile and compute results for one value of the tide parameter. Each additional tide value requires about 30 seconds additional time. These values are for cables divided into 50 sections each. Time should be somewhat proportional to the total number of cable sections. The number of test conditions has much less effect on time than does the tide. As stated previously, a central memory of about 40,000 octal is required.

9. Run and Card Deck Setup Procedures and Special Operation Instructions.

In order to run the FORTRAN source program deck on the University of Washington CDC 6400, the following deck is required:

```
BMOOR,T40.           Job card
ACCOUNT              (Account no., password)
FORTRAN.
LGO(LC=6000)         LC = line count value; depends on how many
                     tides and conditions are run
7/8/9
     FORTRAN DECK
7/8/9
     DATA DECK
6/7/8/9
```

10. Sample Output Data.

Example output from program BRKMOOR is shown in Table B-2; a listing of program BRKMOOR is shown in Table B-3.

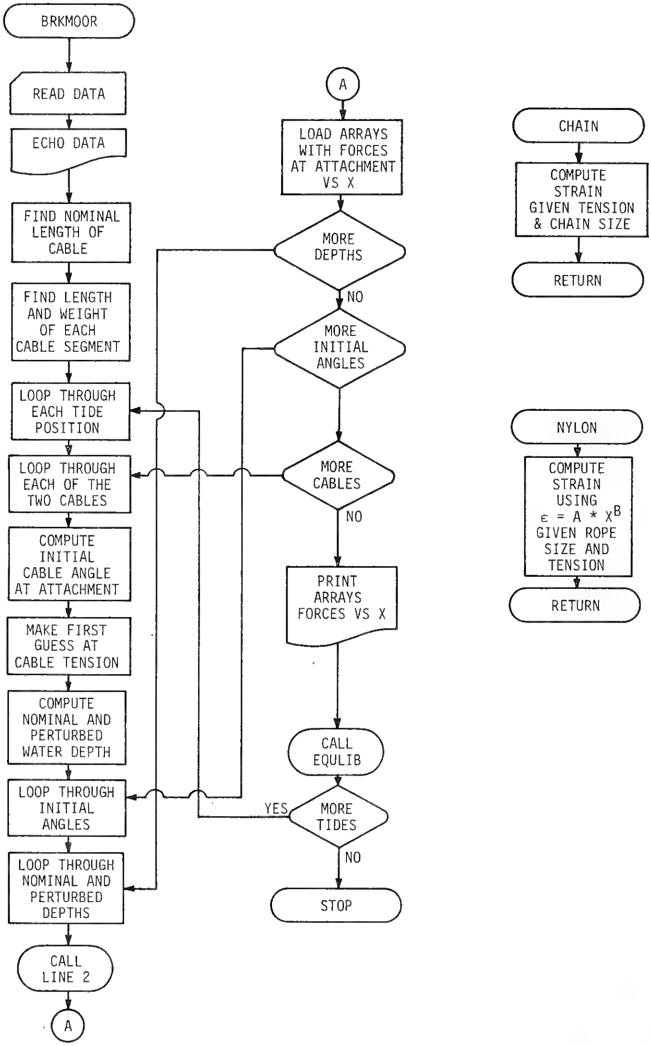

Figure B-2. Flow chart for program BRKMOOR.

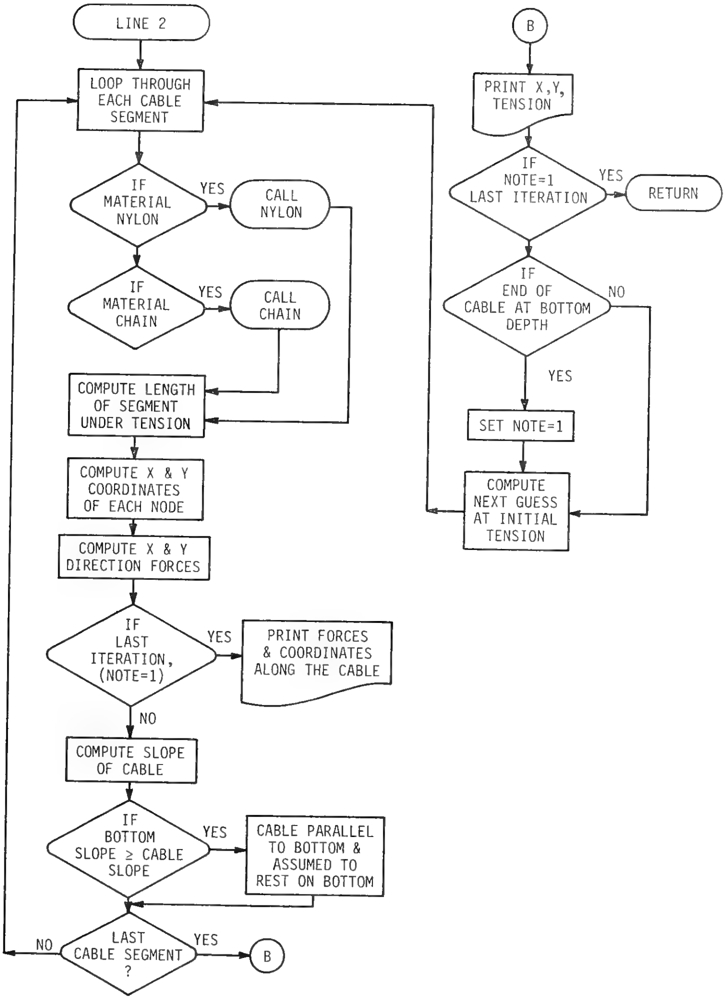

Figure B-2. Continued

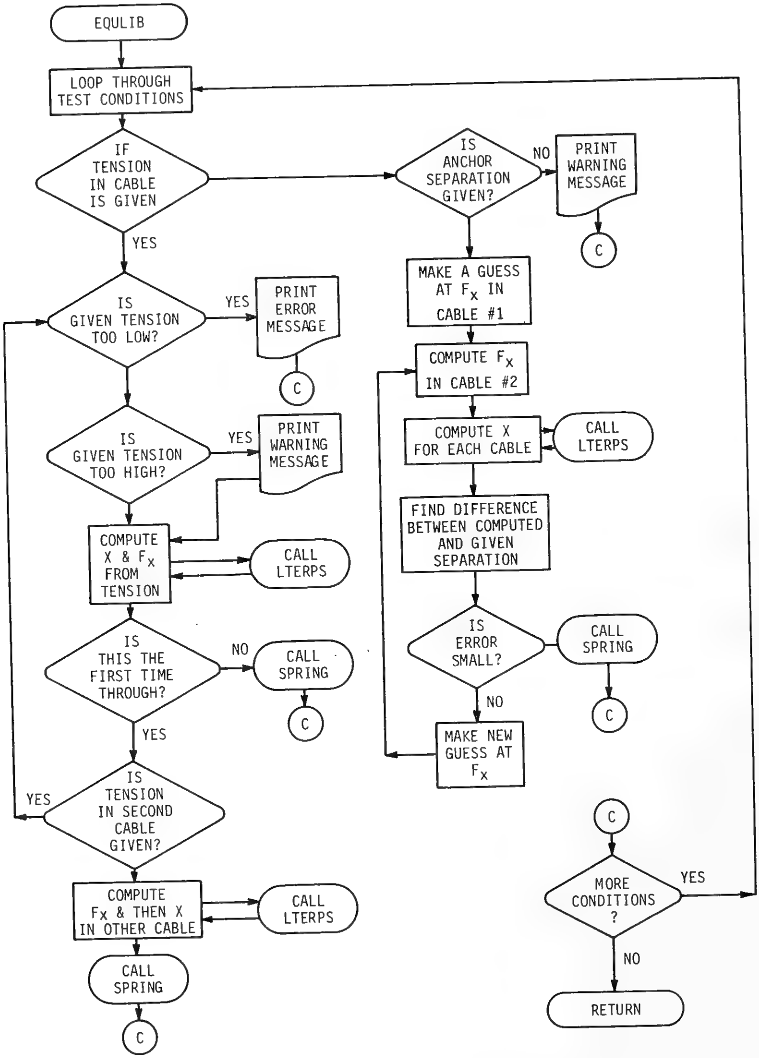

Figure B-2. Continued

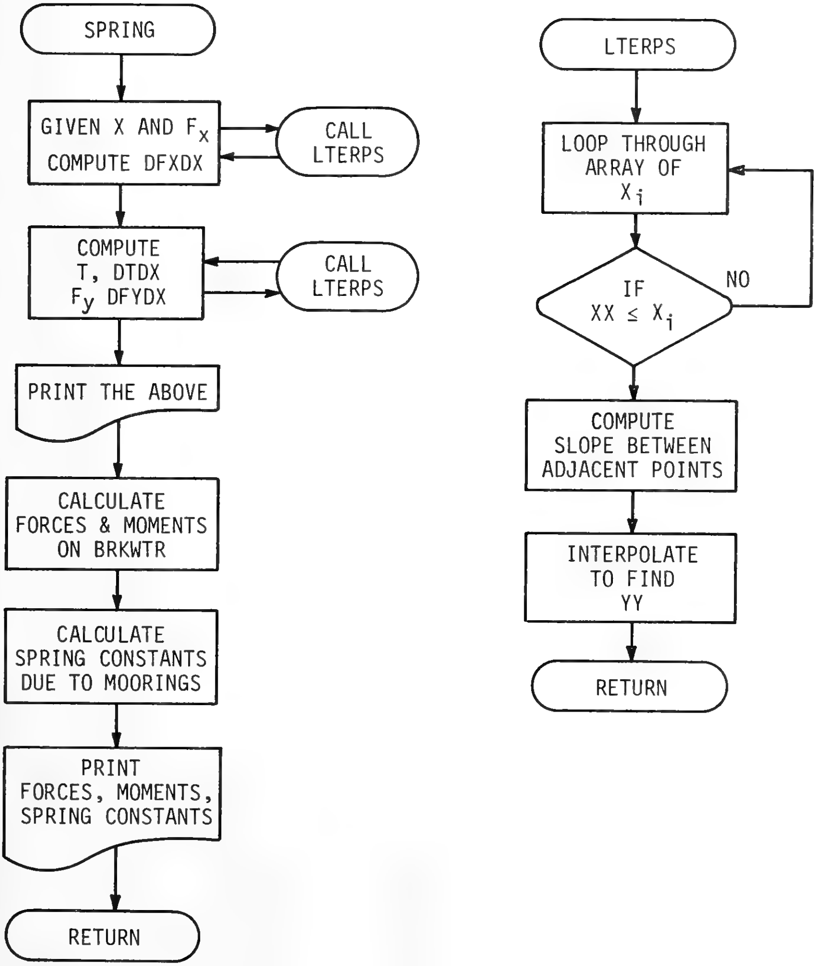

Figure B-2. Continued

IN THE FOLLOWING TABLES - X REL. TO CG, Y REL. TO WATER SURFACE

TEST CASE -- MEASURED CHAIN TEST 3/11/76

MOORING LINE NUMBER= 1   TIDE= -.000

Y	X	TOP TENSION	FORCEX	FORCEY
-7.167	24.605	5.202	.430	-5.184
-7.167	25.294	5.802	.956	-5.722
-7.167	25.893	6.407	1.574	-6.211
-7.167	26.387	7.158	2.326	-6.770
-7.167	26.804	8.101	3.257	-7.417
-7.167	27.174	9.278	4.419	-8.158
-7.167	27.507	10.776	5.899	-9.019
-7.167	27.814	12.704	7.809	-10.021
-7.167	28.099	15.254	10.338	-11.216
-7.167	28.366	18.714	13.777	-12.664
-7.167	28.619	23.557	18.601	-14.454
-7.167	28.859	30.675	25.695	-16.755
-7.167	29.089	41.694	36.687	-19.809
-7.167	29.290	61.608	56.444	-24.690
-7.167	29.410	121.346	114.814	-39.276
-7.239	24.544	5.251	.434	-5.233
-7.239	25.258	5.848	.963	-5.768
-7.239	25.839	6.494	1.595	-6.295
-7.239	26.346	7.240	2.353	-6.847
-7.239	26.769	8.190	3.292	-7.499
-7.239	27.142	9.380	4.468	-8.248
-7.239	27.477	10.900	5.967	-9.122
-7.239	27.790	12.833	7.888	-10.122
-7.239	28.077	15.417	10.449	-11.336
-7.239	28.347	18.906	13.919	-12.795
-7.239	28.602	23.805	18.797	-14.606
-7.239	28.844	31.005	25.971	-16.935
-7.239	29.077	42.115	37.058	-20.010
-7.239	29.277	62.505	57.266	-25.050
-7.239	29.395	125.036	118.305	-40.470
-7.095	24.658	5.160	.426	-5.142
-7.095	25.328	5.757	.948	-5.678
-7.095	25.945	6.327	1.555	-6.133
-7.095	26.427	7.080	2.301	-6.696
-7.095	26.839	8.016	3.223	-7.339
-7.095	27.205	9.179	4.372	-8.071
-7.095	27.536	10.657	5.833	-8.918
-7.095	27.837	12.578	7.732	-9.922
-7.095	28.122	15.085	10.224	-11.092
-7.095	28.386	18.508	13.626	-12.525
-7.095	28.636	23.314	18.410	-14.305
-7.095	28.874	30.353	25.425	-16.579
-7.095	29.102	41.256	36.302	-19.601
-7.095	29.303	60.738	55.647	-24.341
-7.095	29.426	117.875	111.530	-38.152

Table B-2. Example output from program BRKMOOR.

TEST CASE -- MEASURED CHAIN TEST 3/11/76

MOORING LINE NUMBER= 2 TIDE= -.000

Y	X	TOP TENSION	FORCEX	FORCEY
-7.167	-24.605	5.202	-.430	-5.184
-7.167	-25.294	5.802	-.956	-5.722
-7.167	-25.893	6.407	-1.574	-6.211
-7.167	-26.387	7.158	-2.326	-6.770
-7.167	-26.804	8.101	-3.257	-7.417
-7.167	-27.174	9.278	-4.419	-8.158
-7.167	-27.507	10.776	-5.899	-9.019
-7.167	-27.814	12.704	-7.809	-10.021
-7.167	-28.099	15.254	-10.338	-11.216
-7.167	-28.366	18.714	-13.777	-12.664
-7.167	-28.619	23.557	-18.601	-14.454
-7.167	-28.859	30.675	-25.695	-16.755
-7.167	-29.089	41.694	-36.687	-19.809
-7.167	-29.290	61.608	-56.444	-24.690
-7.167	-29.410	121.346	-114.814	-39.276
-7.239	-24.544	5.251	-.434	-5.233
-7.239	-25.258	5.848	-.963	-5.768
-7.239	-25.839	6.494	-1.595	-6.295
-7.239	-26.346	7.240	-2.353	-6.847
-7.239	-26.769	8.190	-3.292	-7.499
-7.239	-27.142	9.380	-4.468	-8.248
-7.239	-27.477	10.900	-5.967	-9.122
-7.239	-27.790	12.833	-7.888	-10.122
-7.239	-28.077	15.417	-10.449	-11.336
-7.239	-28.347	18.906	-13.919	-12.795
-7.239	-28.602	23.805	-18.797	-14.606
-7.239	-28.844	31.005	-25.971	-16.935
-7.239	-29.077	42.115	-37.058	-20.010
-7.239	-29.277	62.505	-57.266	-25.050
-7.239	-29.395	125.036	-118.305	-40.470
-7.095	-24.658	5.160	-.426	-5.142
-7.095	-25.328	5.757	-.948	-5.678
-7.095	-25.945	6.327	-1.555	-6.133
-7.095	-26.427	7.080	-2.301	-6.696
-7.095	-26.839	8.016	-3.223	-7.339
-7.095	-27.205	9.179	-4.372	-8.071
-7.095	-27.536	10.657	-5.833	-8.918
-7.095	-27.837	12.578	-7.732	-9.922
-7.095	-28.122	15.085	-10.224	-11.092
-7.095	-28.386	18.508	-13.626	-12.525
-7.095	-28.636	23.314	-18.410	-14.305
-7.095	-28.874	30.353	-25.425	-16.579
-7.095	-29.102	41.256	-36.302	-19.601
-7.095	-29.303	60.738	-55.647	-24.341
-7.095	-29.426	117.875	-111.530	-38.152

Table B-2. Continued

TEST CASE -- MEASURED CHAIN TEST 3/11/76

FOR THE CONDITIONS --
TIDE = -.00
EXTERNALLY APPLIED HORIZONTAL FORCE, FEXT= .000LB.
HORIZONTAL ANCHOR SEPERATION, SEP= 58.020FEET
NOMINAL TENSION IN CABLE 1 = -.000 LB.
NOMINAL TENSION IN CABLE 2 = -.000 LB.

CABLE NO.	FX	FY	X	Y	DFXDX	DFXDY	DFYDX	DFYDY	TENSION
1	32.933	-18.766	29.011	-7.167	-4.781E+01	1.328E+01	1.346E+01	-5.134E+00	3.793E+01
2	-32.933	-18.766	-29.011	-7.167	-4.781E+01	-1.328E+01	-1.346E+01	-5.134E+00	3.793E+01

CABLE NO.	DTDX	DTDY	DTDR
1	-4.7919E+01	1.4203E+01	1.4203E+01
2	4.7919E+01	1.4203E+01	-1.4203E+01

FORCES AND MOMENTS ON BREAKWATER AT EQULIBRIUM DUE TO MOORING LINES
FS= .0000
FH= -37.5323
MR= .0000

SPRING CONSTANTS SWAY DIRECTION
KM11 = 9.56100E+01
KM12 = .0
KM13 =-2.65637E+01

SPRING CONSTANTS HEAVE DIRECTION
KM21 = .0
KM22 = 1.02676E+01
KM23 = .0

SPRING CONSTANTS ROLL DIRECTION
KM31 = -2.69150E+01
KM32 = .0
KM33 = 1.02676E+01

Table B-2. Continued

RUNT VERSION FEB 74 B   13:04 04/09/76

```
              PROGRAM BRKMOOR(INPUT,OUTPUT,PUNCH,TAPE5=INPUT,TAPE6=OUTPUT)
        C
        C PROGRAM BRKMOOR COMPUTES THE FORCES AND SPRING CONSTANTS THAT A PAIR
        C OF MOORING CABLES IMPART ON A FLOATING BREAKWATER SECTION
        C
        C**************************************************************************
        C  INPUT
        C FIRST CARD--TITLE - 80 ALPHANUMERIC CHARACTERS
        C  BREAKWATER GEOMETRY--
        C  NUMBER OF TEST CONDITIONS
        C  TEST CONDITIONS--ONE CARD FOR EACH SET
        C  TIDE CARD--NUMBER OF TIDE CONDITIONS AND THE CONDITIONS
        C  FOR FIRST CABLE--NUMBER OF SEGMENTS ANCHOR DEPTH AND BOTTOM SLOPE
        C  FOR EACH OF ABOVE CABLE SEGMENTS --CARD WITH SEGMENT PROPERTIES
        C  REPEAT --NUMBER OF SEGMENTS AND THEIR PROPERTIES FOR SECOND CABLE
        C**************************************************************************
        C
    3         COMMON/ONE/NSEG(2),NSECT(2,5),WSECT(2,5), MATL(2,5),DIAM(2,5),
            2  ALSECT(2,5)
    3         COMMON/TWO/WY(2,3),EX(2,3,20),FX(2,3,20),FY(2,3,20),TENS(2,3,20),
            2  FEXT(9),SEP(9),TENS1(9),TENS2(9),NANGLE,NCOND,TITLE(8)
    3         COMMON/FOUR/YCG,XCAB(2),YCAB(2),TIDE(5),ITIDE
    3         DIMENSION WPF(2,5),ALSEG(2,5),         DEPTH(2),BSLOPE(2),ALNOM(2)
    3         PI=3.1415926535
        C***READ A TITLE CARD -- 80 CHARACTERS MAX
    5         READ 3,TITLE
   12     3   FORMAT(8A10)
   12         PRINT 16,TITLE
   20    16   FORMAT(1H1,5X,8A10///)
        C***READ AND ECHO THE BREAKWATER GEOMETRY
   20     2   READ 5,YCG,XCAB(1),YCAB(1),XCAB(2),YCAB(2)
        C  YCG=Y COORDINATE OF CG RELATIVE TO WATER SURFACE
   42     5   FORMAT(5F10.0)
   42         OUTPUT,YCG,XCAB(1),YCAB(1),XCAB(2),YCAB(2)
        C  XCAB(I)=X COORD OF CABLE I ATTACHMENT RELATIVE TO CG
        C  YCAB(I)=Y COORD OF CABLE I ATTACHMENT RELATIVE TO WATER SURFACE
        C  NOTE--CABLE NUMBER 1 IS THE CABLE WITH ITS ANCHOR IN THE +X DIRECTION
        C***INPUT THE NUMBER OF DESIRED CONDITION CARDS  MAX NUMBER=9
   72         READ 10,NCOND
  100    10   FORMAT(I2)
        C***READ AND ECHO DESIRED CONDITIONS
  100         DO 17 ICOND=1,NCOND
  102         READ 15,FEXT(ICOND),SEP(ICOND),TENS1(ICOND),TENS2(ICOND)
  121    15   FORMAT(4F10.0)
  121    17   OUTPUT, FEXT(ICOND),SEP(ICOND),TENS1(ICOND),TENS2(ICOND)
        C  FEXT=EXTERNALLY APPLIED FORCE (HORIZONTAL DIRECTION) LB.
        C  SEP =ANCHOR SEPERATION IN THE X DIRECTION FT.
        C  TENS1=TENSION IN CABLE 1  LB.
        C  TENS2=TENSION IN CABLE 2  LB.
        C  INPUT SEP, OR TENS1 OR TENS2 OR BOTH TENS1 AND TENS2
        C***READ AND ECHO TIDE CONDITIONS
        C  NTIDE=NUMBER OF TIDE CONDITIONS   MAX=5
        C  TIDE=TIDE POSITION RELATIVE TO NOMINAL DEPTH MEASUREMENTS   FT.
  151         READ 20, NTIDE,(TIDE(I),I=1,NTIDE)
  166    20   FORMAT(I1,9X,5F10.0)
```

Table B-3. Listing of program BRKMOOR.

```
 166          OUTPUT,NTIDE,TIDE
        C  LOOP THROUGH THE TWO CABLES
 201          DO 65 I=1,2
        C***INPUT THE CABLE PROPERTIES AND BOTTOM DEPTH AND SLOPE
 203          READ 22,NSEG(I),DEPTH(I),BSLOPE(I)
 217     22   FORMAT(I2,8X,2F10.0)
        C  NSEG= NUMBER OF CABLE SEGMENTS OR MATERIALS
        C  DEPTH= DEPTH OF THE WATER AT THE ANCHOR    FT.
        C  BSLOPE= SLOPE OF THE BOTTOM (FT RISE/FT)
 217          PRINT 25
 223     25   FORMAT(///5X,*I  NUMBER SECTIONS  SEGMENT LENGTH  WT PER FOOT*
             2 4X*     MATERIAL        DIAMETER*/)
 223          NS=NSEG(I)
 226          DO 30 J=1,NS
        C***FOR EACH CABLE SEGMENT INPUT
        C  NSECT(I)= NUMBER OF SECTIONS INTO WHICH CABLE SEGMENT I IS DIVIDED
        C  ALSEG(I)=LENGTH OF CABLE SEGMENT I   FT.
        C  WPF(I)= WEIGHT PER FOOT IN WATER OF CABLE SEGMENT I      LB/FT
        C  MATL=MATERIAL OF CABLE SEGMENT        EITHER NYLON OR CHAIN
        C    MUST BE LEFT JUSTIFIED  IN DATA FIELD
        C  DIAM=DIAMETER OF ROPE OR  CHAIN LINK        INCHES
 230          READ 40,NSECT(I,J) ,ALSEG(I,J),WPF(I,J), MATL(I,J),DIAM(I,J)
 264     40    FORMAT(I5,5X,2F10.0,A10,F10.0)
 264     30   PRINT 50,J,NSECT(I,J),ALSEG(I,J),WPF(I,J), MATL(I,J),DIAM(I,J)
 326     50   FORMAT(X,I5,8X,I5,8X,F10.2,4X,F10.2,9X,A10,  5X,F6.3)
        C***FIND THE NOMINAL LENGTH OF THE CABLE, LENGTH AND WEIGHT OF SECTIONS
 326          ALNOM(I)=0.
 331          DO 60 J=1,NS
 332          ALNOM(I)=ALNOM(I)+ALSEG(I,J)
 343          ALSECT(I,J)=ALSEG(I,J)/NSECT(I,J)
 357     60   WSECT(I,J)=WPF(I,J)*ALSECT(I,J)
 375     65   CONTINUE
 377          BSLOPE(2)=-BSLOPE(2)
        C***LOOP THROUGH THE TIDE POSITIONS
 403          DO 400 ITIDE=1,NTIDE
        C***LOOP THROUGH THE CABLES
 405          DO 150 I=1,2
 406          PRINT 70
 411     70   FORMAT(1H1,5X*NOTE--IN THE FOLLOWING TABLES X AND Y  ARE MEASURED
             2RELATIVE TO THE CABLE ATTACHMENT*//)
        C  D=Y DIRECTION SEPFRATION BETWEEN ANCHOR AND ATTACHMENT
 411          D=DEPTH(I)+TIDE(ITIDE)+YCAB(I)
        C***COMPUTE INITIAL ANGLES TO BE USED
        C  NANGLE=NUMBER OF ANGLES USED    MAX=20
 421          NANGLE=15
 423          PHIMIN=ASIN(D/ALNOM(I))
 431          DELPHI=(PI/2.-PHIMIN)/FLOAT(NANGLE+1)
 443          PHIONE=-PI/2.
        C***COMPUTE A FIRST GUESS FOR THE INITIAL TENSION FOR STEEPEST ANGLE
 444          ALSUM=0.
 445          TZERO=0.
 446          DAF=D+(ALNOM(I)-D)*BSLOPE(I)
 456          NS=NSEG(I)
 461          DO 90 J=1,NS
 463          NSS=NSECT(I,J)
 470          DO 90 K=1,NSS
```

Table B-3. Continued

```
  471          ALSUM=ALSUM+ALSECT(I,J)
  477          IF(ALSUM .GT. DAF) GO TO 95
  502     90   TZERO=TZERO+WSECT(I,J)
  515     95   CONTINUE
        C  COMPUTE THE NOMINAL AND PERTURBED DEPTHS
  515          DREF=D
  517          DELD=DREF/100.
  521          DPLUS=DREF+DELD
  522          DMINUS=DREF-DELD
        C***LOOP THROUGH THE INITIAL ANGLES
  524          DO 100 K=1,NANGLE
  525          PRINT 97,I,K,NANGLE,TIDE(ITIDE)
  541     97   FORMAT(/X*CABLE NUMBER *I1*    INITIAL ANGLE NO. *I2*  OF *I2
             2 *    TIDE = *F5.2/)
  541          PHIONE=PHIONE+DELPHI
        C***LOOP THROUGH THE NOMINAL DEPTH AND PERTURBED DEPTHS
  543          DO 100 J=1,3
  545          IPRINT=0
        C********TO SKIP THE PRINTING OF EACH CATINARY - INSERT A GO TO 1111
  546          IF(J .EQ. 1) IPRINT=1
  551   1111   IF(J .EQ. 1) D=DREF
  555          IF(J .EQ. 2) D=DPLUS
  561          IF(J .EQ. 3) D=DMINUS
  565          WY(I,J)=YCAB(I)-D
  575          OUTPUT,J,K,D,YCAB(I),WY(I,J),PHIONE
  627          CALL LINE2(I,PHIONE,TZERO,D,BSLOPE(I),X,Y,FORCEX,FORCEY,IPRINT)
  642          EX(I,J,K)=XCAB(I)-X*(-1)**I
  660          FX(I,J,K)=FORCEX*(-(-1)**I)
  674          FY(I,J,K)=FORCEY
  703          TENS(I,J,K)=TZERO
        C  WY(I,J)=Y COORD OF THE ANCHOR TO NO. 1 CABLE--WATER SURFACE=ORIGIN
        C  EX(I,J,K)=X COORD OF ANCHOR RELATIVE TO CG OF BREAKWATER
        C  TENS=TENSION AT ATTACHMENT
        C  FX=FORCE AT ATTACHMENT IN X DIRECTION
        C  FY=FORCE AT ATTACHMENT IN Y DIRECTION
  712    100   CONTINUE
        C   END OF CABLE LOOP
  716    150   CONTINUE
  720          PRINT 102
  724    102   FORMAT(1H1,5X*IN THE FOLLOWING TABLES - X REL. TO CG, Y REL. TO WA
             2TER SURFACE*//)
  724          DO 160 I=1,2
  726          PRINT 103,TITLE
  733    103   FORMAT(  5X,8A10  )
  733          PRINT 105,I,TIDE(ITIDE)
  744    105   FORMAT(///5X*MOORING LINE NUMBER= *I1,*   TIDE=*F6.3//
             2  10X,*Y*14X,1HX,8X,*TOP TENSION*7X*FORCEX*7X*FORCEY*/)
  744          DO 120 J=1,3
  746          DO 120 K=1,NANGLE
  747          PRINT 110,WY(I,J),EX(I,J,K),TENS(I,J,K),FX(I,J,K),FY(I,J,K)
 1013    110   FORMAT(5X,5(F11.3,4X))
 1013    120   CONTINUE
 1020          PRINT 125
 1023    125   FORMAT(1H1)
 1023    160   CONTINUE
 1025          CALL EQULIB
```

Table B-3. Continued

```
          C    FND OF TIDE LCOP
  1026     400   CONTINUE
  1031           STOP
  1033           END
```

Table B-3. Continued

```
               SUBROUTINE LINE2(K,PHIONE,TZERO,DEPTH,BSLOPE,X,Y,FORCEX,FORCEY,IP)
  15           COMMON/ONE/NSEG(2),NSECT(2,5),WSECT(2,5), MATL(2,5),DIAM(2,5),
              2  ALSECT(2,5)
         C**THE INPUT TO SUBROUTINE LINE
         C  PHIONE=INITIAL ANGLE OF CABLE
         C  TZERO=INITIAL GUESS OF TENSION AT TOP OF CABLE
         C**SUBROUTINE LINE COMPUTES
         C  TZERO= TENSION AT CABLE TOP
         C  FORCEX=FORCE IN X DIRECTION AT CABLE TOP
         C  FORCEY=FORCE IN Y DIRECTION AT CABLE TOP
         C  X=HORIZONTAL SEPERATION BETWEEN TOP AND BOTTOM OF CABLE
         C  Y=VERTICAL   SEPERATION BETWEEN TOP AND BOTTOM OF CABLE
         C***GO DOWN THE CABLE SECTION BY SECTION COMPUTE TENSION,ANGLE,
         C    EXTENDED LENGTH,X AND Y COORDINATES
  15           PI=3.14159
  16           NITER=0
  17           MNITER=25
  21           NOTE=0
  22           T=TZERO
  23      152  NITER=NITER+1
  25           IF(IP .EQ. 0) GO TO 153
  27           IF(NOTE .EQ. 0) GO TO 153
  31           PRINT 155
  35      155  FORMAT(//5X*I    J        X          Y        TENSION     LSECT*
              2 6X,*LEXT  PHI-DEGREES    FORCEY     FORCEX*/)
  35      153  Y=0.
  37           X=0.
  43           PHI=PHIONE
  44           NSS=NSEG(K)
  47      158  DO 200 I=1,NSS
  51           NS=NSECT(K,I)
  56           DO 200 J=1,NS
  57           PHID=PHI*180./PI
  61           IF(MATL(K,I) .EQ. 5HNYLON )GO TO 165
  67           IF(MATL(K,I) .EQ. 5HCHAIN )GO TO 160
  75      160  CALL CHAIN(DIAM(K,I),T,STRAIN)
 105           GO TO 170
 111      165  CALL NYLON(DIAM(K,I),T,STRAIN)
 121      170  ALEXT=ALSECT(K,I)*(1.+STRAIN)
 134           X=X+ALEXT*COS(PHI)
 145           Y=Y+ALEXT*SIN(PHI)
 152           TCOS=T*COS(PHI)
 156           TSIN=T*SIN(PHI)
 162           IF(IP .EQ. 0) GO TO 185
 170           IF(NOTE .EQ. 0) GO TO 185
 172           PRINT 180,I,J,X,Y,T,ALSECT(K,I),ALEXT,PHID,TSIN,TCOS
 231      180  FORMAT(X,2I5,8F10.3)
 231      185  IF(I .EQ. NSS   .AND. J .EQ. NS) GO TO 200
 247           SLOPE=(TSIN+WSECT(K,I))/TCOS
 257           IF(SLOPE .GE. BSLOPE) SLOPE=BSLOPE
 262           PHI=ATAN(SLOPE)
 266           T=TCOS/COS(PHI)
 271      200  CONTINUE
 302           FORCEX=TZERO*COS(PHIONE)
 311           FORCEY=TZERC*SIN(PHIONE)
```

Table B-3. Continued

```
RUNT VERSION FEB 74 B    13:04 04/09/76

            OUTPUT,NITER,Y,X,TZERO
C***THE SECOND GUESS OF INITIAL TENSION IS COMPUTED
            IF(NITER .GT. 1) GO TO 220
            TZOLD=TZERO
            TZERO=TZERO*ABS(DEPTH/Y)
            YOLD=Y
            T=TZERO
            GO TO 152
C***THE SUBSEQUENT INITIAL TENSIONS ARE COMPUTED USING SECANT ITERATIC
  220       RELER=ABS(1.+Y/DEPTH)
            IF(NOTE .EQ. 1) GO TO 300
            IF(NITER .GE. MNITER .OR. RELER .LE. .0001  ) NOTE=1
            DEROLD=DEPTH+YOLD
            DERR=DEPTH+Y
            T=TZOLD-DEROLD*(TZERO-TZOLD)/(DERR-DEROLD)
            IF(T .LE. 0.) T=TZERO/2.
            YOLD=Y
            TZOLD=TZERO
            TZERO=T
            GO TO 152
  300       RETURN
            END
```

```
NT VERSION FEB 74 B    13:04 04/09/76

      SUBROUTINE CHAIN(D,T,STRAIN)
      PI=3.14159
      E=30.E6
      AREA=D*D*PI/2.
C     C=ELONGATION FACTOR -- C=6 FOR OVAL CHAIN
      C=6.
      STRAIN=C*T/(AREA*E)
      RETURN
      END
```

```
UNT VERSION FEB 74 B    13:04 04/09/76

      SUBROUTINE NYLON(D,T,STRAIN)
      X=T/(D*D)
      A=.02052
      B=.2237
      STRAIN=A*X**B
      RETURN
      END
```

Table B-3. Continued

```
                SUBROUTINE EQULIB
    2           COMMON/TWO/WY(2,3),EX(2,3,20),FX(2,3,2C),FY(2,3,20),TENS(2,3,20),
              2  FEXT(9),SEP(9),TENS1(9),TENS2(9),NANGLE,NCOND,TITLE(8)
    2           COMMON/THREE/X(2),F(2)
    2           DIMENSION SEPDIF(3),FO(3)
          C****EQULIB FINDS THE BREAKWATER EQUILIBRIUM POSITION
          C***LOOP THROUGT THE TEST CONDITIONS
    2           DO 100 IC=1,NCOND
    4           IF(SEP(IC) .NE. 0.) GO TO 20
    7           IF(TENS1(IC) .NE.0.)GO TO 10
   13           IF(TENS2(IC) .NE.0.)GO TO 12
   17           PRINT 155
   23      155  FORMAT(//X*NO INITIAL CONDITIONS SPECIFIED*)
   23           GO TO 100
          C***FOR THE CASES WHERE INITIAL TENSION IS GIVEN THE FOLLOWING IS USED
   24       10  T=TENS1(IC)
   27           I=1
   31           J=2
   32           GO TO 14
   33       12  T=TENS2(IC)
   36           I=2
   40           J=1
   41       14  OUTPUT,I,NANGLE,T
   57           IF(T .GE. TENS(I,1,1)) GO TO 18
   70           PRINT 16
   74           GO TO 100
   75       18  IF(T .GE. TENS(I,1,NANGLE)) PRINT 17
  111       16  FORMAT(//5X*GIVEN TENSION CLOSE TO OR LESS THAN WEIGHT OF VERTICAL
              2 MOORING LINE*/5X*NO FURTHER EVALUATION ATTEMPTED *//)
  111       17  FORMAT(//5X*GIVEN TENSION TOO GREAT FOR EVALUATION WITHOUT*
              2 *EXTRAPOLATION*/5X*USE RESULTS WITH CAUTION*//)
  111           CALL LTERPS (I,1,NANGLE,TENS,EX,T,X(I),DUMMY)
  123           OUTPUT,X(I),T
  137           CALL LTERPS (I,1,NANGLE,TENS,FX,T,F(I),DUMMY)
  151           OUTPUT,F(I)
  162           IF(I .EQ. 1 .AND. TENS2(IC) .NE. 0) GO TO 12
  177           IF(TENS1(IC) .NE. 0 .AND. TENS2(IC) .NE. 0) GO TO 40
  214           F(J)=-F(I)-FEXT(IC)
  224           OUTPUT,F(J)
  234           CALL LTERPS (J,1,NANGLE,FX,EX,F(J),X(J),DUMMY)
  250           OUTPUT,X(J)
          C   NOTE-- F(I)=X DIRECTION FORCE ON CABLE I , X(I)=X COORD OF ANCHOR
  261           GO TO 40
          C***FOR THE CASE WHERE ANCHOR SEPERATION IS GIVEN
          C   MAKE A FIRST AND SECOND GUESS AT FORCE
  262       20  IA=(NANGLE+1)/2
  270           EPS=SEP(IC)*.0001
  274           DO 30 II=1,2
  275           X(1)=EX(1,1,IA)
  305           F(1)=FX(1,1,IA)
  315           OUTPUT,F(1),II,FEXT(IC),SEP(IC),IA
  344           FO(II)=F(1)
  351           F(2)=-F(1)-FEXT(IC)
  361           OUTPUT,F(2)
  371           CALL LTERPS (2,1,NANGLE,FX,EX,F(2),X(2),DUMMY)
```

Table B-3. Continued

```
RUNT VERSION FEB 74 B   13:04 04/09/76

   405          ASEP=X(1)-X(2)
   413          SEPDIF(II)=SEP(IC)-ASEP
   421          OUTPUT,II,IA,X(1),X(2),F(1),F(2),SEP(IC),ASEP,SEPDIF(II)
   466          IF(ABS(SEPDIF(II)) .GT. EPS) GO TO 24
   476          GO TO 40
   477     24   IF(SEPDIF(II) .GE. 0.) GO TO 26
   503          IA=1
   505          GO TO 30
   505     26   IA=NANGLE
   507     30   CONTINUE
        C***USE SECANT INTERPOLATION FOR THE SUBSEQUENT FORCE TRIALS
   511          MN=20
   513          DO 34 K=1,MN
   514          FO(3)=FO(1)-SEPDIF(1)*(FO(2)-FO(1))/(SEPDIF(2)-SEPDIF(1))
   540          IF(FO(3) .LE. 0.) FO(3)=FO(2)/2.
   552          F(1)=FO(3)
   557          F(2)=-F(1)-FEXT(IC)
   567          DO 32 I=1,2
   570     32   CALL LTERPS (I,1,NANGLE,FX,EX,F(I),X(I),DUMMY)
   605          ASEP=X(1)-X(2)
   613          SEPDIF(3)=SEP(IC)-ASEP
   621          OUTPUT,K,X(1),X(2),F(1),F(2),ASEP,SEPDIF(3)
   657          IF(ABS(SEPDIF(3)) .LE. EPS) GO TO 38
   667          IF(K .EQ. MN) GO TO 36
   672          FO(1)=FO(2)
   677          FO(2)=FO(3)
   704          SEPDIF(1)=SEPDIF(2)
   711          SEPDIF(2)=SEPDIF(3)
   716     34   CONTINUE
   720     36   PRINT 37
   724     37   FORMAT(/5X*MAX NUMBER OF ITERATIONS REACHED*/)
   724     38   DO 39 I=1,2
   726          IF(ABS(F(I)) .GT. ABS(FX(I,1,NANGLE))) PRINT 42
   750     39   IF(ABS(F(I)) .LT. ABS(FX(I,1,1))) PRINT 43
   775     42   FORMAT(//5X*ANCHOR SEPERATION TOO GREAT FOR EVALUATION WITHOUT EXT
               2RAPOLATING--USE RESULTS WITH CAUTION*//)
   775     43   FORMAT(//5X*ANCHOR SEPERATION TOO LITTLE FOR EVALUATION WITHOUT EX
               2TRAPOLATION--USE RESULTS WITH CAUTION*//)
   775     40   CALL SPRING(IC)
   777    100   CONTINUE
  1002          RETURN
  1002          END
```

Table B-3. Continued

```
                SUBROUTINE SPRING(IC)
   6            COMMON/TWO/WY(2,3),EX(2,3,20),FX(2,3,20),FY(2,3,20),TENS(2,3,20),
              2  FEXT(9),SEP(9),TENS1(9),TENS2(9),NANGLE,NCOND,TITLE(8)
   6            COMMON/THREE/X(2),F(2)
   6            COMMON/FOUR/YCG,XCAB(2),YCAB(2),TIDE(5),ITIDE
   6            DIMENSION DFXDX(2),DFYDX(2),DFXDY(2),DFYDY(2),D(3),FXX(2,3),
              2  FYX(2,3),FV(2),DTDX(2),DTDY(2),DTDR(2),T(2,3)
   6            REAL KM11,KM12,KM13,KM21,KM22,KM23,KM31,KM32,KM33
          C****SUBROUTINE SPRING COMPUTES THE BREAKWATER SPRING CONSTANTS
          C***COMPUTE THE SPRING CONSTANTS FOR EACH CABLE
          C  HORIZONTAL FORCE AT EQUILIBRIUM=F(I) FOR CABLE I
          C  VERT FORCE AT EQUILIBRIUM=FV(I) FOR CABLE I
   6            DO 14 I=1,2
   7            DO 12 J=1,3
  10            CALL LTERPS (I,J,NANGLE,EX,FX,X(I),FXX(I,J),DF)
  27            IF(J .EQ. 1) DFXDX(I)=-DF
  35            CALL LTERPS (I,J,NANGLE,EX,TENS,X(I),T(I,J),DT)
  54            IF(J .EQ. 1) DTDX(I)=-DT
  62       12   CALL LTERPS (I,J,NANGLE,EX,FY,X(I),FYX(I,J),D(J))
 107            DTDY(I)=(T(I,3)-T(I,2))/(WY(I,2)-WY(I,3))
 133            DFYDX(I)=-D(1)
 140            FV(I)=FYX(I,1)
 147            DFYDY(I)=(FYX(I,2)-FYX(I,3))/(WY(I,2)-WY(I,3))*(-1.)
 174            DFXDY(I)=(FXX(I,2)-FXX(I,3))/(WY(I,2)-WY(I,3))*(-1.)
 221       14   CONTINUE
 223            PRINT 16,TITLE
 230       16   FORMAT(1H1,8A10)
 230            PRINT 15,TIDE(ITIDE),FEXT(IC),SEP(IC),TENS1(IC),TENS2(IC)
 261       15   FORMAT(///X*FOR THE CONDITIONS --*/
              1 5X*TIDE = *F5.2/
              2  5X*EXTERNALLY APPLIED HORIZONTAL FORCE, FEXT= *F10.3*LB.*/
              3  5X*HORIZONTAL ANCHOR SEPERATION, SEP= *F10.3*FEET*/
              4  5X*NOMINAL TENSION IN CABLE 1 =*F10.3* LB.*/
              5  5X*NOMINAL TENSION IN CABLE 2 =*F10.3* LB.*//)
 261            PRINT 18
 265       18   FORMAT(/5X*CABLE NO.   FX*10X*FY*11X,1HX,11X*Y*9X*DFXDX*7X,
              2  *DFXDY*7X*DFYDX*7X*DFYDY*,5X,*TENSION*//)
 265            DO 20 I=1,2
 270       20   PRINT 25, I,F(I),FV(I),X(I),WY(I,1),DFXDX(I),DFYDX(I),DFXDY(I),
              2  DFYDY(I),T(I,1)
 337       25   FORMAT(9X,I1,4(2X,F10.3),5(X,E11.3))
          C***NOW CALCULATE FORCES AND SPRING CONSTANTS FOR THE BREAKWATER
          C  S=SWAY MOTION   +X DIRECTION  FEET
          C  H=HEAVE MOTION    +Y DIRECTION
          C  R=ROLL MOTION    COUNTERCLOCKWISE   RADIANS
          C  FS=FORCES CAUSING SWAY DUE TO THE MOORING LINES
          C  FH=FORCES CAUSING HEAVE DUE TO MOORING LINES
          C  EMR=MOMENTS CAUSING ROLL DUE TO MOORING LINES
          C   CHANGE YCAB TO BE DIST TO CG IN Y DIRECTION
 337            YCAB(1)=YCAB(1)-YCG
 345            YCAB(2)=YCAB(2)-YCG
 352            FS=F(1)+F(2)
 360            FH=FV(1)+FV(2)
 365            EMR=FV(1)*XCAB(1)+FV(2)*XCAB(2)-F(1)*YCAB(1)-F(2)*YCAB(2)
          C***CALCULATE CHANGE IN TENSIONS WITH BREAKWATER MOTIONS
```

Table B-3. Continued

```
 413           DO 26 I=1,2
 414     26    DTDR(I)=DTDY(I)*XCAB(I)-DTDX(I)*YCAB(I)
 432           PRINT 27
 435     27    FORMAT(//5X*CABLE NO.  DTDX*8X*DTDY*8X*DTDR*//)
 435           DO 28 I=1,2
 440     28    PRINT 29,I,DTDX(I),DTDY(I),DTDR(I)
 461     29    FORMAT(9X,I1,3(XE11.4))
       C  SPRING CONSTANTS SWAY DIRECTION
 461           KM11=(DFXDX(1)+DFXDX(2))*(-1.)
 471           KM12=(DFYDX(1)+DFYDX(2))*(-1.)
 500           KM13=(DFYDX(1)*XCAB(1)+DFYDX(2)*XCAB(2)-DFXDX(1)*YCAB(1)-DFXDX(2)*
              2  YCAB(2))*(-1.)
       C  SPRING CONSTANTS HEAVE
 530           KM21=(DFXDY(1)+DFXDY(2))*(-1.)
 537           KM22=(DFYDY(1)+DFYDY(2))*(-1.)
 546           KM23=(DFYDY(1)*XCAB(1)+DFYDY(2)*XCAB(2)
              2  -DFXDY(1)*YCAB(1)-DFXDY(2)*YCAB(2))*(-1.)
       C  SPRING CONSTANTS ROLL DIRECTION
 576           KM31=(DFXDY(1)*XCAB(1)+DFXDY(2)*XCAB(2)-DFXDX(1)*YCAB(1)
              2  -DFXDX(2)*YCAB(2))*(-1.)
 626           KM32=(DFYDY(1)*XCAB(1)+DFYDY(2)*XCAB(2)
              2  -DFYDX(1)*YCAB(1)-DFYDX(2)*YCAB(2))*(-1.)
 656           KM33=(XCAB(1)**2*DFYDY(1)+XCAB(2)**2*DFYDY(2)
              2  +YCAB(1)**2*DFXDX(1)+YCAB(2)**2*DFXDX(2)
              3  -XCAB(1)*YCAB(1)*(DFYDX(1)+DFXDY(1))
              4  -XCAB(2)*YCAB(2)*(DFYDX(2)+DFXDY(2)))*(-1.)
 756           PRINT 30,FS,FH,EMR
 767     30    FORMAT(///5X*FORCES AND MOMENTS ON BREAKWATER AT EQULIBRIUM DUE *
              2 *TO MOORING LINES*/10X*FS= *F12.4/10X*FH= *F12.4/10X*MR= *F12.4)
 767           PRINT 32,KM11,KM12,KM13
1001     32    FORMAT(//5X*SPRING CONSTANTS SWAY DIRECTION*/10X*KM11 = *E12.5/
              2  10X*KM12 = *E12.5/10X*KM13 =*E12.5)
1001           PRINT 34,KM21,KM22,KM23
1013     34    FORMAT(/5X*SPRING CONSTANTS HEAVE DIRECTION*/10X*KM21 = *E12.5/
              2  10X*KM22 = *E12.5/10X*KM23 =*E12.5)
1013           PRINT 36,KM31,KM32,KM33
1025     36    FORMAT(/5X*SPRING CONSTANTS ROLL DIRECTION*/10X*KM31 = *E12.5/
              2  10X*KM32 = *E12.5/10X*KM33 =*E12.5//)
1025           PRINT 38
1031     38    FORMAT(1H1)
1031           RETURN
1032           END
```

Table B-3. Continued

RUNT VERSION FEB 74 B   13:04 04/09/76

```
      SUBROUTINE LTERPS (I,J,N,X,Y,XX,YY,DYDX)
      DIMENSION X(2,3,20),Y(2,3,20)
      NMO=N-1
      DO 10 K=1,NMO
      L=K+1
      IF(XX .EQ. X(I,J,L)) GO TO 30
      IF(ABS(XX) .LT. ABS(X(I,J,L))) GO TO 20
   10 CONTINUE
   20 DYDX=(Y(I,J,L)-Y(I,J,K))/(X(I,J,L)-X(I,J,K))
      YY=Y(I,J,K)+(XX-X(I,J,K))*DYDX
      RETURN
   30 IF(L .EQ. N) GO TO 20
      M=L+1
      DYDX=(Y(I,J,M)-Y(I,J,K))/(X(I,J,M)-X(I,J,K))
      YY=Y(I,J,L)
      RETURN
      END
```

Table B-3. Continued

APPENDIX C

LINEAR HYDRODYNAMIC COEFFICIENTS

The linear theoretical model used in solving the floating breakwater problem has been discussed extensively by Frank (1967). He developed the approach to solving the boundary value problem which has come to be known as the "Frank close-fit method". The reader is referred to the original reference for a complete presentation of the method.

In this approach, the classical linear boundary value problem requires that Laplace's equation be satisfied throughout the fluid domain:

$$\nabla^2 \Phi(x,y,t) = 0 \quad \text{for} \quad y < 0. \tag{C-1}$$

The free-surface boundary condition is applied on the undisturbed free surface:

$$\Phi_{tt}(x,0,t) + g\Phi_y = 0 \quad \text{for} \quad y = 0. \tag{C-2}$$

The body-surface boundary condition requires that no fluid flow through the body surface:

$$\nabla\Phi(x,y,t) \cdot \vec{n}\Big|_{C_o} = \vec{V}_i(s) \cdot \vec{n}(s). \tag{C-3}$$

The bottom boundary condition for infinite depth is of the form:

$$\lim_{y\to-\infty} \Phi_y(x,y,t) = 0. \tag{C-4}$$

In addition there is a radiation condition specifying that the waves travel away from the body.

Because the problem is assumed to be linear, the velocity potential may be decomposed and several boundary value problems considered. If this is done the total potential becomes:

$$\Phi = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 + \Phi_5. \tag{C-5}$$

Here,

Φ_1 = potential representing pure sway motion in calm water,

Φ_2 = potential representing pure heave motion in calm water,

Φ_3 = potential representing pure roll motion in calm water,

Φ_4 = potential representing the waves diffracted by a fixed body,

Φ_5 = incident wave potential.

Another velocity potential may be defined:

Φ_6 = potential for total fixed-body problem,

so that

$$\Phi_6 = \Phi_4 + \Phi_5 .$$

Using this decomposition of the velocity potential, the boundary value problems may be expressed as:

$$\nabla^2 \Phi_i(x,y,t) = 0 \quad \text{for} \quad y < 0,$$

$$\Phi_{i_{tt}}(x,0,t) + g\Phi_{i_y} = 0 \quad \text{for} \quad y = 0,$$

$$\lim_{y \to -\infty} \Phi_{i_y}(x,y,t) = 0, \qquad \text{(C-6)}$$

and

$$\nabla\Phi_i \cdot \vec{n}\Big|_{C_o} = \vec{V}_i(s) \cdot \vec{n}(s) \quad \text{for} \quad i = 1,2,3$$

or

$$\nabla\Phi_i \cdot \vec{n}\Big|_{C_o} = 0 \quad \text{for} \quad i = 4,6.$$

These boundary value problems are solved directly using the Frank method which distributes singularities over the hull surface. These singularities satisfy the radiation condition, Laplace's equation, the free-surface boundary condition and the bottom boundary condition. To satisfy the body boundary condition requires the formulation of a set of linear equations whose solution reveals the strength of each singularity distributed on the body.

Once the velocity potential is found the pressure may be found from Bernoulli's equation:

$$P(x,y,t) = -\rho\Phi_t(x,y,t). \qquad \text{(C-7)}$$

The force on the body surface is:

$$\vec{F} = \int_{C_o} P(s)\, \vec{n}(s)\, ds, \qquad \text{(C-8)}$$

and the moment is:

$$M = \int_{C_o} P(s)\,[\vec{r}\times\vec{n}]\; ds. \qquad \text{(C-9)}$$

The added-mass and damping coefficients are found by considering the cases i = 1,2,3. The forces and moments computed using these potentials may be separated into components in phase with acceleration and velocity. The component in phase with acceleration yields the added-mass coefficients and the component in phase with velocity yields the damping coefficients. Exciting forces and moments are computed when the case i = 6 is considered.

Special Symbols for Appendix C.

$\vec{n}(s)$ = unit interior normal vector to the body surface

s = indicates arc length along body contour

C_o = body contour

P(s) = pressure on body surface

$\vec{V}(s)$ = velocity of body surface

Φ = total velocity potential

APPENDIX D

FLOATING BREAKWATER ANALYSIS

1. Purpose of the Program.

Computer program BRK2D performs a performance analysis for two-dimensional floating breakwaters of arbitrary cross section. This analysis includes predictions of the hydrodynamic coefficients, the dynamics and mooring line forces.

2. Program Description.

Program BRK2D is written using both FORTRAN II and FORTRAN IV statements.

The program consists of the main program BRK2D and the subroutines COEFF, COMP, PHYSCL, POTOUT, DYNAMC, MORTEN, CPV, LNEQF.

The subroutines COEFF and COMP calculate the quantities needed to formulate the linear equations for the velocity potential. COMP calls on LNEQF to solve these linear simultaneous equations.

Subroutine PHYSCL calculates the physical quantities including added-mass and damping coefficients and surface elevations per unit amplitude of motion.

CPV is a subroutine which evaluates the Cauchy principal value integral in the Green function.

LNEQF is a packaged subroutine to solve simultaneous linear equations using the Gaussian reduction method.

3. Type of Computer and Peripherals.

BRK2D was written for use on the CDC 6400 computer. It uses about 55000_8 words of memory. No peripherals other than the card reader, line printer and card punch are required.

4. Input Data.

The first cards in the data deck are label cards for the output. These are shown in the example input in Table D-1 for the example and are not included here. Following these cards, the input for BRK2D is:

Card #1 - Title card, Format (8A10).
80 alphanumeric characters.

Card #2 - Logical control card, Format (5I10,6I5).
N = Number of straight line segments used to fit the hull.
NW = Number of points on the free surface where wave height is to be computed.

NWAVEL = Number of wavelengths at which computations are to be performed.

ISYM = 1 for symmetric section.
= Anything else for non-symmetric section.

ISKIP = 1 Do not solve equations of motion,
2 Do not solve potential problem (read in coefficients from data),
= Anything else solve potential problem and equations of motion.

LC = Number of body segments which represent spaces between multiple hull configurations (1 to 5).

JC = Designates the segment number for segments representing spaces between multiple hulls.

Card #3 - Parameter card, Format (5F10.3,3A10).

AREA = Crossectional area of immersed body.

B = Characteristic beam as specified by BTITLE.

D = Distance below free surface to origin of users coordinate system (all motions are referred to that point).

ROE = Fluid density.

GEE = Acceleration of gravity.

BTITLE = Specifies B.

Card #4 - Beam/wavelength specification, Format (10F8.5).

BOL = Beam/wavelength ratios for computation (up to 10 different ratios may be used).

Card #5 - Offset cards, Format (2F10.3).

There must be N+1 cards giving the offset points. In the version of the program used here, N must be less than or equal to 23 because of dimension statements.

R(1,I) = X-coordinate of offset point.

R(2,I) = Y-coordinate of offset point.

Card #6 - Hydrostatic spring constants, Format (9F8.3).

This is read in subroutine DYNAMC.

RKHYD (1,1) = KH_{11}.
RKHYD (1,2) = KH_{12}.
RKHYD (1,3) = KH_{13}.
RKHYD (2,1) = KH_{21}.
RKHYD (2,2) = KH_{22}.
RKHYD (2,3) = KH_{23}.
RKHYD (3,1) = KH_{31}.
RKHYD (3,2) = KH_{32}.
RKHYD (3,3) = KH_{33}.

Card #7 - Physical properties, Format (6F10.3,3F5.2,I5).

This is read in subroutine DYNAMC.

AREA = Crossectional area.

B = Characteristic beam.

XG = X-coordinate of the center of gravity.

YG = Y-coordinate of the center of gravity.

RMASS = Mass per unit length of breakwater.

RINERT = Mass moment of inertia per unit length of breakwater.

DAMP(1) = Added damping in sway. In the equations of motion sway damping will be 1+DAMP(1) times the computed hydrodynamic damping.
DAMP(2) = Added damping in heave.
DAMP(3) = Added damping in roll.
NPUNCH = 0, punch data cards containing computed transmission coefficient, motion response and mooring-force coefficient.
= Anything else, do not punch data cards.

Card #8 - Mooring spring constants, Format (9F8.3).
This is read in subroutine DYNAMC.
RKMOR(1,1) = KM_{11}.
RKMOR(1,2) = KM_{12}.
RKMOR(1,3) = KM_{13}.
RKMOR(2,1) = KM_{21}.
RKMOR(2,2) = KM_{22}.
RKMOR(2,3) = KM_{23}.
RKMOR(3,1) = KM_{31}.
RKMOR(3,2) = KM_{32}.
RKMOR(3,3) = KM_{33}.

Card #9 - Mooring-line response parameters, Format (6F10.2).
This card is read in subroutine MORTEN.
DELT(1,1) = $\Delta F/\Delta\alpha_1$ for shoreward mooring line. This is the change in mooring line force per unit displacement in sway.
DELT(1,2) = $\Delta F/\Delta\alpha_2$ for shoreware mooring line.
DELT(1,3) = $\Delta F/\Delta\alpha_3$ for seaward mooring line.
DELT(2,1) = $\Delta F/\Delta\alpha_1$ for seaward mooring line
DELT(2,2) = $\Delta F/\Delta\alpha_2$ for seaward mooring line.
DELT(2,3) = $\Delta F/\Delta\alpha_3$ for seaward mooring line.

Note: The last 3 cards (#7, #8, and #9) provide the information needed for the dynamic analysis. If it is desirable to perform calculations varying the data, these cards may be repeated with different input data. There is a limit of 25 different sets of data. In the example data shown in Table D-1, there are 3 different conditions used.

5. Mathematical Procedures and Program Limitations.

The mathematics has been described in the report and Appendix C.

The main limitations are that at most 23 offset points may be used to describe the shape. This has been found to be very adequate for the configurations considered thus far. Little change in the results occurs when more than 15 points are used. Computer time increases about as the square of the number of points.

A listing of the program is given in Table D-2.

6. Flow Chart.

A flow chart is given in a figure of this appendix.

```
MU11/QM                       MU12/QM
MU13/(QM*B)                   MU21/QM
MU22/QM                       MU23/(QM*B)
MU31/(QM*B)                   MU32/(QM*B)
MU33/(QM*B*B)
LAMBDA11/QD                   LAMBDA12/QD
LAMBDA13/(QD*B)               LAMBDA21/QD
LAMBDA22/QD                   LAMBDA23/(QD*B)
LAMBDA31/(QD*B)               LAMBDA32/(QD*B)
LAMBDA33/(QD*B*B)
FX/QF                         FY/QF
   MZ/(QF*B)
GEN BY SWAY/SWAY              GEN BY HEAVE/HEAVE
GEN BY ROLL/ROLL(RAD)*B       REFLECTED BY FXD BDY/ETA
INCIDENT/ETA                  REFLECTED + INCIDENT/ETA
TRANS BY FXD BDY/ETA
   BEAM/WAVELENGTH               DIMENSIONAL FREQUENCY - HZ
ADDED MASS  QM = AREA*ROE     DAMPING  QD = AREA*ROE*W
WAVE FORCES QF=AREA*ROE*ETA*W2PHASE REL TO ETA AT X=0 - DEG
PHASE REL TO BODY MOTION - DEGWAVE FIELD - AMPLITUDE RATIOS
POSITION - X/WAVELENGTH       DIMENSIONAL POSITION - X
SWAY AMPLITUDE/ETA            HEAVE AMPLITUDE/ETA
ROLL AMPLITUDE(RAD)*B/ETA
GEN BY RESULTANT SWAY/ETA     GEN BY RESULTANT HEAVE/ETA
GEN BY RESULTANT ROLL/ETA     TOTAL TRANSMITTED/ETA
TOTAL REFLECTED/ETA
MOTION RESPONSE
OAK HARBOR BREAKWATER - CORPS OF ENGINEERS TESTS                       17 MAY 1975
     23         0        10         0          0    1    12
    12.6      10.0        0.0    1.9905      32.2FULL BEAM
    .1 .159290   .180 .216311    .250    .280 .312208    .371    .429 .487825
    -5.0      0.0
    -5.0     -1.25
    -5.0     -2.50
    -5.0     -3.75
    -5.0     -5.00
  -4.583     -5.00
  -4.583     -3.75
  -3.223     -3.75
  -3.223     -2.50
  -3.223     -1.25
  -4.583     -1.25
  -4.583      0.00
   4.583      0.00
   4.583     -1.25
   3.223     -1.25
   3.223     -2.50
   3.223     -3.75
   4.583     -3.75
   4.583     -5.00
     5.0     -5.00
     5.0     -3.75
     5.0     -2.50
     5.0     -1.25
     5.0      0.0
   0.0      0.0      0.0      0.0     64.5      0.0      0.0      0.0   1165.
    12.6      10.0       0.0     -2.34      25.1      621.   0.   0.   0.    1
    0.      0.      0.      0.      0.      0.      0.      0.      0.
    12.6      10.0       0.0     -2.34      25.1      621.   0.   0.   0.
118.8   -5.24   166.2   -5.732  10.21   -3.372  159.9   2.063   281.8
-1376.    410.6    -1607.    1172.    280.9    1713.
    12.6      10.0       0.0     -2.34      25.1      621.   1.   1.   1.
118.8   -5.24   166.2   -5.732  10.21   -3.372  159.9   2.063   281.8
-1376.    410.6    -1607.    1172.    280.9    1713.
```

Table D-1. Example input for program BRK2D (Oak Harbor breakwater).

RUNT VERSION FEB 74 B   17:12 04/23/76

```
              PROGRAM BRK2D (INPUT,OUTPUT,PUNCH,TAPE5=INPUT,TAPE6=OUTPUT)
        C***LATEST REVISION ***** 27 AUGUST 1975
        C***PROGRAM BRK2D COMPUTES THE FIRST-ORDER RESPONSE OF AN OSCILLATING
        C     CYLINDER ON OR NEAR THE FREE SURFACE OF AN IDEAL FLUID OF
        C     INFINITE DEPTH
   3          COMMON RI12(25,25),RK56(25,25), POT(25,25), HOW(25,25),FF(25,6),
             1FI(25,6),  RI(25,25), RJ(25,25), RK(25,4), RL(25,4),
             2RMU(3,3,10), RLAM(3,3,10), FB(3,10), DELFB(3,10), HWB(25,6,10),
             3 DELW(25,6,10) , XOL(25,10)
   3          COMMON/ONE/X(25),Y(25),XB(25),YB(25),ANG(25),DEL(25),VV(25)
             1,FEIN(25), FIIN(25), RNORM(25,3), JC(5)
   3          COMMON/ONE2/CC3(25),SS3(25)
   3          COMMON /TWO/ N,NNW, NWAVEL, ISYM, ISKIP, NC, PIE,GAMMA,M,TK,TP
   3          COMMON/THREE/ WAVEL(10), WN(10), BOL(10),IL
   3          COMMON/SIX/XN(5),CN(5)
   3          COMMON  /SEVEN/ AREA, B, D, ROE, GEE, BTITLE(3), TITLE(8)
   3          COMMON / EIGHT/LBLMU(3,3,3), LBLAM(3,3,3), LBLFB(3,3),LBLHWB(7,3),
             1LBL(10,3), DEG(3,10)
   3          COMMON /NINE/ LBLRAR(3,3), LBLHWR(5,3), LBLR(5,3)
   3          COMMON/TEN/DELT(2,3),FOR(2,10),PHAS(2,10),FORND(2,10),PHASD(2,10)
   3          REAL K
   3          DATA XN/.263560319718,1.413403059107,3.596425771041,
             1      7.085810005859,12.640800844276/
   3          DATA CN/.521755610583,.398666811083,.0759424496817,
             1      .00361175867992,.00002336997239/
   3          PIE=ATAN2(0.,-2.)
   7          TP=2.*PIE
  10          GAMMA=0.57721566
        C***BEGIN READING INPUT DATA AND PRINTING ECHO CHECK
  12     3000 FORMAT (6A10)
        C*****READ LABLES FOR PRINT OUT
  12          READ 3000, (((LBLMU(I,J,L), L = 1,3), J = 1,3), I = 1,3)
  36          READ 3000, (((LBLAM(I,J,L), L = 1,3), J = 1,3), I = 1,3)
  63          READ 3000,    ((LBLFB(J,L), L = 1,3), J = 1,3)
 103          READ 3000,   ((LBLHWB(J,L), L = 1,3), J = 1,7)
 123          READ 3000,   ((   LBL(J,L), L = 1,3), J = 1,10)
 143          READ 3000,   ((LBLRAR(J,L), L = 1,3), J = 1,3)
 163          READ 3000,   ((LBLHWR(J,L), L = 1,3), J = 1,5)
 203          READ 3000, (LBLR(1,L), L = 1,3)
 220          READ 20, TITLE
 226       20 FORMAT (8A10)
 226          PRINT 30, TITLE
 234       30 FORMAT (1H1, 8A10///)
 234          READ 50, N, NW, NWAVEL, ISYM, ISKIP, LC, JC
 256     50   FORMAT (5I10, 6I5)
        C           N = NUMBER OF STRAIGHT LINE SEGMENTS TO BE USED TO FIT
        C               THE HULL.....NOTE.  THERE MUST BE N+1 OFFSET POINTS
        C           NW = NUMBER OF POINTS ON FREE SURFACE WHERE WAVE HEIGHT IS
        C               TO BE COMPUTED.  THIS IS IN ADDITION TO THE COMPUTATION OF
        C               WAVE HEIGHT 4.0 WAVELENGTHS ON EITHER SIDE OF THE BODY
        C               WHICH IS PERFORMED AUTOMATICALLY
        C           NWAVEL = NUMBER OF WAVELENGTHS AT WHICH COMPUTATIONS ARE TO
        C               BE PERFORMED
        C           ISYM = 1 FOR SYMMETRIC SECTION
        C                 = ANYTHING ELSE FOR NON-SYMMETRIC SECTION
```

Table D-2. Listing of program BRK2D

```
      C            ISKIP = 1 DO NOT SOLVE EQUATIONS OF MOTION
      C                  = 2 DO NOT SOLVE POTENTIAL PROBLEM (READ IN COEFS)
      C                  = ANYTHING ELSE SOLVE FOR COEFFICIENTS AND DYNAMICA
      C            NUMBER OF BODY SEGMENTS WHICH REPRESENT FREE SURFACE BETWEE
      C                   CATAMAARAN HULS.  SEGMENT NUMBERS  SPECIFIED BY JC(5
255         NNW = NW + 2
260         NC = N - LC
262         NW1 = 25 - N - 2
264         IF (NW .LT. 0) NW = 0
267         IF (NW .GT. NW1) NW = NW1
273         PRINT 60, N, NW, NWAVEL, ISYM, ISKIP, LC, JC
315      60 FORMAT (10X*NUMBER OF SEGMENTS =*, I4//
           1     10X*NUMBER OF FREE-SURFACE STATIONS =*, I4//
           2     10X*NUMBER OF WAVELENGTHS =*, I4//
           3     10X*ISYM =*,I4// 10X*ISKIP =*, I4//
           4     10X*NC = *I5, *JC =* 5I5 /)
315         READ 70, AREA, B, D, ROE, GEE, (BTITLE(I), I = 1,3)
342    70   FORMAT (5F10.3, 3A10)
      C            AREA = CROSSECTIONAL AREA OF IMMERSED BODY
      C            B = CHARACTERISTIC LENGTH AS SPECIFIED BY BTITLE
      C            D = DISTANCE BENEATH SURFACE OF ORIGIN OF USERS COORDINATE
      C            SYSTEM (+).  ALL MOTIONS REFERED TO THAT POINT AND BODY
      C            SHAPE SPECIFIED IN THAT SYSTEM
      C            ROE = FLUID DENSITY
      C            GEE = ACCELERATION OF GRAVITY
342         PRINT 80, AREA,B, (BTITLE(I), I = 1,3), D, ROE, GEE
367    80   FORMAT(10X *AREA = *, F10.3 //, 10X *B = *F10.3 ,5X, 3A10
           2 //10X *D = * F10.3 // 10X *FLUID DENSITY =* F10.5//
           3     10X*ACCELERATION OF GRAVITY =*, F10.3/)
367         IF(ISKIP .EQ. 2) GO TO 303
372          READ 100, (BOL(I), I = 1, NWAVEL)
406     100 FORMAT (10F8.5)
      C         BOL = BEAM/WAVELENGTH RATIO FOR COMPUTATIONS
406          DO 600  I = 1,NWAVEL
413    600  WAVEL(I) = B/BOL(I)
      C            WAVEL(I) = DIMENSIONAL WAVELENGTH OF INCIDENT WAVES
417          PRINT 110, (BOL(I), I = 1, NWAVEL)
433    110  FORMAT (10X*BEAM/WAVELENGTH RATIOS OF INCIDENTWAVES*//(20X10F11.5
           1))
      C*****INITIALIZE OUTPUT VARIABLES
433         DO 113 IL = 1,10
435         WN(IL) = 0.0
437         BOL(IL) = 0.0
442         DO 114 I = 1,3
444         FB(I,IL) = 0.0
450         DELFB(I,IL) = 0.0
455         DO 114 J = 1,3
456         RMU(I, J, IL) = 0.0
465         RLAM(I, J, IL) = 0.0
474    114  CONTINUE
500         DO 112 I = 1, 25
501         XOL(I,IL) = 0.0
505         DO 112 J = 1,6
507         HWB(I,J,IL) = 0.0
516         DELW(I,J,IL) =0.0
525    112  CONTINUE
```

Table D-2. Continued

```
 531      113  CONTINUE
      C*****COMPUTE (B/WAVEL) AND NONDIMENSIONAL WAVE NO.
 533           DO 115 IL = 1, NWAVEL
 534           BOL(IL) = B/WAVEL(IL)
 541      115  WN(IL)= TP * B/ WAVEL(IL)
      C***READ IN OFFSETS OF CYLINDER
 551           NUP = N + 1
 553           NUPP = NUP + 2
 555           NTOP = NUPP + NW - 1
 557           N1 = N + 1 + NW
 561           READ 130, (RI(1,I),RI(2,I),I=1,NUP)
 603       130 FORMAT (2F10.5)
      C             RI(1,I),RI(2,I) = DIMENSIONAL X, Y COORDINATE OF OFFSET
      C                    POINTS, RESPECTIVELY
 603           IF (NW .LT. 1) GO TO 185
      C***READ IN ADDITIONAL POINTS ON THE FREE SURFACE WHERE WAVE HEIGHTS
      C        ARE TO BE COMPUTED.  TWO STORAGE LOCATIONS MUST BE LEFT BLANK
      C        FOR THE POSITION 4 WAVELENGTHS FROM THE BODY
 606           READ 130, (RI(1,I),RI(2,I),I=NUPP,NTOP)
      C             RI(1,I),RI(2,I) = COORDINATES OF POINTS ON FREE SURFACE WHERE
      C        WAVE HEIGHT IS TO BE COMPUTED.    THIS IS TRUE FOR I .GT. N + 3
      C***NON-DIMENSIONALIZE OFFSETS
 631           DO 180 I = NUPP,NTOP
 633           X(I) = RI(1,I)/B
 642      180  Y(I) = -1.0E-08
 647       185 CONTINUE
 647           DO 190 I = 1,NUP
 651           XB(I) = RI(1,I)/B
 660      190  YB(I) = RI(2,I)/B
      C...  COMPUTE MIDPOINT,ANGLE AND LENGTH OF STRAIGHT-LINE SEGMENTS.
      C*****AND COMPONENTS OF NORAAL TO BODY
 671           JF = 0
 672           DO 200 J=1,N
 674           X(J)=0.5*(XB(J)+XB(J+1))
 705           Y(J)=0.5*(YB(J)+YB(J+1))
 717           T1=YB(J+1)-YB(J)
 725           T2=XB(J+1)-XB(J)
 732           ANG(J)=ATAN2(T1,T2)
 740           CC3(J)=COS(ANG(J))
 747           SS3(J)=SIN(ANG(J))
 756           VV(J)=X(J)*CC3(J)+Y(J)*SS3(J)
 772           DEL(J ) = SQRT(T2**2 + T1**2)
1007           RNORM(J ,1) = -SS3(J)
1015           RNORM(J ,2) =  CC3(J)
1023           RNORM(J ,3) =  VV(J)
1031       200 CONTINUE
1034           PRINT 30, TITLE
1041           PRINT 250
1045       250 FORMAT (60X*CYLINDER GEOMETRY*///19X*DIMENSIONAL OFFSETS*,
              1      11X*NON-DIMENSIONAL OFFSETS*, 5X*MIDPOINTS OF SEGMENTS*//
              2      6X*I*, 16X*X*, 9X*Y*, 19X*X*, 9X*Y*, 19X*X*, 9X*Y*,
              3      18X*SLOPE*, 4X*LENGTH*/)
1045           PRINT 270, (I,RI(1,I),RI(2,I),XB(I),YB(I),X(I),Y(I),ANG(I),
              1      DEL(I),I=1,N)
1113       270 FORMAT (X, I6, 4(10X2F10.3))
1113           NL = N + 1
```

Table D-2. Continued

```
      PRINT 270, NL, RI(1,NL), RI(2,NL), XB(NL), YB(NL)
      PRINT 281
  281 FORMAT (//10X, *POSITIONS FOR WAVE HEIGHT CALCULATIONS*/)
  280 FORMAT (//)
      IF (NW .LT. 1) GO TO 290
      PRINT 271, (I,RI(1,I),RI(2,I),X(I),Y(I),I=NUPP,NTOP)
  271 FORMAT(X,I6, 2(10X,  2F10.3))
      PRINT 280
  290 M = N + NW + 2
C*****TRANSFER TO COORDINATE SYSTEM IN FREE SURFACE
      DO 285 I = 1,N
      YB(I) = YB(I) - D/B
  285 Y(I) = Y(I) - D/B
      YB(NUP) = YB(NUP) - D/B
C   COMPUTE FACTORS OF I AND K INDEPENDANT OF FREQUENCY
      CALL COEFF
      YSURF = -1.0E-08 * B
C...  START FREQUENCY ITERATION.
      DO 301 IL = 1, NWAVEL
      K = WN(IL)
C     ALL POTENTIALS INITIALIZED TO ZERO.
C*****FE(I,J) = NONDIMENSIONAL AMPLITUDE OF POTENTIAL AT POINT I DUE TO
C*****MODE J. (ASSOSIATED WITH COS(WT) ).  FI(I,J) IS SIMILAR TO FE(I,J)
C*****BUT ASSOSIATED WITH SIN(WT).  J = 1,2,3,4,5,6 IMPLY RESPECTIVELY
C*****SWAY, HEAVE, ROLL, DIFRACTED, INCIDENT AND DIFRACTED + INCIDENT
      DO 1 I=1,25
      DO 1 J = 1,6
      FE(I,J)=0.
      FI(I,J)=0.
    1 CONTINUE
C***ADD POINTS TO THE OFFSET ARRAY FOUR WAVELENGTHS FROM THE ORIGIN
C     ON THE FREE SURFACE
      X(N+1) = 4.0 * WAVEL(IL)/B
      X(N+2) = -4.0 * WAVEL(IL)/B
      Y(N+1) = YSURF
      Y(N+2) = YSURF
C***COMPUTE INCIDENT WAVE POTENTIALS AND NORMAL VELOCITIES
      DO 402 I = 1,M
      DO404 IC = 1,5
  404 IF(I .EQ. JC(IC)) GO TO 402
      EY = EXP(K*Y(I))
      CKX = COS(K*X(I))
      SKX = SIN(K*X(I))
      IF(I .GT. N) GO TO 403
      FEIN(I) = EY*(SS3(I)*SKX + CC3(I)*CKX)
      FIIN(I) =-EY*(SS3(I)*CKX - CC3(I)*SKX)
  403 FE(I,5) = EY*CKX*(1./K)
      FI(I,5) = EY*SKX*(1./K)
  402 CONTINUE
      AK = K/B
      WRF = SQRT(GEE*AK)
      WF = WRF/TP
      WT = 1.0/WF
      PRINT 300, K, WRF, WF, WT, WAVEL(IL)
  300 FORMAT (//, * WAVE NUMBER = K =*, F9.5, 5X*CIRCULAR FREQUENCY =*,
     1      F9.5, 5X*FREQUENCY =*, F9.5, 5X*PERIOD =*, F10.5,
```

Table D-2. Continued

```
         2      5X*WAVELENGTH =*, F10.4)
              TK=2.0/K
       C      FIRST-ORDER POTENTIALS ON CYLINDER ARE FIRST CALCULATED.
              CALL COMP(K)
       C...   FIRST-ORDER PHYSICAL QUANTITIES ARE CALCULATED.
              CALL PHYSCL(K)
          301 CONTINUE
         1009 FORMAT (10F8.5)
              ISKIP1 = 2
       C*****PUNCH RESULTS OF POTENTIAL SOLUTION ON CARDS
              PUNCH 20, TITLE
              PUNCH 50, N, NW, NWAVEL, ISYM, ISKIP1, LC, JC
              PUNCH 70, AREA, B, D, ROE, GEE, BTITLE
              PUNCH 1009, (WN(IL),IL = 1,10), (BOL(IL), IL = 1,10)
              DO 310 I = 1,3
              PUNCH 1009 , (FB(I,IL), IL = 1,10), (DELFB(I,IL), IL = 1,10)
              DO 310 J = 1,3
          310 PUNCH 1009, (RMU(I,J,IL), IL= 1,10), (RLAM(I,J,IL), IL = 1,10)
              DO 320 I = 1,NNW
              PUNCH 1009, (XOL(I,IL),IL = 1,10)
              DO 320 J = 1,6
          320 PUNCH  1009, (HWB(I,J,IL), IL = 1,10) ,(DELW(I,J,IL), IL = 1,10)
          303 CONTINUE
          116 CONTINUE
              CALL DYNAMC
          302 CONTINUE
              STOP
              END
```

Table D-2. Continued

```
                SUBROUTINE DYNAMC
    2           COMMON RI12(25,25),RK56(25,25), POT(25,25), HOW(25,25),FF(25,6),
               1FI(25,6),  RI(25,25), RJ(25,25), RK(25,4), RL(25,4),
               2RMU(3,3,10), RLAM(3,3,10), FB(3,10), DELFB(3,10), HWB(25,6,10),
               3 DELW(25,6,10) , XOL(25,10)
    2           COMMON/ONE/X(25),Y(25),XB(25),YB(25),ANG(25),DEL(25),VV(25)
               1,FEIN(25), FIIN(25), RNORM(25,3), JC(5)
    2           COMMON /TWO/ N,NNW, NWAVEL, ISYM, ISKIP, NC, PIE,GAMMA,M,TK,TP
    2           COMMON/THREE/ WAVEL(10), WN(10), BOL(  ),TL
    2           COMMON/FOUR/RAR(3,10),DELR(3,10), HWR(25,3,10), DELWR(25,3,10),
               2 HWT(25,10),DELWT(25,10),RKHYD(3,3), RKMOR(3,3), RKTB(3,3),
               3 XG, YG, RMASS, RINERT, DAMP(3)
    2           COMMON  /SEVEN/ AREA, B, D, ROE, GEE, BTITLE(3), TITLE(8)
    2           COMMON/TEN/DELT(2,3),FOR(2,10),PHAS(2,10),FORND(2,10),PHASD(2,10)
    2           DIMENSION A(6,6), C(6), ERASE(6)
    2           IF ( ISKIP .NE. 2) GO TO 100
          C*****READ POTENTIAL COEFS IF ISKIP = 2
    5           READ  1009, (WN(IL),IL = 1,10), (BOL(IL), IL = 1,10)
   27      1009 FORMAT(10F8.3)
   27           DO 110 I = 1,3
   31           READ  1009, (FB(I,IL), IL = 1,10), (DELFB(I,IL), IL = 1,10)
   56           DO 110 J = 1,3
   60      110  READ  1009, (RMU(I,J,IL), IL= 1,10), (RLAM(I,J,IL), IL = 1,10)
  115           DO 120 I = 1 , NNW
  117           READ  1009,(XOL(I, IL), IL = 1,10)
  133           DO 120 J = 1,6
  135      120  READ   1009, (HWB(I,J,IL), IL = 1,10) ,(DELW(I,J,IL), IL = 1,10)
  173      100  CONTINUE
          C*****OUTPUT POTENTIAL COEFS
  173           CALL POTOUT
  174           IF(ISKIP .EQ. 1) GO TO 140
          C*****READ DIMENSIONAL JYDROSTATIC SPRING CONSTANTS
  177           READ 1008,((RKHYD(I,J),J=1,3),I=1,3)
          C*****START LOOPING THROUGH DIFFERENT DYNAMIC CONFIGURATIONS
  217           DO 140 K1 = 1,50
  221           READ 1010, AREA, B, XG, YG, RMASS, RINERT,DAMP(1),DAMP(2),DAMP(3),
               1        NPUNCH
  253      1010 FORMAT (6F10.3, 3F5.2, I5)
  253           IF (EOF,5) 121, 122
  256       121 STOP
  260       122 CONTINUE
  260           DO 5 K2 = 1,3
  262       5   IF(DAMP(K2) .EQ. -0.0) DAMP(K2) = 0.0
          C           XG,YG = COORDINATES OF THE CENTER OF GRAVITY OF THE BODY
          C                .....NOTE.  MOMENTS AND MOMENTS OF INERTIA ARE COMPUTED
          C                ABOUT THE CENTER OF GRAVITY
          C          DAMP ADDS CORRECTION FOR VISCOUS OR NONLINEAR DAMPING
          C*****READ DIMENSIONAL MOORING SPRING CONSTANTS
  272           READ 1008,((RKMOR(I,J),J=1,3),I=1,3)
  312      1008 FORMAT (9F8.3)
          C*****NONDIMENTIONALIZE SPRING CONSTANTS ,MASS, MOMNNT OF INERTIA
          C*****AND CG COORDINATES
  312           Q = AREA* ROE* GEE/B
  316           DO 130 I = 1,3
  317           DO 130 J = 1,3
```

Table D-2. Continued

```
 320          IF(RKMOR(I,J) .EQ. -0.0) RKMOR(I,J) = 0.0
 331          RKTB(I,J)= (RKHYD(I,J) + RKMOR(I,J))/Q
 346     130  IF(I.EQ. 3 .OR. J .EQ. 3)RKTB(I,J) =RKTB(I,J)/B
 372          RKTB(3,3) = RKTB(3,3)/B
 402          RMASSB = RMASS/(AREA*ROE)
 406          RINERB  = RINERT/(AREA*ROE*B*B)
 412          XGB = XG/B
 413          YGB = YG/B
        C*****START WAVELENGTH LOOP
 415          DO 150 IL = 1,10
 416          IF (IL .GT. NWAVEL) GO TO 160
        C*****SET VALUES IN NONDIMENTIONALIZED ALGEBRAIC EQUATIONS OF MOTION
 421          A(1,1) = RKTB(1,1) - WN(IL) * (RMASSB + RMU(1,1,IL))
 445          A(2,2)= RKTB(2,2) - WN(IL) * (RMASSB + RMU(2,2,IL))
 471          A(3,3)= RKTB(3,3) -YGB*RMASSB -WN(IL) * (RINERB + RMU(3,3,IL) +
             1 (XGB**2 +YGB**2) * RMASSB)
 531          A(1,2) = RKTB(1,2) - WN(IL) * RMU(1,2,IL)
 552          A(1,3) = RKTB(1,3) - WN(IL) * (RMU(1,3,IL) -YGB*RMASSB)
 576          A(2,3) = RKTB(2,3) - WN(IL) * (RMU(2,3,IL) +XGB*RMASSB)
 623          A(2,1) = A(1,2)
 633          A(3,1) = A(1,3)
 643          A(3,2) = A(2,3)
 652          DO 20 I = 1,3
 654          DO 10 J = 1,3
 655          A(I+3, J+3) = A(I,J)
 666          A(I,J+3) =RLAM(I,J,IL)*SQRT(WN(IL))
        C  ADD CORRECTION FOR VISCOUS DAMPING
 705          IF (I .EQ. J) A(I,J+3) = (1.0 + DAMP(I))*A(I,J+3)
 723      10  A(I+3,J) = - A(I,J+3)
 736          C(I) = FB(I,IL)* SIN(DELFB(I,IL))
 753      20  C(I+3) = FB(I,IL) * COS(DELFB(I,IL))
 771          SCALE = 1.
 773          NN = 6
        C*****SOLVE ALGEBRAIC EQS OF MOTION. B(1), B(2), B(3) = AMPLITUDES
        C*****OF COS(WT), B(4), B(5), B(6) = AMPLITUDES OF SIN(WT) FOR SWAY, HEA
        C*****AND ROLL AT CENTER FO USERS COORDINATE SYSTEM.
 774          LL = LNEQF(6,NN,1,A,C,SCALE,ERASE)
1005          DO 30 I = 1,3
        C*****AMPLITUDE AND PHASE OF RESPONSE
1006          RAR(I,IL) = SQRT(C(I)**2 + C(I+3)**2)
1032      30  DELR(I,IL) = ATAN2(C(I),C(I+3))
1047          DO 40 I = 1, NNW
1050          AW = 0.
1051          BW = 0.
1052      90  DO 50 J = 1,3
        C*****RESULTANT WAVE AMPLITUDE AND PHASE FOR SWAY, HEAVE ROLL.
1054          HWR(I,J,IL) = HWB(I,J,IL) * RAR(J,IL)
1072          DELWR(I,J,IL) = DELW(I,J,IL) + DELR(J,IL)
1111          AW = AW + HWR(I,J, IL) * SIN(DELWR(I,J,IL))
1132      50  BW = BW + HWR(I,J,IL) * COS(DELWR(I,J,IL) )
1155          IF(XOL(I,IL).LT. 0.) GO TO 70
        C*****TOTAL REFLECTED WAVE (VECTOR ADDITION)
1163          AW = AW + HWB(I,6,IL) * SIN(DELW(I,6,IL))
1204          BW = BW + HWB(I,6,IL) * COS(DELW(I,6,IL))
1225          GO TO 45
        C*****TOTAL TRANSMITTED WAVE(VECTOR ADDITION)
```

Table D-2. Continued

```
   70   AW = AW + HWB(I,4,IL) * SIN(DELW(I,4,IL))
        BW = BW + HWB(I,4,IL) * COS(DELW(I,4,IL))
   45   HWT(I,IL)=SQRT(AW**2 + BW**2)
        DELWT(I,IL)=ATAN2(AW,BW)
   40   CONTINUE
        GO TO 150
C*****SET OUTPUTS FOR IL .GT. NWAVEL
  160   DO 170 I = 1,3
        RAR(I,IL) = 0.0
  170   DELR(I,IL) = 0.0
        DO 180 I = 1,25
        HWT(I,IL) = 0.0
        DELWT(I,IL) = 0.0
        DO 180 J = 1,3
        HWR(I,J,IL) = 0.0
  180   DELWR(I,J,IL) = 0.0
  150   CONTINUE
C***** OUT PUT DYNAMIC RESULTS
        CALL DYNOUT
        NMOR = 0
        DO 139 IP = 1,3
        DO 139 IQ = 1,3
        IF (RKMOR(IP,IQ) .EQ. 0.0) GO TO 139
        NMOR = NMOR + 1
   139  CONTINUE
        IF (NMOR .NE. 0) CALL MORTEN
        IF (NPUNCH .NE. 0) GO TO 140
        PUNCH 2000
 2000   FORMAT (*1111111111*)
        PUNCH 2005, (BOL(IQ),HWT(1,IQ),RAR(1,IQ),RAR(2,IQ),RAR(3,IQ),
      1        IQ = 1,10)
 2005   FORMAT (5F10.4)
        PUNCH 2000
        PUNCH 2010, (BOL(IQ),FORND(1,IQ),FORND(2,IQ),IQ=1,10)
 2010   FORMAT (F10.4,2E20.4)
  140   CONTINUE
        RETURN
        END
```

Table D-2. Continued

```
      SUBROUTINE MORTEN
C***SUBROUTINE MORTEN COMPUTES FORCES IN THE MOORING LINES
      COMMON/FOUR/RAR(3,10),DELR(3,10), HWR(25,3,10), DELWR(25,3,10),
     2 HWT(25,10),DELWT(25,10),RKHYD(3,3), RKMOR(3,3), RKTB(3,3),
     3 XG, YG, RMASS, RINERT, DAMP(3)
      COMMON  /SEVEN/ AREA, B, D, ROE, GEE, BTITLE(3), TITLE(8)
      COMMON/TEN/DELT(2,3),FOR(2,10),PHAS(2,10),FORND(2,10),PHASD(2,10)
      READ 10, ((DELT(I,J),J=1,3),I=1,2)
   10 FORMAT (6F10.2)
C        DELT(1,I),I=1,3 = CHANGE IN FORCE IN SHOREWARD MOORING LINE
C                          PER UNIT DISPLACEMENT IN SWAY, HEAVE AND ROLL
C        DELT(2,I),I=1,3 = CHANGE IN FORCE IN SEAWARD MOORING LINE
C                          PER UNIT DISPLACEMENT IN SWAY, HEAVE AND ROLL
      CAB = 1.0/(ROE*GEE*AREA)
      CONS = 180.0/ACOS(-1.0)
      DO 100 J = 1,2
      PRINT 20
   20 FORMAT (////20X*MOORING LINE MODEL RESULTS*/)
      IF (J .EQ. 1) PRINT 18
      IF (J .EQ. 2) PRINT 19
   18 FORMAT (30X*SHOREWARD MOORING LINE*/)
   19 FORMAT (30X*SEAWARD MOORING LINE*/)
      PRINT 30, (DELT(J,K),K=1,3)
   30 FORMAT (* CHANGE IN FORCE PER UNIT DISPLACEMENT IN SWAY, HEAVE*
     1     * AND ROLL, RESPECTIVELY =*, 3F10.4//)
C***COMPUTE FORCES IN MOORING LINES AND PHASE
      DO 50 I = 1,10
      AA = RAR(1,I)*DELT(J,1)
      AB = RAR(2,I)*DELT(J,2)
      AC = RAR(3,I)*DELT(J,3)/B
      TS = AA*SIN(DELR(1,I)) + AB*SIN(DELR(2,I)) + AC*SIN(DELR(3,I))
      TC = AA*COS(DELR(1,I)) + AB*COS(DELR(2,I)) + AC*COS(DELR(3,I))
      FOR(J,I) = SQRT(TS*TS + TC*TC)
      PHAS(J,I) = ATAN2(TC,TS)
      FORND(J,I) = CAB*FOR(J,I)
      PHASD(J,I) = CONS*PHAS(J,I)
   50 CONTINUE
C***PRINT RESULTS
      PRINT 80, (FOR(J,I),I=1,10),(PHASD(J,I),I=1,10),
     1     (FORND(J,I),I=1,10)
   80 FORMAT (3X*MOORING LINE RESPONSE*/5X*FORCE AMPLITUDE/ETA*, 11X,
     1     10E10.3/5X*PHASE REL TO ETA AT X=0 - DEG *, 10F10.4//
     2     5X30HFORCE AMPLITUDE/ROE*G*AREA*ETA, 10E10.3)
  100 CONTINUE
      RETURN
      END
```

Table D-2. Continued

```
                SUBROUTINE COEFF
        C       THIS SUBROUTINE CALCULATES THE PARTS OF I(I,J) AND K(I,J)
        C       WHICH ARE INDEPENDENT OF FREQUENCY NUMBER K.
   2            COMMON RI12(25,25),RK56(25,25), POT(25,25), HOW(25,25),FE(25,6),
               1FI(25,6),  RI(25,25), RJ(25,25), RK(25,4), RL(25,4),
               2RMU(3,3,10), RLAM(3,3,10), FB(3,10), DELFB(3,10), HWB(25,6,10),
               3 DELW(25,6,10) , XOL(25,10)
   2            COMMON/ONE/X(25),Y(25),XB(25),YB(25),ANG(25),DEL(25) ,VV(25)
               1,FEIN(25), FIIN(25), RNORM(25,3), JC(5)
   2            COMMON /TWO/ N,NNW, NWAVEL, ISYM, ISKIP, NC, PIE,GAMMA,M,TK,TP
   2            COMMON/ONE2/CC3(25),SS3(25)
   2            N2 = N/2
   6            DO 1 I = 1,M
  10            IF(I .GT. N) GO TO 7
  13            IF(ISYM .EQ. 1 .AND. I .GT. N2) GO TO 7
  26            X11 = X(I) - XB(1)
  34            Y11=Y(I)-YB(1)
  41            X21 = X11 + XB(1)
  45            Y21=Y(I)+YB(1)
  53            PP1=ALOG(X11**2+Y11**2)
  66            PQ1=ALOG(X11**2+Y21**2)
 101            TP1=ATAN2(Y11,X11)
 105            TQ1=ATAN2(Y21,X11)
 111            DO 1 J = 1,N
 112            X12=X(I)-XB(J+1)
 120            Y12=Y(I)-YB(J+1)
 124            Y22=Y(I)+YB(J+1)
 131            PP2=ALOG(X12**2+Y12**2)
 144            PQ2=ALOG(X12**2+Y22**2)
 157            TP2=ATAN2(Y12,X12)
 163            TQ2=ATAN2(Y22,X12)
        C      CORRECTION FOR DISCONTINUITY IN ATAN2 AT PIE
 167            IF(X11 .GT. 0. .OR. X12 .GT. 0.) GO TO 6
 201            IF(TP2 .GT. 0. .AND. TP1 .LT. 0.) TP1 = TP1 + TP
 214            IF(TP2 .LT. 0. .AND. TP1 .GT. 0.) TP1 = TP1 - TP
 227          6 C3 = CC3(J)
 232            S3=SS3(J)
 235            A1=PIE
 237            IF(I-J)2,3,2
 241          2 A1=TP1-TP2
 243          3 A2=TQ2-TQ1
 245            A5=C3*(-XB(J+1)+XB(J)-X12*0.5*PP2+X11*0.5*PP1
               1+Y12*TP2-Y11*TP1)+S3*(YB(J)-YB(J+1)-X12*TP2
               1-Y12*0.5*PP2+X11*TP1+Y11*0.5*PP1)
 307            A6=C3*(-XB(J+1)+XB(J)-X12*0.5*PQ2+X11*0.5*PQ1
               1+Y22*TQ2-Y21*TQ1)-S3*(-YB(J)+YB(J+1)-X12*TQ2
               1-Y22*0.5*PQ2+X11*TQ1+Y21*0.5*PQ1)
 351          4 X11=X12
 353            Y11=Y12
 354            Y21=Y22
 356            PP1=PP2
 357            PQ1=PQ2
 361            TP1=TP2
 362            TQ1=TQ2
 364            RI12(I,J) = A1 - A2
```

Table D-2. Continued

COEFF

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```
  372          RK56(I,J) = A5 - A6
  377          GO TO 1
  400        7 DO 200 L = 1,N
  402          RI12(I,L) = 0.0
  407      200 RK56(I,L) = 0.0
  416        1 CONTINUE
  423          RETURN
  424          END
```

Table D-2. Continued

```
      SUBROUTINE COMP(K)
C     THIS SUBROUTINE COMPUTES THE COEFFICIENTS DEPENDENT ON K
C     AND CALLS ON LNEQF TO SOLVE THE SIMULTANEOUS EQUATIONS
C     FOR THE VELOCITY POTENTIALS FE(I,JJ) AND FI(I,JJ),FOR FE2
      COMMON RI12(25,25),RK56(25,25), POT(25,25), HOW(25,25),FE(25,6),
     1FI(25,6),  RI(25,25), RJ(25,25), RK(25,4), RL(25,4),
     2RMU(3,3,10), RLAM(3,3,10), FB(3,10), DELFB(3,10), HWB(25,6,10),
     3 DELW(25,6,10) , XOL(25,10)
      COMMON/ONE/X(25),Y(25),XB(25),YB(25),ANG(25),DEL(25),VV(25)
     1,FEIN(25), FIIN(25), RNORM(25,3), JC(5)
      COMMON/ONE2/CC3(25),SS3(25)
      COMMON /TWO/ N,NNW, NWAVEL, ISYM, ISKIP, NC, PIE,GAMMA,M,TK,TP
      DIMENSION A(50,50),B(50,4),ERASE(50)
      REAL K
      N2 = N/2
      DO 1 I=1,M
      DO 6 I2= 1,4
       RK(I,I2) = 0.0
    6 RL(I,I2) = 0.0
      DO 4 IC = 1,5
    4 IF ( I .EQ. JC(IC)) GO TO 1
      IF(ISYM .NE. 1) GO TO 8
      IF(I .GT. N2 .AND. I .LE. N) GO TO 9
    8 X11 = X(I) - XB(1)
      X21 = X11 +XB(1)
      Y21=Y(I)+YB(1)
      PQ1=ALOG(X11**2+Y21**2)
      TQ1=ATAN2(Y21,X11)
      CALL CPV(X11,Y21,E21,C11,S11,A911,A1011,K)
      C21=C11
      S21=S11
      A921=A911
      A1021=A1011
      DO 7 J=1,N
      X12=X(I)-XB(J+1)
      Y22=Y(I)+YB(J+1)
      PQ2=ALOG(X12**2+Y22**2)
      TQ2=ATAN2(Y22,X12)
      S3=SS3(J)
      C3=CC3(J)
      CALL CPV(X12,Y22,E22,C12,S12,A912,A1012,K)
      DO 13 IC = 1,5
   13 IF(J .EQ. JC(IC)) GO TO 41
      A3=A1011-A1012
      A4=E21*S11-E22*S12
      A7=S3*(0.5*(PQ1-PQ2)+A912-A911)+C3*(TQ1-TQ2+A1011-A1012)
      A8=E21*SIN(K*X11-ANG(J))-E22*SIN(K*X12-ANG(J))
    5 RI(I,J) = 2. * A3 + RI12(I,J)
      IF (I .NE. J) GO TO 3
      RI(I,J) = RI(I,J) - TP
    3 RJ(I,J) = -TP*A4
      POT(I,J) = TK*A7 + RK56(I,J)
      HOW(I,J) = -TK*PIE*A8
      DO 10 L = 1,3
      RK(I,L) = RK(I,L) + POT(I,J) * RNORM(J,L)
```

Table D-2. Continued

```
 10   RL(I,L) = RL(I,L) + HOW(I,J) * RNORM(J,L)
      RK(I,4) = RK(I,4) - FEIN(J)*POT(I,J) + FITN(J)*HOW(I,J)
      RL(I,4) = RL(I,4) - FEIN(J)*HOW(I,J) - FITN(J)*POT(I,J)
   41 IF(J-N)2,7,7
    2 X11=X12
      Y21=Y22
      PQ1=PQ2
      TO1=TQ2
      A911=A912
      A1011=A1012
      C11=C12
      S11=S12
      E21=E22
    7 CONTINUE
      GO TO 1
 9    IS = N - I + 1
      DO 12 L = 1,3
      RK(I,L) = RK(IS,L) * (-1.0)**L
 12   RL(I,L) = RL(IS,L)*(-1.0)**L
      DO 11 J = 1,N
      DO 16 IC = 1,5
 16   IF (J .EQ. JC(IC)) GO TO 11
      JS = N - J + 1
      RI(I,J) = RI(IS, JS)
      RJ(I,J) = RJ(IS,JS)
      RK(I,4) = RK(I,4) - FEIN(J)*POT(IS,JS) + FTIN(J)*HOW(IS,JS)
      RL(I,4) = RL(I,4) - FEIN(J)*HOW(IS,JS) - FTIN(J)*POT(IS,JS)
 11     CONTINUE
 1     CONTINUE
      I2 = 0
   32 DO 22 I=1,N
      DO 14 IC = 1,5
 14   IF(I .EQ. JC(IC)) GO TO 22
      I2 = I2 + 1
      II = I2 + NC
      DO 31 L = 1,4
      B(I2,L) = RK(I,L)
 31   B(II,L) = RL(I,L)
      J2 = 0
      DO 22 J=1,N
      DO 15 IC = 1,5
 15   IF (J .EQ. JC(IC)) GO TO 22
      J2 = J2 + 1
      JN = J2 + NC
      A(I2, J2) = RI(I,J)
      A(I2,JN) = - RJ(I,J)
      A(II,J2) = RJ(I,J)
      A(II,JN) = RI(I,J)
   22 CONTINUE
      SCALE=1.
      NN = 2*NC
      LL=LNEQF(50,NN,4,A,B,SCALE,ERASE)
      PRINT 27,SCALE
   27 FORMAT(//,5X,*DETERMINANT= *,1PE12.4)
      I2 = 0
      DO 26 I = 1,N
```

Table D-2. Continued

```
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            DO 17 IC = 1,5
      17    IF(I .EQ. JC(IC)) GO TO 26
            I2 = I2 + 1
            II = I2 + NC
            DO 35 L = 1,4
            FE(I,L) = B(I2,L)
      35    FI(I,L) = B(II,L)
         26 CONTINUE
         29 RETURN
            END
```

Table D-2. Continued

```
               SUBROUTINE PHYSCL(K)
   6           COMMON RI12(25,25),RK56(25,25), POT(25,25), HOW(25,25),FE(25,6),
              1FI(25,6),  RI(25,25), RJ(25,25), RK(25,4), RL(25,4),
              2RMU(3,3,10), RLAM(3,3,10), FB(3,10), DELFB(3,10), HWB(25,6,10),
              3 DELW(25,6,10) , XOL(25,10)
   6           COMMON/ONE/X(25),Y(25),XB(25),YB(25),ANG(25),DEL(25),VV(25)
              1,FEIN(25), FIIN(25), RNORM(25,3), JC(5)
   6           COMMON /TWO/ N,NNW, NWAVEL, ISYM, ISKIP, NC, PIE,GAMMA,M,TK,TP
   6           COMMON/THREE/ WAVEL(10), WN(10), BOL(10),TL
   6           COMMON  /SEVEN/ AREA, B, D, ROE, GEE, BTITLE(3), TITLE(8)
   6           REAL K
   6           DO 3 I = 1,N
         C*****MODE 6 = INCIDENT + DIFRACTED POTENTIALS
   7           FE(I,6) = FE(I,4) + FE(I,5)
  23     3     FI(I,6) = FI(I,4) + FI(I,5)
  42           FACM = (B**2)/AREA
  47           FACL = FACM*SQRT(K)
  53           FACF = FACM * K
  55           DO 1 L = 1,3
  56           DO1 M1 = 1,6
  57           RA = 0.0
  60           RM = 0.0
  61           IF(M1 .EQ. 4) GO TO 1
  63           IF(M1 .EQ. 5) GO TO 1
         C*****INTIGRATE PRESSURE COMPONENTS OVER BODY
  66           DO 5 I = 1,N
  70           RM = RM + FE(I,M1) * RNORM(I,L) * DEL(I)
 104     5     RA = RA + FI(I,M1) * RNORM(I,L) * DEL(I)
 123           IF(M1 .GT. 4) GO TO 8
         C*****ADDED MASS AND DAMPING IN DIRECTION L DUE TO MOTION M1 AT
         C*****WAVELENGTH IL.
 126           RMU(L,M1, IL) = RM*FACM
 136           RLAM(L,M1, IL) = RA*FACL
 145           GO TO 1
         C*****WAVE FORCE AMPLITUDE AND PHASE IN DIRECTION M1 DUE TO
         C*****INCIDENT  WAVE AT WAVELENGTH IL
 146     8     FB(L,     IL) = SQRT(RM**2 + RA**2) * FACF
 166           DELFB(L,IL) = ATAN2(-RA,RM)
 200     1     CONTINUE
 205           IW = N + 1
 207           IMAX = N + NNW
 211           DO 30 I = IW,IMAX
 213           DO 6 L = 1,4
         C*****COMPUTE POTENTIAL AT FREE SURFACE POINTS USING  GREENS THEORUM
 214           DO 4 J = 1, N
 215           DO 10 IC = 1,5
 216     10    IF(J .EQ. JC(IC)) GO TO 4
 224           FE(I,L) = FE(I,L) + FE(J,L)*RI(I,J)  -FI(J,L)*RJ(I,J)
 255           FI(I,L) = FI(I,L) + FE(J,L)*RJ(I,J)  +FI(J,L)*RI(I,J)
 306     4     CONTINUE
 311           FE(I,L) = (FE(I,L) - RK(I,L))/TP
 326     6     FI(I,L) = (FI(I,L) - RL(I,L))/TP
         C*****MODE 6 = INCIDENT + DIFRACTED POTENTIALS
 344           FE(I,6) = FE(I,4) + FE(I,5)
 361           FI(I,6) = FI(I,4) + FI(I,5)
```

Table D-2. Continued

```
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   375            II = I - N
         C*****NON DIMENTIONALIZE FREE SURFACE POSITION WITH WAVELENGTH
   377            XOL(II,IL) =  X(I) * B/ WAVEL(IL)
   410            DO 2 M1 = 1,6
         C*****WAVE AMPLITUDE AND PHASE AT POINT II DUE TO MODE M1 AT WAVELENGTH
   412            HWB(II,M1,IL) = SQRT(FE(I,M1)**2 + FI(I,M1)**2) * K
   443      2     DELW(II,M1,IL) = ATAN2(-FI(I,M1), FE(I,M1))
   470       30   CONTINUE
   472      7     RETURN
   473            END
```

Table D-2. Continued

```
              SUBROUTINE POTOUT
   2          COMMON RI12(25,25),RK56(25,25), POT(25,25), HOW(25,25),FE(25,6),
             1FI(25,6),  RI(25,25), RJ(25,25), RK(25,4), RL(25,4),
             2RMU(3,3,10), RLAM(3,3,10), FB(3,10), DELFB(3,10), HWB(25,6,10),
             3 DELW(25,6,10) , XOL(25,10)
   2          COMMON /TWO/ N,NNW, NWAVEL, ISYM, ISKIP, NC, PIE,GAMMA,M,TK,TP
   2          COMMON/THREE/ WAVEL(10), WN(10), BOL(10),IL
   2          COMMON  /SEVEN/ AREA, B, D, ROE, GEE, BTITLE(3), TITLE(8)
   2          COMMON / EIGHT/LBLMU(3,3,3), LBLAM(3,3,3), LBLFB(3,3),LBLHWB(7,3),
             1LBL(10,3), DEG(3,10)
   2     1001 FORMAT(//3X, 3A10, / (5X, 3A10, 10F10.4))
   2     1002 FORMAT (//3X, 3A10, / (5X, 3A10, 10F10.4 /5X, 3A10, 10F10.4/))
   2     1003 FORMAT( 5X, 3A10, 10F10.4 / 5X, 3A10, 10F10.4 /)
   2     1004 FORMAT( //3X, 3A10, 2X, 10F10.4/ 3X, 3A10, 2X, 10F10.4)
   2          PRINT 2000, BTITLE
  10     2000 FORMAT (1H1, 20X, *NONDIMENSIONAL POTENTIAL COEFFICIENTS* /// 25X
             1 * W = SQRT(G/B),   W2 = G/B* / 25X*B = *, 3A10 /
             1      25X*G = ACCELERATION OF GRAVITY*/
             1      25X*ROE = MASS DENSITY OF FLUID*/
             225X *ETA = INCIDENT WAVE AMPLITUDE */25X,*WAVEL = INCIDENT OR GENE
             3RATED WAVE LENGTH*//)
  10          DO 9 IL = 1,10
  12        9 DEG(1,IL) = SQRT((GEE*BOL(IL)) /(TP*B))
  32          PRINT 1004,(LBL(1,K),K = 1,3), (BOL(IL), IL = 1,10),
             1 (LBL(2,K), K = 1,3), (DEG(1,IL), IL = 1,10)
  77          PRINT 1001, (LBL(3,K),K= 1,3), (((LBLMU(I,J,K),K= 1,3),
             1(RMU(I,J,IL), IL = 1,10), J = 1,3), I = 1,3)
 150          PRINT 1001 ,(LBL(4,K),K = 1,3), (((LBLAM(I,J,K),K = 1,3),
             1(RLAM(I,J,IL), IL= 1,10), J = 1,3), I = 1,3)
 221          DO 1 I = 1,3
 223          DO 1 IL = 1,10
 224        1 DEG(I,IL) = 57.298 * DELFB(I,IL)
 241          PRINT 1002, (LBL(5,K), K = 1,3), ((LBLFB(I,K),K= 1,3),
             1(FB(I,IL),IL = 1,10), (LBL(5,K), K = 1,3),(DEG(I,IL),IL=1,10)
             2 , I = 1,3)
 324          DO 2 I = 1,NNW
 326          DO 8 IL = 1,10
 327          DEG(1,IL) = 0.0
 334          IF(IL .GT. NWAVEL     ) GO TO 8
 337          DEG(1,IL) =XOL(I,IL)*B/BOL(IL)
 353        8  CONTINUE
 355          PRINT 1002, (LBL(8,K), K = 1,3), (LBL(9,K), K = 1,3),
             1 (XOL(I,IL), IL = 1,10), (LBL(10,K), K=1,3 ), (DEG(1,IL),IL=1,10)
 436          DO 3 J = 1,3
 440          DO 3 IL = 1,10
 441        3 DEG(J,IL) = 57.298 * DELW(I,J,IL)
 460          PRINT 1003, ((LBLHWB(J,K), K = 1,3), (HWB(I,J,IL), IL = 1,10),
             1 (LBL(7,K), K = 1,3), (DEG(J,IL), IL = 1,10), J = 1,3)
 534          IF (XOL(I,1) .LT. 0.) GO TO 4
 542          DO 5 IL = 1,10
 544        5 DEG(1,IL) = 57.298 * DELW(I,6,IL)
 561          PRINT 1003, (LBLHWB(7,K), K=1,3), (HWB(I,6,IL), IL = 1,10),
             1 (LBL(6,K),K=1,3), (DEG(1,IL), IL = 1,10)
 632          GO TO 2
 633        4 DO 7 J = 1,3
```

Table D-2. Continued

```
RUNT VERSION FEB 74 B    17:12 04/23/76

            DO 7 IL = 1,10
      7     DEG(J,IL) = 57.298 * DELW(I,J+3, IL)
            PRINT 1003,((LBLHWB(J,K), K = 1,3), (HWB(I,J,IL), IL = 1,10),
           1(LBL(6,K), K=1,3), (DEG(J-3,IL), IL = 1,10), J= 4,6)
      2     CONTINUE
            RETURN
            END
```

Table D-2. Continued

```
      FUNCTION LNEQF(M,N,N1,A,B,DTRMNT,Z)
C.. SOLVES SIMULTANEOUS LINEAR EQUATIONS BY GAUSSIAN REDUCTION.
C.. FORTRAN IV EQUIVALENT OF LNEQS.

      REAL A(M,M),B(M,M) ,Z(M),DTRMNT,RMAX,RNEXT,W,DOV
      NM1=N-1
      DO 40 J=1,NM1
      J1=J+1
C.. FIND ELEMENT OF COL J, ROWS J-N, WHICH HAS MAX ABSOLUTE VALUE.
      LMAX=J
      RMAX=ABS(A(J,J))
      DO 8 K=J1,N
      RNEXT=ABS(A(K,J))
      IF (RMAX .GE. RNEXT) GO TO 8
      RMAX=RNEXT
      LMAX=K
    8 CONTINUE
      IF (LMAX .NE. J) GO TO 10
C.. MAX ELEMENT IN COLUMN IS ON DIAGONAL
      IF (A(J,J)) 20,94,20
C.. MAX ELEMENT IS NOT ON DIAGONAL. EXCHANGE ROWS J AND LMAX.
   10 DO 12 L=J,N
      W=A(J,L)
      A(J,L)=A(LMAX,L)
   12 A(LMAX,L)=W
      DO 14 L=1,N1
      W=B(J,L)
      B(J,L)=B(LMAX,L)
   14 B(LMAX,L)=W
      DTRMNT = -DTRMNT
C.. ZERO COLUMN J BELOW THE DIAGONAL.
   20 Z(J)=1./A(J,J)
      DO 30 K=J1,N
      IF (A(K,J)) 22,30,22
   22 W=-Z(J)*A(K,J)
      DO 24 L=J1,N
   24 A(K,L)=W*A(J,L)+A(K,L)
      DO 26 L=1,N1
   26 B(K,L)=W*B(J,L)+B(K,L)
   30 CONTINUE
   40 CONTINUE
      IF (A(N,N)) 42,94,42
   42 Z(N)=1./A(N,N)
C.. OBTAIN SOLUTION BY BACK SUBSTITUTION.
      DO 50 L=1,N1
   50 B(N,L)=Z(N)*B(N,L)
      DO 60 K=1,NM1
      J=N-K
      J1=J+1
      DO 58 L=1,N1
      W=0.
      DO 56 I=J1,N
   56 W=A(J,I)*B(I,L)+W
   58 B(J,L)=(B(J,L)-W)*Z(J)
   60 CONTINUE
```

Table D-2. Continued

LNEQF

```
RUNT VERSION FEB 74 B    17:12 04/23/76

          C.. EVALUATE DETERMINANT.
   364            IF (DTRMNT) 70,74,70
   366         70 DO 72 J=1,N
   370         72 DTRMNT=DTRMNT*A(J,J)
   377         74 LNEOF=1
   401            RETURN

          C.. SINGULAR MATRIX, SET ERROR FLAG.
   401         94 LNEOF = 2
   403            DTRMNT=0.
   404            RETURN
   405            END
```

Table D-2. Continued

```
      SUBROUTINE CPV(X,Y,E,C1,S1,A9,A10,K)
C ....CAUCHY PRINCIPAL VALUE INTEGRAL.
      COMMON /TWO/ N,NNW, NWAVEL, ISYM, ISKIP, NC, PIE,GAMMA,M,TK,TP
      COMMON/SIX/XN(5),CN(5)
      REAL K
      IF (Y .GE. 0.0) Y = -1.0E-08
      TT=ATAN2(Y,X)
      TH=PIE/2.+TT
C.....FOR NEGATIVE X,CORRECTION TO RANGE OF ATAN2.
      IF(X.LT.0.)TH=TH+TP
      AA=K*Y
      E=EXP(AA)
      BB=K*X
      C1=COS(BB)
      S1=SIN(BB)
      R=K*SQRT(X**2+Y**2)
      SUM1=0.
      SUM2=0.
      IF(R.GE.10.)GO TO 13
      SUM11=0.
      SUM22=0.
      FAC=1.0
      SUM1C=1.
      SUM2C=1.
      SDLTH=0.
      CDLTH=0.
      ASSIGN 3 TO LDC
      IF(X.EQ.0.)ASSIGN 8 TO LDC
      RL=1.0
      DO 1 L=1,100
      DL=L
      FAC=FAC*DL
      RL=R*RL
      DLFAC=FAC*DL
      DLTH=DL*TH
      A1=RL/DLFAC
      IF(ABS(CDLTH).LE.1.E-07)GO TO 2
      SUM1C=ABS(A1/SUM1)
      IF(SUM1C.LE.1.E-05)GO TO 7
    2 CDLTH=COS(DLTH)
      SUM11=A1*CDLTH
      SUM1=SUM1+SUM11
    7 GO TO LDC,(3,8)
    8 SUM2C=0.
      GO TO 5
    3 IF(ABS(SDLTH).LE.1.E-07)GO TO 4
      SUM2C=ABS(A1/SUM2)
      IF(SUM2C.LE.1.E-05)GO TO 5
    4 SDLTH=SIN(DLTH)
      SUM22=A1*SDLTH
      SUM2=SUM2+SUM22
    5 IF(SUM1C.LE.1.E-05.AND.SUM2C.LE.1.E-05)GO TO 6
    1 CONTINUE
    6 C=GAMMA+ALOG(R)+SUM1
C.....DISCONTINUITY OF 2PIE IF X NEGATIVE IN SI FUNCTION.
```

Table D-2. Continued

```
RUNT VERSION FEB 74 B    17:12 04/23/76

          IF(X.LT.0.)TH=TH-TP
          S=TH+SUM2
          A9=E*(C1*C+S1*S)
          A10=E*(-C1*S+S1*C)
          GO TO 9
C...      LAGUERRE QUADRATURE-FIVE POINT.
       13 DO 14 I=1,5
          A=XN(I)+AA
          TERM=CN(I)/(A*A+BB*BB)
          SUM1=TERM*A+SUM1
       14 SUM2=TERM+SUM2
          F=1.
          IF(X.LT.0.)F=-1.
          A9=F*PIE*S1*E-SUM1
          A10=-F*PIE*C1*E+BB*SUM2
        9 RETURN
          END
```

Table D-2. Continued

```
                SUBROUTINE DYNOUT
   2            COMMON RI12(25,25),RK56(25,25), POT(25,25), HOW(25,25),FE(25,6),
               1FI(25,6),  RI(25,25), RJ(25,25), RK(25,4), RL(25,4),
               2RMU(3,3,10), RLAM(3,3,10), FB(3,10), DELFB(3,10), HWB(25,6,10),
               3 DELW(25,6,10) , XOL(25,10)
   2            COMMON /TWO/ N,NNW, NWAVEL, ISYM, ISKIP, NC, PIE,GAMMA,M,TK,TP
   2            COMMON/THREE/ WAVEL(10), WN(10), BOL(10),TL
   2            COMMON/FOUR/RAR(3,10),DELR(3,10), HWR(25,3,10), DELWR(25,3,10),
               2 HWT(25,10),DELWT(25,10),RKHYD(3,3), RKMOR(3,3), RKTB(3,3),
               3 XG, YG, RMASS, RINERT, DAMP(3)
   2            COMMON  /SEVEN/ AREA, B, D, ROE, GEE, BTITLE(3), TITLE(8)
   2            COMMON /NINE/ LBLRAR(3,3), LBLHWR(5,3), LBLR(5,3)
   2            COMMON / EIGHT/LBLMU(3,3,3), LBLAM(3,3,3), LBLFB(3,3),LBLHWB(7,3),
               1LBL(10,3), DEG(3,10)
   2       1001 FORMAT(//3X, 3A10, / (5X, 3A10, 10F10.4))
   2       1002 FORMAT (//3X, 3A10, / (5X, 3A10, 10F10.4 /5X, 3A10, 10F10.4/))
   2       1003 FORMAT( 5X, 3A10, 10F10.4 / 5X, 3A10, 10F10.4 /)
   2       1004 FORMAT( //3X, 3A10, 2X, 10F10.4/ 3X, 3A10, 2X, 10F10.4)
   2            PRINT 2000, AREA, B, XG, YG, RMASS, RINERT,DAMP(1),DAMP(2),DAMP(3)
  33       2000 FORMAT(1H1, 20X*DYNAMIC MODEL RESULTS*//* AREA=*F10.3,5X*B=*F10.3,
               1 5X *XG=*F10.3,5X*YG=*F10.3,5X*MASS=*F10.3,5X*INERTIA=*F10.3//
               3* ADDITIONAL DAMPING ADDED-   IN SWAY-*F6.2* LAMDA11      IN HEAVE-
               3*F6.2* LAMDA22      IN ROLL-*F6.2* LAMDA33* //)
  33            PRINT 2001,((RKHYD(I,J),J=1,3),I=1,3), ((RKMOR(I,J), J=1,3),I=1,3)
  67       2001 FORMAT(* SPRING CONSTANTS          K11         K12         K13         K21
               1        K22         K23         K31         K32         K33*/
               2* HYDROSTATIC*7X,9F10.3 / * MOORING*11X,9F10.3///)
  67            DO 9 IL = 1,10
  71       9    DEG(1,IL) = SQRT((GEE*BOL(IL)) /(TP*B))
 111            PRINT 1004,(LBL(1,K),K = 1,3), (BOL(IL), IL = 1,10),
               1 (LBL(2,K), K = 1,3), (DEG(1,IL), IL = 1,10)
 156            DO 1 I = 1,3
 160            DO 1 IL = 1,10
 161       1    DEG(I,IL) = 57.298 *  DELR(I,IL)
 176            PRINT 1002,(LBLR(1,K), K = 1,3),((LBLRAR(I,K), K = 1,3),
               1 (RAR(I,IL),IL = 1,10), (LBL(6,K),K = 1,3), (DEG(I,IL),IL=1,10), I
               2 = 1,3)
 261            DO 2 I = 1,NNW
 263            DO 8 IL = 1,10
 264       8    DEG(1,IL) =XOL(I,IL)*B/BOL(IL)
 301            PRINT 1002, (LBL(8,K), K = 1,3), (LBL(9,K), K = 1,3),
               1 (XOL(I,IL), IL = 1,10), (LBL(10,K), K=1,3 ), (DEG(1,IL),IL=1,10)
 362            DO 3 J = 1,3
 364            DO 3 IL = 1,10
 365       3    DEG(J,IL) = 57.298 *DELWR(I,J,IL)
 404            PRINT 1003, ((LBLHWR(J,K), K = 1,3), (HWR(I,J,IL), IL = 1,10),
               1 (LBL(6,K), K = 1,3), (DEG(J,IL), IL = 1,10), J = 1,3)
 460            IF (XOL(I,1) .LT. 0.) GO TO 4
 465            DO 5 IL = 1,10
 470            DEG(2,IL) = 57.298 * DELWT(I,IL)
 501       5    DEG(1,IL) = 57.298 * DELW(I,6,IL)
 516            PRINT 1003, (LBLHWB(7,K), K=1,3), (HWB(I,6,IL), IL = 1,10),
               1 (LBL(6,K),K=1,3), (DEG(1,IL), IL = 1,10)
 567            PRINT 1003, (LBLHWR(4,K),K=1,3), (HWT(I,IL),IL = 1,10),
               1 (LBL(6,K), K = 1,3), (DEG(2,IL), IL = 1,10)
```

Table D-2. Continued

RUNT VERSION FEB 74 B   17:12 04/23/76

```
 637          GO TO 2
 640     4     DO 7 IL = 1,10
 642          DEG(1,IL) = 57.298 * DELW(I,4,IL)
 655     7    DEG(2,IL) = 57.298 * DELWT(I,IL)
 670          PRINT 1003, (LBLHWB(4,K),K = 1,3), (HWB(I,4,IL),IL= 1,10),
             1(LBL(6,K), K = 1,3), (DEG(1,IL), IL = 1,10),(LBLHWR(5,K),K=1,3),
             2(HWT(I,IL), IL = 1,10),(LBL(6,K),K = 1,3),(DEG(2,IL),IL=1,10)
1005     2    CONTINUE
1010          RETURN
1010          END
```

Table D-2. Continued

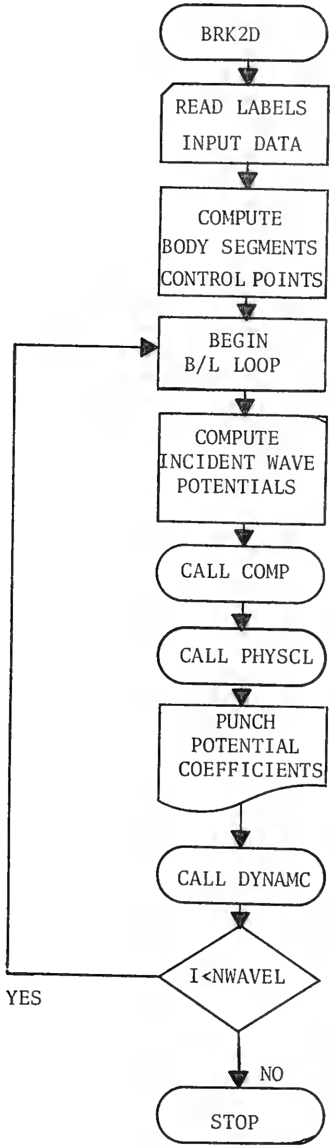


Figure. Flow chart for program BRK2D.

7. Program Comments and Glossary of Terms.

The program listing contains many comments which aid in following the logic of the program. Descriptions of variables also appear where they are read into the program.

8. Run Time and Memory Size.

BRK2D requires about 70 seconds of central processor time on the CDC 6400 computer to compile and compute results for 10 different beam wavelength ratios. A central memory of about 55,000 octal is required.

9. Run and Card Deck Setup Procedures and Special Operation Instructions.

In order to run the FORTRAN source program deck on the University of Washington CDC 6400, the following deck is required:

```
BRK2D,CM55000,T100.              Job card
ACCOUNT                          (Account No., password)
FORTRAN
LGO(LC=6000)                     LC = line count value
7/8/9
    FORTRAN DECK
7/8/9
    DATA DECK
6/7/8/9
```

10. Sample Output Data.

Table D-3 is the output for the Oak Harbor breakwater. The input is given in Table D-1.

```
OAK HARBOR BREAKWATER - CORPS OF ENGINEERS TESTS                    17 MAY 1975

      NUMBER OF SEGMENTS =  23
      NUMBER OF FREE-SURFACE STATIONS =    0
      NUMBER OF WAVELENGTHS =  10
      ISYM =    0
      ISKIP =    0
      NC =      1JC =   12    -0    -0    -0    -0
      AREA =      12.600
      B =      10.000      FULL BEAM
      D =         .000
      FLUID DENSITY =   1.99050
      ACCELERATION OF GRAVITY =     32.200
      BEAM/WAVELENGTH RATIOS OF INCIDENTWAVES
                 .10000     .15929     .18999     .21681     .25000     .28000     .31221     .37100     .42300     .48733
```

Table D-3. Example output for program BRK2D (Oak Harbor breakwater)

CYLINDER GEOMETRY

I	DIMENSIONAL OFFSETS X	DIMENSIONAL OFFSETS Y	NON-DIMENSIONAL OFFSETS X	NON-DIMENSIONAL OFFSETS Y	MIDPOINTS OF SEGMENTS X	MIDPOINTS OF SEGMENTS Y	SLOPE	LENGTH
1	-5.000	.000	-.500	.000	-.500	-.063	-1.571	.125
2	-5.000	-1.250	-.500	-.125	-.500	-.188	-1.571	.125
3	-5.000	-2.500	-.500	-.250	-.500	-.313	-1.571	.125
4	-5.000	-3.750	-.500	-.375	-.500	-.438	-1.571	.125
5	-5.000	-5.000	-.500	-.500	-.479	-.500	.000	.042
6	-4.583	-5.000	-.458	-.500	-.458	-.438	1.571	.125
7	-4.583	-3.750	-.458	-.375	-.390	-.375	.000	.136
8	-3.223	-3.750	-.322	-.375	-.322	-.313	1.571	.125
9	-3.223	-2.500	-.322	-.250	-.322	-.188	1.571	.125
10	-3.223	-1.250	-.322	-.125	-.390	-.125	3.142	.136
11	-4.583	-1.250	-.458	-.125	-.458	-.063	1.571	.125
12	-4.583	.000	-.458	.000	.000	.000	.000	.917
13	4.583	.000	.458	.000	.458	-.063	-1.571	.125
14	4.583	-1.250	.458	-.125	.390	-.125	3.142	.136
15	3.223	-1.250	.322	-.125	.322	-.188	-1.571	.125
16	3.223	-2.500	.322	-.250	.322	-.313	-1.571	.125
17	3.223	-3.750	.322	-.375	.390	-.375	.000	.136
18	4.583	-3.750	.458	-.375	.458	-.438	-1.571	.125
19	4.583	-5.000	.458	-.500	.479	-.500	.000	.042
20	5.000	-5.000	.500	-.500	.500	-.438	1.571	.125
21	5.000	-3.750	.500	-.375	.500	-.313	1.571	.125
22	5.000	-2.500	.500	-.250	.500	-.188	1.571	.125
23	5.000	-1.250	.500	-.125	.500	-.063	1.571	.125
24	5.000	.000	.500	.000				

POSITIONS FOR WAVE HEIGHT CALCULATIONS

WAVE NUMBER = K = .62832 CIRCULAR FREQUENCY = 1.42239 FREQUENCY = .22638 PERIOD = 4.41735 WAVELENGTH = 100.0000

DETERMINANT= 37.1372E+14

WAVE NUMBER = K = 1.00085 CIRCULAR FREQUENCY = 1.79520 FREQUENCY = .28571 PERIOD = 3.50000 WAVELENGTH = 62.7766

DETERMINANT= 19.6121E+14

WAVE NUMBER = K = 1.13097 CIRCULAR FREQUENCY = 1.90833 FREQUENCY = .30372 PERIOD = 3.29250 WAVELENGTH = 55.5556

DETERMINANT= 45.2450E+14

WAVE NUMBER = K = 1.36226 CIRCULAR FREQUENCY = 2.09439 FREQUENCY = .33333 PERIOD = 3.00000 WAVELENGTH = 46.1231

DETERMINANT= 15.0907E+15

Table D-3. Continued

```
WAVE NUMBER = K =  1.57080    CIRCULAR FREQUENCY =  2.24899    FREQUENCY =   .35794    PERIOD =  2.79378    WAVELENGTH =  40.0000

    DETERMINANT=  30.5858E+15

WAVE NUMBER = K =  1.75929    CIRCULAR FREQUENCY =  2.38011    FREQUENCY =   .37881    PERIOD =  2.63987    WAVELENGTH =  35.7143

    DETERMINANT=  45.3555E+15

WAVE NUMBER = K =  1.96166    CIRCULAR FREQUENCY =  2.51327    FREQUENCY =   .40000    PERIOD =  2.50000    WAVELENGTH =  32.0299

    DETERMINANT=  54.4151E+15

WAVE NUMBER = K =  2.33106    CIRCULAR FREQUENCY =  2.73971    FREQUENCY =   .43604    PERIOD =  2.29337    WAVELENGTH =  26.9542

    DETERMINANT=  32.0082E+15

WAVE NUMBER = K =  2.69549    CIRCULAR FREQUENCY =  2.94609    FREQUENCY =   .46889    PERIOD =  2.13272    WAVELENGTH =  23.3100

    DETERMINANT=  12.9867E+14

WAVE NUMBER = K =  3.06509    CIRCULAR FREQUENCY =  3.14159    FREQUENCY =   .50000    PERIOD =  2.00000    WAVELENGTH =  20.4992

    DETERMINANT=  19.1494E+16
```

Table D-3. Continued

NONDIMENSIONAL POTENTIAL COEFFICIENTS

W = SQRT(G/B), W2 = G/B
B = FULL BEAM
G = ACCELERATION OF GRAVITY
ROE = MASS DENSITY OF FLUID
ETA = INCIDENT WAVE AMPLITUDE
WAVEL = INCIDENT OR GENERATED WAVE LENGTH

BEAM/WAVELENGTH	.1000	.1593	.1800	.2168	.2500	.2800	.3122	.3710	.4290	.4878
DIMENSIONAL FREQUENCY - HZ	.2264	.2857	.3037	.3333	.3579	.3788	.4000	.4360	.4689	.5000
ADDED MASS QM = AREA*ROE										
MU11/QM	7.3700	5.9465	5.4755	4.9561	4.8480	5.0504	5.6805	9.7945	-53.1777	-4.7733
MU12/QM	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	-.0000	-.0000
MU13/(QM*B)	1.2305	.9193	.8018	.6315	.5123	.4185	.3137	-.0480	4.7716	.9614
MU21/QM	.0000	-.0000	-.0000	.0000	-.0000	-.0000	-.0000	-.0000	.0000	.0000
MU22/QM	1.5889	.4458	.2118	.3495	.4699	.5476	.6100	.6927	.7546	.8097
MU23/(QM*B)	-.0000	-.0000	.0000	.0000	.0000	.0000	.0000	.0000	-.0000	-.0000
MU31/(QM*B)	1.2048	.8883	.7692	.5920	.4636	.3578	.2328	-.2308	6.0540	1.1125
MU32/(QM*B)	.0000	.0000	.0000	-.0000	.0000	-.0000	-.0000	.0000	.0000	.0000
MU33/(QM*B*B)	.4844	.4377	.4201	.3959	.3821	.3750	.3727	.3917	-.0644	.2917
DAMPING QD = AREA*ROE*W										
LAMBDA11/QD	2.0190	3.7933	4.0288	4.0948	3.9270	3.6660	3.2821	1.9613	39.5124	5.5165
LAMBDA12/QD	.0000	.0000	.0000	.0000	.0000	.0000	.0000	-.0000	.0000	.0000
LAMBDA13/(QD*B)	.3504	.6782	.7279	.7550	.7407	.7113	.6676	.5239	.1058	.6507
LAMBDA21/QD	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
LAMBDA22/QD	.1598	1.3091	.7819	.3464	.2012	.1342	.0915	.0486	.0268	.0141
LAMBDA23/(QD*B)	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
LAMBDA31/(QD*B)	.3491	.6786	.7295	.7594	.7482	.7224	.6842	.5629	-.7141	.6002
LAMBDA32/(QD*B)	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	-.0000	.0000
LAMBDA33/(QD*B*B)	.0606	.1213	.1318	.1400	.1411	.1402	.1392	.1489	-.0019	.0708
WAVE FORCES QF=AREA*ROE*ETA*W2										
FX/QF	4.4250	5.4149	5.4209	5.2373	4.9783	4.7161	4.4149	3.6704	8.9774	4.2984
PHASE REL TO ETA AT X=0 - DEG	72.8793	60.8041	59.8750	59.1117	59.6297	62.2586	66.0442	75.1616	86.5835	92.8458
FY/QF	1.2106	3.1799	2.4019	1.5443	1.1456	.9150	.7381	.5158	.3661	.2555
PHASE REL TO ETA AT X=0 - DEG	159.0771	89.0067	69.6025	58.9553	57.9583	59.5246	62.4899	69.8752	79.1007	90.8790
MZ/(QF*B)	.7530	.9455	.9536	.9325	.9963	.8598	.8222	.7784	.1632	.5379
PHASE REL TO ETA AT X=0 - DEG	72.5953	60.0131	57.8515	56.6160	57.6501	59.7944	62.9679	69.9328	93.0317	92.4742
WAVE FIELD - AMPLITUDE RATIOS										
POSITION - X/WAVELENGTH	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000
DIMENSIONAL POSITION - X	400.0000	251.1143	222.2222	184.4925	160.0000	142.8571	128.1197	107.8167	93.2401	81.9966
GEN BY SWAY/SWAY	.3497	.6893	.7688	.8919	.9729	1.0247	1.0543	.9433	4.4957	1.8878
PHASE REL TO BODY MOTION - DEG	162.8661	150.7298	148.7587	147.8852	149.2450	151.6560	155.0695	162.2626	-175.4311	-175.9364
GEN BY HEAVE/HEAVE	.0929	.3838	.3258	.2499	.2120	.1886	.1688	.1399	.1154	.0919
PHASE REL TO BODY MOTION - DEG	79.2908	-.3982	-19.5930	-29.7700	-30.2551	-28.1815	-24.6664	-16.4918	-7.2745	2.7097

Table D-3. Continued

GEN BY ROLL/ROLL(RAD)*B	.0607	.1215	.1389	.1644	.1835	.1988	.2144	.2494	.0121	.2227
PHASE REL TO BODY MOTION - DEG	162.8661	150.7288	148.7588	147.8853	149.2451	151.6562	155.0697	162.2624	-175.4425	-175.9368
TRANS BY FXD BDY/ETA	.9870	.4382	.1626	.0349	.0426	.0448	.0429	.0386	.1027	.0399
PHASE REL TO ETA AT X=0 - DEG	-26.3043	-111.8988	-124.4512	-63.8978	-22.2265	-16.4142	-17.2571	-31.5947	53.4327	-4.8102
WAVE FIELD - AMPLITUDE RATIOS										
POSITION - X/WAVELENGTH	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000
DIMENSIONAL POSITION - X	-400.0000	-251.1143	-222.2222	-184.4925	-160.0000	-142.8571	-128.1197	-107.8167	-93.2401	-81.9966
GEN BY SWAY/SWAY	.3497	.6803	.7688	.8919	.9729	1.0247	1.0543	.9433	4.4957	1.8978
PHASE REL TO BODY MOTION - DEG	-17.1409	-29.2782	-31.2483	-32.1218	-30.7620	-28.3509	-24.9375	-17.7444	4.5758	4.0706
GEN BY HEAVE/HEAVE	.0929	.3838	.3258	.2499	.2120	.1886	.1688	.1399	.1154	.0919
PHASE REL TO BODY MOTION - DEG	79.2908	-.3982	-19.5930	-29.7700	-30.2551	-26.1815	-24.5664	-16.4918	-7.2745	2.7097
GEN BY ROLL/ROLL(RAD)*B	.0607	.1215	.1389	.1644	.1835	.1988	.2144	.2494	.0121	.2227
PHASE REL TO BODY MOTION - DEG	-17.1409	-29.2782	-31.2482	-32.1217	-30.7619	-28.3507	-24.9373	-17.7445	4.5644	4.0701
REFLECTED BY FXD BDY/ETA	.1190	.8163	.9230	.9491	.9529	.9543	.9551	.9546	.9576	.9582
PHASE REL TO ETA AT X=0 - DEG	63.7635	149.0770	128.1707	117.3206	118.2930	122.8550	129.8806	145.6856	170.5966	-174.8329
INCIDENT/ETA	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
PHASE REL TO ETA AT X=0 - DEG	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
REFLECTED + INCIDENT/ETA	1.0580	.5156	.8433	1.0148	1.0024	.9356	.8292	.5783	.1660	.0977
PHASE REL TO ETA AT X=0 - DEG	5.7907	54.4560	59.3719	56.2053	56.8324	58.9699	62.1284	68.5420	70.5503	-62.1498

Table D-3. Continued

DYNAMIC MODEL RESULTS

AREA= 12.600 B= 10.000 XG= .000 YG= -2.340 MASS= 25.100 INERTIA= 621.000

ADDITIONAL DAMPING ADDED- IN SWAY- .00 LAMDA11 IN HEAVE- .00 LAMDA22 IN ROLL- .00 LAMDA33

SPRING CONSTANTS	K11	K12	K13	K21	K22	K23	K31	K32	K33
HYDROSTATIC	.000	.000	.000	.000	64.500	.000	.000	.000	1165.000
MOORING	.000	.000	.000	.000	.000	.000	.000	.000	.000

BEAM/WAVELENGTH	.1000	.1593	.1800	.2168	.2500	.2800	.3122	.3710	.4290	.4878
DIMENSIONAL FREQUENCY - HZ	.2264	.2857	.3037	.3333	.3579	.3788	.4000	.4360	.4689	.5000
MOTION RESPONSE										
SWAY AMPLITUDE/ETA	.7219	.6490	.5957	.5043	.4229	.3499	.2722	.1327	.0011	.1391
PHASE REL TO ETA AT X=0 - DEG	-90.2310	-90.4540	-90.5725	-90.7827	-90.9813	-91.1565	-91.3291	-91.5455	-35.8354	85.6505
HEAVE AMPLITUDE/ETA	1.4444	2.1755	2.3789	1.3831	.7476	.4732	.3122	.1638	.0931	.0538
PHASE REL TO ETA AT X=0 - DEG	-2.2345	-27.3638	-54.9607	-99.8204	-112.5778	-115.2004	-114.4117	-108.7807	-100.2661	-88.8296
ROLL AMPLITUDE(RAD)*B/ETA	.4747	.2050	.2613	.3337	.3871	.4308	.4746	.5503	.6670	.7232
PHASE REL TO ETA AT X=0 - DEG	-90.0905	-90.8493	-90.8892	-91.0865	-91.3080	-91.5186	-91.7496	-92.2407	-91.6298	-93.9513
WAVE FIELD - AMPLITUDE RATIOS										
POSITION - X/WAVELENGTH	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000
DIMENSIONAL POSITION - X	400.0000	251.1143	222.2222	184.4925	160.0000	142.8571	128.1197	107.8167	93.2401	81.9966
GEN BY RESULTANT SWAY/ETA	.2524	.4415	.4579	.4498	.4115	.3586	.2870	.1251	.0049	.2626
PHASE REL TO ETA AT X=0 - DEG	72.6350	60.2648	58.1863	57.1025	58.2637	60.4995	63.7403	70.7171	-211.2665	-90.2859
GEN BY RESULTANT HEAVE/ETA	.1341	.8349	.7750	.3456	.1585	.0892	.0527	.0229	.0107	.0049
PHASE REL TO ETA AT X=0 - DEG	77.0563	-27.7620	-74.5537	-129.5904	-142.8329	-143.3819	-139.0781	-125.2726	-107.5406	-86.1198
GEN BY RESULTANT ROLL/ETA	.0288	.0249	.0363	.0549	.0710	.0856	.1018	.1373	.0081	.1611
PHASE REL TO ETA AT X=0 - DEG	72.7756	59.8795	57.8696	56.7988	57.9371	60.1376	63.3201	70.0217	-267.0723	-269.8881
TRANS BY FXD BDY/ETA	.9870	.4382	.1626	.0349	.0426	.0448	.0429	.0386	.1027	.0399
PHASE REL TO ETA AT X=0 - DEG	-26.3043	-111.8989	-124.4512	-63.8978	-22.2265	-16.4142	-17.2571	-31.5947	53.4327	-4.6102
TOTAL TRANSMITTED/ETA	.9995	.9965	.5946	.1438	.3420	.3728	.3477	.2345	.0986	.1164
PHASE REL TO ETA AT X=0 - DEG	-2.1888	-25.8277	-50.8773	61.0959	60.7136	59.2666	60.0027	62.6052	57.1886	-70.7104
WAVE FIELD - AMPLITUDE RATIOS										
POSITION - X/WAVELENGTH	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000
DIMENSIONAL POSITION - X	-400.0000	-251.1143	-222.2222	-184.4925	-160.0000	-142.8571	-128.1197	-107.8167	-93.2401	-81.9966
GEN BY RESULTANT SWAY/ETA	.2524	.4415	.4579	.4498	.4115	.3586	.2870	.1251	.0049	.2626
PHASE REL TO ETA AT X=0 - DEG	-107.3719	-119.7422	-121.8207	-122.9045	-121.7433	-119.5075	-116.2666	-109.2899	-31.2595	89.7210
GEN BY RESULTANT HEAVE/ETA	.1341	.8349	.7750	.3456	.1585	.0892	.0527	.0229	.0107	.0049
PHASE REL TO ETA AT X=0 - DEG	77.0563	-27.7620	-74.5537	-129.5904	-142.8329	-143.3819	-139.0781	-125.2726	-107.5406	-86.1198
GEN BY RESULTANT ROLL/ETA	.0288	.0249	.0363	.0549	.0710	.0856	.1018	.1373	.0081	.1611

Table D-3. Continued

PHASE REL TO ETA AT X=0 - DEG	-107.2314	-120.1274	-122.1374	-123.2092	-122.0699	-119.8693	-116.6869	-109.9853	-87.0653	-89.8811
REFLECTED BY FXD BDY/ETA	.1190	.8163	.9230	.9491	.9529	.9543	.9551	.9546	.9576	.9582
PHASE REL TO ETA AT X=0 - DEG	63.7635	149.0770	128.1707	117.3206	118.2930	122.8550	129.6806	145.6855	170.5966	-174.8329
TOTAL REFLECTED/ETA	.0310	.4211	.7647	.9427	.8963	.8859	.8961	.9306	.9531	.9524
PHASE REL TO ETA AT X=0 - DEG	-92.2593	-117.2714	-144.7676	170.6416	158.1971	155.8797	157.0076	162.9862	171.8175	179.3934

Table D-3. Continued

DYNAMIC MODEL RESULTS

AREA= 12.600 B= 10.000 XG= .000 YG= -2.340 MASS= 25.100 INERTIA= 621.000

ADDITIONAL DAMPING ADDED- IN SWAY- .00 LAMDA11 IN HEAVE- .00 LAMDA22 IN ROLL- .00 LAMDA33

SPRING CONSTANTS	K11	K12	K13	K21	K22	K23	K31	K32	K33
HYDROSTATIC	.000	.000	.000	.000	64.500	.000	.000	.000	1165.000
MOORING	118.800	-5.240	166.200	-5.732	10.210	-3.372	159.900	2.063	281.800

BEAM/WAVELENGTH	.1000	.1593	.1800	.2168	.2500	.2800	.3122	.3710	.4290	.4878
DIMENSIONAL FREQUENCY - HZ	.2264	.2857	.3037	.3333	.3579	.3788	.4000	.4360	.4689	.5000
MOTION RESPONSE										
SWAY AMPLITUDE/ETA	.8185	.8065	.7043	.5776	.4819	.3955	.3041	.1442	.0020	.1366
PHASE REL TO ETA AT X=0 - DEG	-82.8642	-87.2662	-97.2183	-86.1074	-86.7460	-87.7094	-88.8030	-90.5595	-71.1733	85.8405
HEAVE AMPLITUDE/ETA	1.6748	2.2183	2.4999	1.5130	.7948	.4934	.3212	.1669	.0954	.0565
PHASE REL TO ETA AT X=0 - DEG	2.0115	-22.8265	-49.0770	-98.0382	-112.7051	-115.7896	-115.0728	-109.1711	-100.3317	-98.9394
ROLL AMPLITUDE(RAD)*B/ETA	1.4487	.1117	.2186	.3219	.3922	.4499	.5035	.5618	.6917	.7152
PHASE REL TO ETA AT X=0 - DEG	-95.3538	-21.0161	-71.8097	-85.7725	-86.5531	-87.4561	-88.6553	-90.8574	-91.2293	-93.7687
WAVE FIELD - AMPLITUDE RATIOS										
POSITION - X/WAVELENGTH	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000
DIMENSIONAL POSITION - X	400.0000	251.1143	222.2222	184.4925	160.0000	142.8571	128.1197	107.8167	93.2401	81.9966
GEN BY RESULTANT SWAY/ETA	.2862	.5487	.5414	.5152	.4688	.4053	.3206	.1360	.0091	.2593
PHASE REL TO ETA AT X=0 - DEG	80.0019	63.4625	61.5404	61.7778	62.4990	63.9466	66.2665	71.7031	-240.6044	-90.0959
GEN BY RESULTANT HEAVE/ETA	.1555	.8512	.8145	.3781	.1685	.0930	.0542	.0234	.0110	.0052
PHASE REL TO ETA AT X=0 - DEG	81.3023	-23.2247	-68.6701	-127.8082	-142.9603	-143.9711	-139.7392	-125.6629	-107.6062	-86.2296
GEN BY RESULTANT ROLL/ETA	.0879	.0135	.0304	.0529	.0720	.0895	.1080	.1451	.0083	.1593
PHASE REL TO ETA AT X=0 - DEG	67.5123	129.7128	76.9491	62.1128	62.6920	64.2001	66.4144	71.4051	-266.6719	-269.7055
TRANS BY FXD BDY/ETA	.9870	.4382	.1626	.0349	.0426	.0448	.0429	.0386	.1027	.0399
PHASE REL TO ETA AT X=0 - DEG	-26.3043	-111.9989	-124.4512	-63.8979	-22.2265	-16.4142	-17.2571	-31.5947	53.4327	-4.8102
TOTAL TRANSMITTED/ETA	.9949	.8985	.6083	.1794	.3937	.4200	.3852	.2519	.1038	.1144
PHASE REL TO ETA AT X=0 - DEG	4.5843	-15.7336	-39.5304	73.0441	66.9047	63.9223	63.5057	64.5501	58.7840	-70.1549
WAVE FIELD - AMPLITUDE RATIOS										
POSITION - X/WAVELENGTH	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000
DIMENSIONAL POSITION - X	-400.0000	-251.1143	-222.2222	-184.4925	-160.0000	-142.8571	-128.1197	-107.8167	-93.2401	-81.9966
GEN BY RESULTANT SWAY/ETA	.2862	.5487	.5414	.5152	.4688	.4053	.3206	.1360	.0091	.2593
PHASE REL TO ETA AT X=0 - DEG	-100.0050	-116.5444	-118.4666	-119.2292	-117.5080	-116.0603	-113.7405	-108.3039	-66.5974	89.9110
GEN BY RESULTANT HEAVE/ETA	.1555	.8512	.8145	.3781	.1685	.0930	.0542	.0234	.0110	.0052
PHASE REL TO ETA AT X=0 - DEG	81.3023	-23.2247	-68.6701	-127.8082	-142.9603	-143.9711	-139.7392	-125.6629	-107.6062	-86.2296
GEN BY RESULTANT ROLL/ETA	.0879	.0135	.0304	.0529	.0720	.0895	.1080	.1451	.0083	.1593

Table D-3. Continued

PHASE REL TO ETA AT X=0 - DEG	-112.4946	-50.2942	-103.0579	-117.8941	-117.3149	-115.8069	-113.5926	-108.6019	-86.6649	-89.6985
REFLECTED BY FXD BDY/ETA	.1190	.8163	.9230	.9491	.9529	.9543	.9551	.9546	.9576	.9582
PHASE REL TO ETA AT X=0 - DEG	63.7635	149.0773	128.1707	117.3206	118.2930	122.8550	129.8806	145.6856	170.5966	-174.8329
TOTAL REFLECTED/ETA	.1029	.4451	.7619	.9367	.8745	.8645	.8807	.9261	.9527	.9528
PHASE REL TO ETA AT X=0 - DEG	-94.0142	-110.3085	-135.0236	177.3225	162.8662	159.5332	159.7122	164.1800	172.2029	179.5602

MOORING LINE MODEL RESULTS

SHOREWARD MOORING LINE

CHANGE IN FORCE PER UNIT DISPLACEMENT IN SWAY, HEAVE AND ROLL, RESPECTIVELY =-1376.0000 410.6000-1637.0000

MOORING LINE RESPONSE										
FORCE AMPLITUDE/ETA	1.487E+03	1.083E+03	6.545E+02	2.712E+02	4.557E+02	4.481E+02	3.856E+02	2.279E+02	7.544E+01	9.646E+01
PHASE REL TO ETA AT X=0 - DEG	22.5037	45.3005	69.8203	-32.2325	-21.5524	-14.6238	-9.9398	-4.8284	-4.2163	-176.6191
FORCE AMPLITUDE/ROE*G*AREA*ETA	1.841E+00	1.341E+00	8.105E-01	3.358E-01	5.643E-01	5.548E-01	4.775E-01	2.823E-01	9.341E-02	1.194E-01

MOORING LINE MODEL RESULTS

SEAWARD MOORING LINE

CHANGE IN FORCE PER UNIT DISPLACEMENT IN SWAY, HEAVE AND ROLL, RESPECTIVELY = 1172.0000 280.9000 1713.0000

MOORING LINE RESPONSE										
FORCE AMPLITUDE/ETA	1.311E+03	1.352E+03	1.482E+03	1.151E+03	8.384E+02	6.660E+02	5.251E+02	3.135E+02	1.472E+02	2.216E+01
PHASE REL TO ETA AT X=0 - DEG	154.4105	151.8842	159.7943	-179.5353	-176.5792	-176.7023	-176.8630	-176.6128	-177.4416	10.1138
FORCE AMPLITUDE/ROE*G*AREA*ETA	1.623E+00	1.674E+00	1.835E+00	1.426E+00	1.038E+00	8.247E-01	6.502E-01	3.882E-01	1.823E-01	2.744E-02

Table D-3. Continued

DYNAMIC MODEL RESULTS

AREA= 12.600 B= 10.000 XG= .000 YG= -2.340 MASS= 25.100 INERTIA= 621.000

ADDITIONAL DAMPING ADDED- IN SWAY- 1.00 LAMDA11 IN HEAVE- 1.00 LAMDA22 IN ROLL- 1.00 LAMDA33

SPRING CONSTANTS	K11	K12	K13	K21	K22	K23	K31	K32	K33
HYDROSTATIC	.000	.000	.000	.000	64.500	.000	.000	.000	1165.000
MOORING	118.800	-5.240	166.200	-5.732	10.210	-3.372	159.900	2.063	281.800

BEAM/WAVELENGTH	.1000	.1593	.1800	.2168	.2500	.2800	.3122	.3710	.4290	.4878
DIMENSIONAL FREQUENCY - HZ	.2264	.2857	.3037	.3333	.3579	.3788	.4000	.4360	.4689	.5000
MOTION RESPONSE										
SWAY AMPLITUDE/ETA	.5857	.4320	.4106	.3716	.3400	.3057	.2587	.1387	.0019	.1119
PHASE REL TO ETA AT X=0 - DEG	-94.6025	-56.3210	-57.5115	-59.6797	-62.4719	-66.2453	-71.6435	-84.5311	-78.6415	61.0574
HEAVE AMPLITUDE/ETA	1.5999	1.1799	1.3829	1.2531	.7680	.4916	.3222	.1671	.0954	.0561
PHASE REL TO ETA AT X=0 - DEG	11.0451	-12.5409	-35.9320	-80.3707	-103.0333	-110.3550	-111.9992	-107.8820	-99.6718	-89.2259
ROLL AMPLITUDE(RAD)*B/ETA	2.4528	1.3678	1.1093	.8053	.6258	.5281	.4912	.5468	.6908	.6026
PHASE REL TO ETA AT X=0 - DEG	-61.0343	-109.1099	-112.0633	-113.1534	-109.7176	-102.3773	-92.2317	-81.7364	-90.7043	-98.0733
WAVE FIELD - AMPLITUDE RATIOS										
POSITION - X/WAVELENGTH	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000
DIMENSIONAL POSITION - X	400.0000	251.1143	222.2222	184.4925	160.0000	142.8571	128.1197	107.8167	93.2401	81.9966
GEN BY RESULTANT SWAY/ETA	.2048	.2939	.3157	.3315	.3308	.3132	.2728	.1308	.0088	.2112
PHASE REL TO ETA AT X=0 - DEG	78.2636	94.4078	91.2472	88.2055	86.7731	85.4107	83.4260	77.7315	-254.0727	-114.8790
GEN BY RESULTANT HEAVE/ETA	.1486	.4529	.4506	.3131	.1629	.0927	.0544	.0234	.0110	.0052
PHASE REL TO ETA AT X=0 - DEG	90.3359	-12.9391	-55.5251	-110.1407	-133.2884	-138.5365	-136.6656	-124.3738	-106.9463	-86.5162
GEN BY RESULTANT ROLL/ETA	.1489	.1664	.1541	.1324	.1148	.1050	.1053	.1364	.0083	.1342
PHASE REL TO ETA AT X=0 - DEG	101.8318	41.6189	36.6955	34.7319	39.5275	49.2789	62.8379	80.5261	-266.1468	-274.0101
TRANS BY FXD BDY/ETA	.9870	.4382	.1626	.0349	.0426	.0448	.0429	.0386	.1027	.0399
PHASE REL TO ETA AT X=0 - DEG	-26.3043	-111.9988	-124.4512	-63.8978	-22.2265	-16.4142	-17.2571	-31.5947	53.4327	-4.8102
TOTAL TRANSMITTED/ETA	.8970	.3933	.2964	.0857	.2709	.3248	.3248	.2336	.1044	.0771
PHASE REL TO ETA AT X=0 - DEG	3.6729	-15.3782	-19.2820	71.7761	82.5810	78.0874	75.6150	72.5741	58.1883	-120.7664
WAVE FIELD - AMPLITUDE RATIOS										
POSITION - X/WAVELENGTH	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000	-4.0000
DIMENSIONAL POSITION - X	-400.0000	-251.1143	-222.2222	-184.4925	-160.0000	-142.8571	-128.1197	-107.8167	-93.2401	-81.9966
GEN BY RESULTANT SWAY/ETA	.2048	.2939	.3157	.3315	.3308	.3132	.2728	.1308	.0088	.2112
PHASE REL TO ETA AT X=0 - DEG	-101.7434	-85.5992	-88.7597	-91.8015	-93.2339	-94.5963	-96.5810	-102.2755	-74.0657	65.1280
GEN BY RESULTANT HEAVE/ETA	.1486	.4529	.4506	.3131	.1629	.0927	.0544	.0234	.0110	.0052
PHASE REL TO ETA AT X=0 - DEG	90.3359	-12.9391	-55.5251	-110.1407	-133.2884	-138.5365	-136.6656	-124.3738	-106.9463	-86.5162
GEN BY RESULTANT ROLL/ETA	.1489	.1664	.1541	.1324	.1148	.1050	.1053	.1364	.0083	.1342

Table D-3. Continued

PHASE REL TO ETA AT X=0 - DEG	-78.1752	-138.3989	-143.3115	-145.2759	-140.4794	-130.7280	-117.1690	-99.4609	-86.1399	-94.0032
REFLECTED BY FXD BDY/ETA	.1190	.8163	.9230	.9491	.9529	.9543	.9551	.9546	.9576	.9582
PHASE REL TO ETA AT X=0 - DEG	63.7635	149.0779	128.1707	117.3206	118.2930	122.8550	129.8806	145.6856	170.5966	-174.8329
TOTAL REFLECTED/ETA	.0996	.3707	.4353	.6777	.7417	.7647	.8026	.8897	.9538	.9752
PHASE REL TO ETA AT X=0 - DEG	-65.9434	-166.6858	-172.9573	167.8642	154.6875	152.8944	155.6557	163.2463	172.2152	-177.7925

MOORING LINE MODEL RESULTS

SHOREWARD MOORING LINE

CHANGE IN FORCE PER UNIT DISPLACEMENT IN SWAY, HEAVE AND ROLL, RESPECTIVELY =-1376.0000 410.6000-1607.0000

MOORING LINE RESPONSE										
FORCE AMPLITUDE/ETA	1.328E+03	6.348E+02	3.809E+02	1.324E+02	3.242E+02	3.559E+02	3.342E+02	2.179E+02	7.524E+01	8.660E+01
PHASE REL TO ETA AT X=0 - DEG	16.5361	19.8163	35.8873	-66.3177	-51.4041	-38.4782	-28.3381	-13.7787	-4.3807	-135.5908
FORCE AMPLITUDE/ROE*G*AREA*ETA	1.644E+00	7.869E-01	4.716E-01	1.639E-01	4.015E-01	4.407E-01	4.138E-01	2.698E-01	9.317E-02	1.072E-01

MOORING LINE MODEL RESULTS

SEAWARD MOORING LINE

CHANGE IN FORCE PER UNIT DISPLACEMENT IN SWAY, HEAVE AND ROLL, RESPECTIVELY = 1172.0000 280.9000 1713.0000

MOORING LINE RESPONSE										
FORCE AMPLITUDE/ETA	1.197E+03	8.884E+02	9.528E+02	8.790E+02	6.718E+02	5.511E+02	4.595E+02	2.995E+02	1.471E+02	4.929E+01
PHASE REL TO ETA AT X=0 - DEG	143.6852	143.5624	149.2268	155.1982	171.4939	171.9765	172.7651	177.2141	-177.8580	93.7362
FORCE AMPLITUDE/ROE*G*AREA*ETA	1.483E+00	1.100E+00	1.189E+00	1.088E+00	8.319E-01	6.824E-01	5.690E-01	3.709E-01	1.821E-01	6.103E-02

Table D-3. Continued

APPENDIX E

DERIVATION OF PRESSURE TO SECOND ORDER FOR TWO PROGRESSIVE WAVES AT DIFFERENT FREQUENCIES

Consider the problem of the nonlinear interactions of waves at two distinct frequencies traveling in the same direction. The complete boundary value problem is well known.

The Laplace equation,

$$\nabla^2\phi = 0, \qquad \text{(E-1)}$$

applies throughout the fluid below the free surface.

The boundary condition,

$$\frac{\partial^2\phi}{\partial t^2} + g\,\frac{\partial\phi}{\partial y} + 2\nabla\phi\cdot\nabla\,\frac{\partial\phi}{\partial t} + \frac{1}{2}\,\nabla\phi\cdot\nabla\,(\nabla\phi\cdot\nabla\phi) = 0, \qquad \text{(E-2)}$$

must be satisfied on the free surface, $y = \eta$. The boundary condition on the bottom is:

$$\lim_{y\to-\infty}\frac{\partial\phi}{\partial y} = 0 \qquad \text{(E-3)}$$

for an infinitely deep fluid. In addition a radiation condition requiring the generated waves to travel away from the body is needed to ensure uniqueness of the solution.

In this formulation the x axis lies in the direction of incident wave propagation.

The difficulty in solving this boundary value problem stems from the nonlinearity of the free-surface boundary condition.

In order to "linearize" the free-surface boundary condition, expand the velocity potential, ϕ, in a Taylor series about the undisturbed free surface:

$$\phi(x,\eta,t) = \phi(x,0,t) + \eta\left[\frac{\partial\phi(x,y,t)}{\partial y}\right]_{y=0} + \frac{1}{2}\,\eta^2\left[\frac{\partial\phi(x,y,t)}{\partial y}\right]_{y=0} + O(\eta^3). \qquad \text{(E-4)}$$

Also expand η and ϕ in power series:

$$\eta(x,t) = \varepsilon\eta^{(1)}(x,t) + \varepsilon^2\eta^{(2)}(x,t) + O(\varepsilon^3),$$

$$\phi(x,y,t) = \varepsilon\phi^{(1)}(x,y,t) + \varepsilon^2\phi^{(2)}(x,y,t) + O(\varepsilon^3). \qquad \text{(E-5)}$$

Substituing the expansion for ϕ into the free-surface boundary condition:

$$\varepsilon \frac{\partial^2\phi^{(1)}(x,y,t)}{\partial t^2} + \varepsilon^2 \frac{\partial^2\phi^{(2)}}{\partial t^2} + g\varepsilon \frac{\partial\phi^{(1)}}{\partial y} + g\varepsilon^2 \frac{\partial\phi^{(2)}}{\partial y}$$

$$+ 2[\varepsilon\{\frac{\partial\phi^{(1)}}{\partial x} \vec{i} + \frac{\partial\phi^{(1)}}{\partial y} \vec{j}\} + \varepsilon^2\{ \frac{\partial\phi^{(2)}}{\partial x} \vec{i} + \frac{\partial\phi^{(2)}}{\partial y} \vec{j}\}] \cdot$$

$$[\vec{i} \frac{\partial}{\partial x} + \vec{j} \frac{\partial}{\partial y}] [\varepsilon\frac{\partial\phi^{(1)}}{\partial t} + \varepsilon^2 \frac{\partial\phi^{(2)}}{\partial t}]$$

$$+ \frac{1}{2} [\varepsilon\frac{\partial\phi^{(1)}}{\partial x} \vec{i} + \frac{\partial\phi^{(1)}}{\partial y} \vec{j}\} + \varepsilon^2\{\frac{\partial\phi^{(2)}}{\partial x} \vec{i} + \frac{\partial\phi^{(2)}}{\partial y} \vec{j}\}] \cdot$$

$$[\vec{i} \frac{\partial}{\partial x} + \vec{j} \frac{\partial}{\partial y}]\Big[[\varepsilon\{\frac{\partial\phi^{(1)}}{\partial x} \vec{i} + \frac{\partial\phi^{(1)}}{\partial y} \vec{j}\} + \varepsilon^2\{\frac{\partial\phi^{(2)}}{\partial x} \vec{i} + \frac{\partial\phi^{(2)}}{\partial y} \vec{j}\}] \cdot$$

$$[\varepsilon\{\frac{\partial\phi^{(1)}}{\partial x} \vec{i} + \frac{\partial\phi^{(1)}}{\partial y} \vec{j}\} + \varepsilon^2\{\frac{\partial\phi^{(2)}}{\partial x} \vec{i} + \frac{\partial\phi^{(2)}}{\partial y} \vec{j}\}]\Big] + O(\varepsilon^3) = 0 \quad \text{(E-6)}$$

on $y = \eta$.

Now use the Taylor expansion for $\phi(x,\eta,t)$ and neglect terms of order ε^3 in the boundary condition:

$$\varepsilon\{\frac{\partial^2\phi^{(1)}(x,0,t)}{\partial t^2} + \varepsilon\eta^{(1)}(x,t) \frac{\partial^3\phi^{(1)}}{\partial y\partial t^2}\} + \varepsilon^2 \frac{\partial^2\phi^{(2)}}{\partial t^2}$$

$$+ g\varepsilon\{\frac{\partial\phi^{(1)}}{\partial y} + \varepsilon\eta^{(1)} (x,t) \frac{\partial^2\phi^{(1)}}{\partial y^2}\} + g\varepsilon^2 \frac{\partial\phi^{(2)}}{\partial y}$$

$$+ 2\varepsilon^2[\frac{\partial\phi^{(1)}}{\partial x} \frac{\partial^2\phi^{(1)}}{\partial t\partial x} + \frac{\partial\phi^{(1)}}{\partial y} \frac{\partial^2\phi^{(1)}}{\partial t\partial y}] + O(\varepsilon^3) = 0. \quad \text{(E-7)}$$

Grouping terms by order:

First Order ε:

$$\frac{\partial^2\phi^{(1)}}{\partial t^2} + g \frac{\partial\phi^{(1)}}{\partial y} = 0 \quad \text{on } y = 0. \quad \text{(E-8)}$$

Second Order ε^2:

$$\frac{\partial^2\phi^{(2)}}{\partial t^2} + g \frac{\partial\phi^{(2)}}{\partial y} + \eta^{(1)} \frac{\partial}{\partial y} \{\frac{\partial^2\phi^{(1)}}{\partial t^2} + g \frac{\partial\phi^{(1)}}{\partial y}\} + 2 \frac{\partial\phi^{(1)}}{\partial x} \frac{\partial^2\phi^{(1)}}{\partial x\partial t}$$

$$+ 2 \frac{\partial\phi^{(1)}}{\partial y} \frac{\partial\phi^{(1)}}{\partial y\partial t} = 0 \quad \text{on } y = 0. \quad \text{(E-9)}$$

Using the dynamic boundary condition on the free surface, one finds:

$$\eta(x,t) = -\frac{1}{g}\left\{\frac{\partial\phi}{\partial t} + \frac{1}{2}\nabla\phi\cdot\nabla\phi\right\} \quad \text{on } y = \eta. \tag{E-10}$$

Substituting the expansions into this equation yields:

$$\varepsilon\eta^{(1)}(x,t) + \varepsilon^2\eta^{(2)} + O(\varepsilon^3) = -\frac{1}{g}\left\{\frac{\partial\phi}{\partial t} + \frac{1}{2}\nabla\phi\cdot\nabla\phi\right\}_{y=0}$$

$$-\frac{\eta}{g}\frac{\partial}{\partial y}\left\{\frac{\partial\phi}{\partial t} + \frac{1}{2}\nabla\phi\cdot\nabla\phi\right\}_{y=0} + O(\eta^2). \tag{E-11}$$

Substituting for ϕ, the right-hand side becomes:

$$= -\frac{1}{g}\left\{\varepsilon\frac{\partial\phi^{(1)}}{\partial t} + \varepsilon^2\frac{\partial\phi^{(2)}}{\partial t} + \frac{\varepsilon^2}{2}\left[\left(\frac{\partial\phi^{(1)}}{\partial x}\right)^2 + \left(\frac{\partial\phi^{(1)}}{\partial y}\right)^2\right]\right\}$$

$$-\frac{\varepsilon^2\eta^{(1)}}{g}\left\{\frac{\partial^2\phi^{(1)}}{\partial y\partial t}\right\} + O(\varepsilon^3), \quad \text{on } y = 0.$$

First Order ε:

$$\eta^{(1)}(x,t) = -\frac{1}{g}\frac{\partial\phi^{(1)}(x,0,t)}{\partial t}. \tag{E-12}$$

Second Order ε^2:

$$\eta^{(2)}(x,t) = -\frac{1}{g}\left\{\eta^{(1)}\frac{\partial\phi^{(1)}}{\partial y\partial t} + \frac{\partial\phi^{(1)}}{\partial t}\right\} - \frac{1}{2g}\left\{\left(\frac{\partial\phi^{(1)}}{\partial x}\right)^2 + \left(\frac{\partial\phi^{(1)}}{\partial y}\right)^2\right\}$$

on $y = 0$

or

$$\eta^{(2)}(x,t) = -\frac{1}{g}\left\{-\frac{1}{g}\frac{\partial\phi^{(1)}}{\partial t}\frac{\partial^2\phi^{(1)}}{\partial y\partial t} + \frac{\partial\phi^{(2)}}{\partial t}\right\} - \frac{1}{2g}\left\{\left(\frac{\partial\phi^{(1)}}{\partial x}\right)^2 + \left(\frac{\partial\phi^{(1)}}{\partial y}\right)^2\right\} \quad \text{on } y = 0. \tag{E-13}$$

Using the first-order relationship above in the second-order boundary condition on the free surface (E-9), one finds:

$$\frac{\partial^2\phi^{(2)}}{\partial t^2} + g\frac{\partial\phi^{(2)}}{\partial y} = +\frac{1}{g}\frac{\partial\phi^{(1)}}{\partial t}\frac{\partial}{\partial y}\left\{\frac{\partial^2\phi^{(1)}}{\partial t^2} + g\frac{\partial\phi^{(1)}}{\partial y}\right\}$$

$$-2\frac{\partial\phi^{(1)}}{\partial x}\frac{\partial^2\phi^{(1)}}{\partial x\partial t} - 2\frac{\partial\phi^{(1)}}{\partial y}\frac{\partial^2\phi^{(1)}}{\partial y\partial t} \tag{E-14}$$

1. First-Order Solution of the Boundary Value Problem.

This solution results from the superposition of the velocity potentials for individual waves:

$$\phi^{(1)}(x,y,t) = \frac{gA_1}{\omega_1} e^{k_1 y} \cos(k_1 x - \omega_1 t + \delta_1)$$

$$+ \frac{gA_2}{\omega_2} e^{k_2 y} \cos(k_2 x - \omega_2 t + \delta_2). \qquad \text{(E-15)}$$

Check the solution:

$$\nabla^2\phi^{(1)} = 0.$$

$$\lim_{y \to -\infty} \frac{\partial\phi^{(1)}}{\partial y} \to 0 \quad \text{because of exponential function.}$$

$$\frac{\partial^2\phi^{(1)}}{\partial t^2} + g\frac{\partial\phi^{(1)}}{\partial y} = - g\omega_1 A_1 e^{k_1 y} \cos(k_1 x - \omega_1 t + \delta_1)$$

$$- g\omega_2 A_2 e^{k_2 y} \cos(k_2 x - \omega_2 t + \delta_2)$$

$$+ g\{\omega_1 A_1 e^{k_1 t} \cos(k_1 x - \omega_1 t + \delta_1)$$

$$+ \omega_2 A_2 e^{k_2 y} \cos(k_2 x - \omega_2 t + \delta_2)\} = 0.$$

Therefore, this is a solution.

Surface elevation then becomes:

$$\eta^{(1)}(x,t) = -\frac{1}{g}\frac{\partial\phi^{(1)}(x,0,t)}{\partial t} = - A_1 \sin(k_1 x - \omega_1 t + \delta_1)$$

$$- A_2 \sin(k_2 x - \omega_2 t + \delta_2). \qquad \text{(E-16)}$$

To prepare for the second-order solution, construct the right-hand side of the free-surface boundary condition (E-14):

$$\left[\frac{1}{2}\frac{\partial\phi^{(1)}}{\partial t}\frac{\partial}{\partial y}\left\{\frac{\partial^2\phi^{(1)}}{\partial t^2} + g\frac{\partial\phi^{(1)}}{\partial y}\right\} - 2\frac{\partial\phi^{(1)}}{\partial x}\frac{\partial^2\phi^{(1)}}{\partial x\partial t}\right.$$

$$\left. - 2\frac{\partial\phi^{(1)}}{\partial y}\frac{\partial^2\phi^{(1)}}{\partial y\partial t}\right]_{y=0} = \frac{1}{g}\{gA_1 \sin(k_1 x - \omega_1 t + \delta_1)$$

$$+ gA_2 \sin(k_2 x - \omega_2 t + \delta_2)\}\{0\} - 2\{-\omega_1 A_1 \sin(k_1 x - \omega_1 t + \delta_1) \qquad \text{(E-17)}$$

$$- \omega_2 A_2 \sin(k_2x - \omega_2 t + \delta_2)\}\times\{\omega_1{}^2 A_1 \cos(k_1x - \omega_1 t + \delta_1)$$

$$+ \omega^2{}_2 A_2 \cos(k_2x - \omega_2 t + \delta_2)\} - 2\{\omega_1 A_1 \cos(k_1x - \omega_1 t + \delta_1)$$

$$+ \omega_2 A_2 \cos(k_2x - \omega_2 t + \delta_2)\}\times\{\omega_1{}^2 A_1 \sin(k_1x - \omega_1 t + \delta_1)$$

$$+ \omega_2{}^2 A_2 \sin(k_2x = \omega_2 t + \delta_2)\} = 0.$$

Since this condition is homogeneous, the first-order potential is the solution to the second-order problem.

2. Second-Order Results.

The free-surface elevation will be modified when terms of second order are included:

$$\eta^{(2)}(x,t) = \frac{1}{g^2}\{\frac{\partial\phi^{(1)}}{\partial t}\frac{\partial^2\phi^{(1)}}{\partial y\partial t}\} - \frac{1}{2g}\{(\frac{\partial\phi^{(1)}}{\partial x})^2 + (\frac{\partial\phi^{(1)}}{\partial y})^2\}\Big|_{y=0}$$

$$= + \frac{1}{g^2}\{gA_1 \sin(k_1x - \omega_1 t + \delta_1) + gA_2 \sin(k_2x - \omega_2 t + \delta_2)\} \times$$

$$\{A_1\,\omega_1{}^2 \sin(k_1x - \omega_1 t + \delta_1) + A_2\,\omega_2{}^2 \sin(k_2x - \omega_2 t + \delta_2)\}$$

$$- \frac{1}{2g}\{[- \omega_1 A_1 \sin(k_1x - \omega_1 t + \delta_1) - \omega_2 A_2 \sin(k_2x - \omega_2 t + \delta_2)]^2$$

$$+ [\omega_1 A_1 \cos(k_1x - \omega_1 t + \delta_1) + \omega_2 A_2 \cos(k_2x - \omega_2 t + \delta_2)]^2\}$$

or

$$g\eta^{(2)}(x,t) = \omega_1{}^2 A_1{}^2 \sin^2(k_1x - \omega_1 t + \delta_1)$$

$$+ \omega_1{}^2 A_1 A_2 \sin(k_2x - \omega_2 t + \delta_2) \sin(k_1x - \omega_1 t + \delta_1)$$

$$+ \omega_2{}^2 A_1 A_2 \sin(k_1x - \omega_1 t + \delta_1) \sin(k_2x - \omega_2 t + \delta_2)$$

$$+ \omega_2{}^2 A_2{}^2 \sin^2(k_2x - \omega_2 t + \delta_2)$$

$$\frac{1}{2}\{\omega_1{}^2 A_1{}^2 \sin^2(k_1x - \omega_1 t + \delta_1)$$

$$+ 2\omega_1\omega_2 A_1 A_2 \sin(k_1x - \omega_1 t + \delta_1)\sin(k_2x - \omega_2 t + \delta_2)$$

$$+ \omega_2^{\ 2} A_2^{\ 2} \sin^2(k_2 x - \omega_2 t + \delta_2)$$

$$+ \omega_1^{\ 2} A_1^{\ 2} \cos^2(k_1 x_1 - \omega_1 t + \delta_1)$$

$$+ 2\omega_1 \omega_2 A_1 A_2 \cos(k_1 x - \omega_1 t + \delta_1)\cos(k_2 x - \omega_2 t + \delta_2)$$

$$+ \omega_2^{\ 2} A_2^{\ 2} \cos^2(k_2 x - \omega_2 t + \delta_2).$$

Using the trigonometric relationships:

$$g\eta^2(x,t) = \omega_1^{\ 2} A_1^{\ 2} \sin^2(k_1 x - \omega_1 t + \delta_1) + \omega_2^{\ 2} A_2^{\ 2} \sin^2(k_2 x - \omega_2 t + \delta_2)$$

$$+ \frac{1}{2}\, \omega_1^{\ 2} A_1 A_2 \{\cos[(k_1 - k_2)x - (\omega_1 - \omega_2)t + \delta_1 - \delta_2]$$

$$- \cos[(k_1 + k_2)x - (\omega_1 + \omega_2)t + \delta_1 + \delta_2]\}$$

$$+ \frac{1}{2}\, \omega_2^{\ 2} A_1 A_2 \{\cos[(k_1 - k_2)x - (\omega_1 - \omega_2)t + \delta_1 - \delta_2]$$

$$- \cos[(k_1 + k_2)x - (\omega_1 + \omega_2)t + \delta_1 + \delta_2]\}$$

$$- \frac{1}{2} \{\omega_1^{\ 2} A_1^{\ 2} + \omega_2^{\ 2} A_2^{\ 2}\} - \omega_1 \omega_2 A_1 A_2 \cos[(k_1 - k_2)\, x$$

$$- (\omega_1 - \omega_2)t + \delta_1 - \delta_2].$$

Combining further:

$$g\eta^{(2)}(x,t) = - \frac{1}{2}\, \omega_1^{\ 2} A_1^{\ 2} \cos[2\{k_1 x - \omega_1 t + \delta_1\}]$$

$$- \frac{1}{2}\, \omega_2^{\ 2} A_2^{\ 2} \cos[2\{k_2 x - \omega_2 t + \delta_2\}] \qquad \text{(E-18)}$$

$$- \frac{1}{2} (\omega_1^{\ 2} + \omega_2^{\ 2}) A_1 A_2 \cos[(k_1 + k_2)x - (\omega_1 + \omega_2)t + \delta_1 + \delta_2]$$

$$+ \frac{1}{2} (\omega_1^{\ 2} - 2\omega_1\omega_2 + \omega_2^{\ 2}) A_1 A_2 \cos[(k_1 - k_2)x - (\omega_1 - \omega_2)t + \delta_1 - \delta_2],$$

which is the final form for the second-order term for free-surface elevation.

Now, turn to the equation for pressure which is necessary to compute the force on the body.

Take the pressure to be zero at the free surface. Then Bernoulli's equation may be written:

$$P = -\rho \frac{\partial\phi}{\partial t} - \frac{1}{2}\rho\nabla\phi\cdot\nabla\phi - \rho g y. \tag{E-19}$$

Substituting the expansion for ϕ:

$$P = -\rho\{\varepsilon \frac{\partial\phi^{(1)}}{\partial t} + \varepsilon^2 \frac{\partial\phi^{(2)}}{\partial t} + \frac{1}{2}[\varepsilon^2(\frac{\partial\phi^{(1)}}{\partial x})^2$$

$$+ \varepsilon^2 (\frac{\partial\phi^{(1)}}{\partial y})^2] + gy\} + 0(\varepsilon^3).$$

Since $\phi^{(2)} = 0$, we can drop this term and proceed to separate the equation by order:

$$p^{(1)} = -\rho\frac{\partial\phi^{(1)}}{\partial t} - \rho g y \tag{E-20}$$

and

$$p^{(2)} = -\frac{\rho}{2}[(\frac{\partial\phi^{(1)}}{\partial x})^2 + (\frac{\partial\phi^{(1)}}{\partial y})^2]. \tag{E-21}$$

Substituting the velocity potential into the equation, one finds:

$$p^{(1)} = -\rho g\{A_1 e^{k_1 y} \sin(k_1 x - \omega_1 t + \delta_1)$$

$$+ A_2 e^{k_2 y} \sin(k_2 x - \omega_2 t + \delta_2) + y\} \tag{E-22}$$

for the first order, and

$$p^{(2)} = -\frac{\rho}{2}\{[-\omega_1 A_1 e^{k_1 y} \sin(k_1 x - \omega_1 t + \delta_1)$$

$$- \omega_2 A_2 e^{k_2 y} \sin(k_2 x - \omega_2 t + \delta_2)]^2$$

$$+ [\omega_1 A_1 e^{k_1 y} \cos(k_1 x - \omega_1 t + \delta_1)$$

$$+ \omega_2 A_2 e^{k_2 y} \cos(k_2 x - \omega_2 t + \delta_2)]^2\}$$

for the second order. Note that this is identical to part of the equation for surface elevation. The second-order pressure may be reduced to:

$$p^{(2)} = -\frac{\rho}{2}\{\omega_1^2 A_1^2 e^{2k_1 y} + \omega_2^2 A_2^2 e^{2k_2}-$$

$$- 2\omega_1\omega_2 A_1 A_2 e^{(k_1+k_2)y}\cos[(k_1 - k_2)x - (\omega_1 - \omega_2)t + \delta_1 - \delta_2]\} \quad \text{(E-23)}$$

which indicates that the second-order pressure is composed of a component independent of time and at the "difference frequency".

This is surprising since the equation for the free-surface elevation (eq. 18) includes terms at twice the incident wave frequencies and at the sum of these two frequencies. Using trigonometric relationships the first two terms in equation (E-23) could be expanded to yield terms at twice the incident wave frequency. A term at the sum of the two incident wave frequencies may appear in the pressure computed using the velocity potentials representing wave diffraction or forced oscillation. It might also appear if the present analysis were carried to the third order. The derivation included here was intended to reveal the presence of a low-frequency component in the exciting force and has not been used to determine the other velocity potentials or carried beyond the second order.

3. List of Special Symbols for Appendix E.

A_1, A_2	=	Wave amplitudes
g	=	Acceleration of gravity
k_1, k_2	=	Wave numbers, $\frac{\omega_1^2}{g}$, $\frac{\omega_2^2}{g}$, respectively
x, y	=	Cartesian coordinates (x-directed parallel to the direction of wave propagation, y-directed vertically upward)
δ_1, δ_2	=	Wave phase angles
$\eta(x,t)$	=	Free-surface elevation
$\phi(x,y,t)$	=	Velocity potential
ω_1, ω_2	=	Wave circular frequencies

APPENDIX F

PHYSICAL PROPERTIES OF SEVERAL FLOATING BREAKWATERS

1. Proposed Oak Harbor Floating Breakwater (Davidson, 1971).

a. Physical Properties.

m = mass per unit length = 25.1 slug/ft

I = mass moment of inertia = 621 slug-ft^2/ft

x_g = x-coordinate of center of gravity = 0.0 ft.
(on centerline)

y_g = y-coordinate of center of gravity = -2.34 ft (below WL)

KH_{22} = 64.5 lb/ft/ft

KH_{33} = 1,165 ft-lb/ft

All other KH_{ij} = 0

b. Mooring Line Tension Response (change per unit displacement).

$\frac{\Delta T}{\Delta x}$ = 1,170 lb/ft

$\frac{\Delta T}{\Delta y}$ = 281 lb/ft

$\frac{\Delta T}{\Delta \theta}$ = 1,710 lb

c. Computed Mooring Spring Constants (depth = 29.5 feet)

KM_{11} = 119 lb/ft/ft

KM_{12} = -5.24 lb/ft/ft

KM_{13} = 166 lb/ft

KM_{21} = -5.73 lb/ft/ft

KM_{22} = 10.2 lb/ft/ft

KM_{23} = -3.37 lb/ft

KM_{31} = 160 lb/ft

KM_{32} = 2.06 lb/ft

KM_{33} = 282. ft-lb/ft

Rectangular Breakwater Tested by Nece and Richey (1972).

Physical Properties (at prototype scale). The cross section is a rectangle of beam 10 feet and draft 5 feet.

m = 100 slugs/ft

I = 2,740 slug-ft^2/ft

x_g = 0.0 ft (on centerline)

y_g = -1.0 ft (below WL)

KH_{22} = 640 lb/ft/ft

KH_{33} = 5,340 ft-lb/ft

All other KH_{ij} = 0

All KM_{ij} = 0.

Rectangular Breakwater Tested by Sutko and Haden (1974).

Physical Properties of Model. The cross section is a rectangle of beam 0.333 feet and draft 0.222 feet.

m = 0.143 slug/ft

I = 0.023 slug-ft^2/ft

x_g = 0.0 ft (on centerline)

y_g = -0.123 ft (below WL)

KH_{22} = 20.7 lb/ft/ft

KH_{33} = 0.244 ft-lb/ft

All other KH_{ij} = 0

All KM_{ij} = 0

Alaska-Type Breakwater.

a. PhysicaL Properties.

m = 62.3 slug/ft

I = 4,234 slug-ft/ft

x_g = 0.0 ft

y_g = -1.3 ft (below WL)

KH_{22} = 528 lb/ft/ft

KH_{33} = 32,885 ft-lb/ft

All other KH_{ij} = 0

b. Mooring Line Tension Response (change per unit displacement).

$\frac{\Delta T}{\Delta x}$ = 97.0 lb/ft

$\frac{\Delta T}{\Delta y}$ = 90.5 lb/ft

$\frac{\Delta T}{\Delta \theta}$ = -572 lb

c. Computed Mooring Spring Constants (tide = +7.0 feet).

KM_{11} = 3.0 lb/ft/ft

KM_{12} = 0.245 lb/ft/ft

KM_{13} = -9.23 lb/ft

KM_{21} = 0.302 lb/ft/ft

KM_{22} = 1.91 lb/ft/ft

KM_{23} = -2.68 lb/ft

KM_{31} = -9.52 lb/ft

KM_{32} = -2.82 lb/ft

KM_{33} = 88.9 ft-lb/ft

5. Friday Harbor Breakwater.

a. Physical Properties.

m = 61.02 slugs/ft

I = 4,160 slugs-ft^3/ft

x_g = 0.0 ft (on centerline)

y_g = -0.49 ft (below WL)

KH_{22} = 884 lb/ft/ft

KH_{33} = 55,610 ft-lb/ft

All other KH_{ij} = 0

b. Mooring Line Tension Response.

$\frac{\Delta T}{\Delta x}$ = 222 lb/ft

$\frac{\Delta T}{\Delta y}$ = 25.0 lb/ft

$\frac{\Delta T}{\Delta \theta}$ = 657 lb

c. Computed Mooring Spring Constants (tide = +5.33 feet).

KM_{11} = 6.46 lb/ft/ft

KM_{12} = 0.510 lb/ft/ft

KM_{13} = 18.5 ft-lb/ft/ft

KM_{21} = 0.510 lb/ft/ft

KM_{22} = 0.390 lb/ft/ft

KM_{23} = 1.71 ft-lb/ft/ft

KM_{31} = 18.6 lb/ft

KM_{32} = 1.71 lb/ft

KM_{33} = 64.6 ft-lb/ft

APPENDIX G

DATA SUMMARY SHEETS FOR FRIDAY HARBOR FLOATING BREAKWATER (WINTER 1975)

Appendix G contains a summary of all the data recorded at the Friday Harbor breakwater during the winter season of 1975. Seven tapes were recorded during this period, with a total of 95 records. The tapes are numbered in sequence from FH7-1 through FH13-8. The date of each tape is given along with the pertinent statistical data for each record in the tapes. The number of days and hours given for each record begins with the day and hour given for that particular tape.

All minimum and maximum values are measured from zero mean. The transmitted wave data were digitally high-pass filtered (cutoff frequency was 0.05 hertz) before these calculations to remove tidal draft.

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH7 - 1330 - 12/30/74)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	SW	NE	SE	WAVE GAGES TRAN 1	TRAN 2	INC.	REF.	ACCELEROMETERS N.VER.	HOR.	S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX,	2.8	58.1	39.10	30.90	31.92	17.55	.113	.110	.297	.209	.219	.105	.266
1	0	.45	MIN.	-2.1	-57.4	-20.90	-33.10	-16.08	-18.79	-.137	-.133	-.317	-.226	-.159	-.109	-.242
	0		MEAN	2.1	109.9	.00	981.12	856.26	959.38	6.938	7.226	4.118	4.539	13.121	13.399	13.102
			STDEV	1.06	27.87	9.155	9.811	7.016	6.077	.0385	.0367	.0848	.0505	.0445	.0218	.0574
			MAX,	8.1	60.7	57.90	161.55	42.34	96.34	.167	.181	.742	.695	.317	.289	.408
2	2	.35	MIN.	-11.2	-65.3	-78.10	-110.45	-37.66	-60.62	-.176	-.296	-.487	-.457	-.334	-.246	-.523
	20		MEAN	14.1	180.3	.00	1181.83	930.07	11370.02	7.630	7.509	4.058	4.643	13.483	13.698	13.044
			STDEV	3.62	14.27	24.055	51.877	14.026	30.339	.0534	.0558	.1519	.1622	.0869	.0666	.1127
			MAX,	13.2	93.2	75.58	325.98	66.36	193.09	.135	.128	.766	.806	.386	.268	.500
3	2	.27	MIN.	-7.7	-95.8	-12.42	-174.02	-53.64	-84.99	-.153	-.162	-.540	-.577	-.307	-.299	-.430
	21		MEAN	17.6	178.5	55.01	1161.24	867.82	1025.22	5.990	5.834	4.034	4.634	13.268	13.686	13.035
			STDEV	3.27	19.63	16.689	65.078	13.839	38.205	.0444	.0469	.1626	.1842	.0788	.0734	.1156
			MAX,	11.8	51.7	75.58	445.25	43.05	278.10	.205	.205	.823	.997	.334	.273	.507
4	3	.39	MIN.	-9.7	-116.3	-12.42	-182.75	-40.95	-112.16	-.196	-.176	-.559	-.539	-.338	-.347	-.593
	0		MEAN	21.6	178.7	1.63	1075.80	759.38	1027.13	5.174	4.994	4.080	4.648	13.431	13.548	13.029
			STDEV	3.93	24.09	.000	89.072	14.051	55.777	.0663	.0673	.1715	.2035	.0920	.0806	.1317
			MAX,	14.1	61.9	15.65	333.14	47.80	221.93	.183	.204	.778	.831	.206	.204	.423
5	3	.34	MIN.	-9.6	-95.6	-.35	-226.86	-60.20	-128.83	-.172	-.156	-.502	-.500	-.256	-.181	-.423
	1		MEAN	20.5	189.5	3.08	1069.49	719.23	952.61	5.093	4.908	4.150	4.609	13.227	13.681	13.028
			STDEV	3.91	19.78	2.057	97.282	16.930	61.033	.0567	.0598	.1687	.1721	.0701	.0626	.1032
			MAX,	8.2	57.2	40.51	156.49	23.37	90.27	.093	.137	.802	.856	.342	.297	.571
6	5	.19	MIN.	-5.6	-68.8	-35.49	-95.51	-36.63	-47.19	-.113	-.107	-.452	-.501	-.330	-.249	-.444
	9		MEAN	16.2	172.9	120.45	990.82	874.81	904.88	5.526	5.300	4.024	4.635	13.463	13.743	12.965
			STDEV	2.89	14.72	18.688	50.922	11.194	27.538	.0328	.0334	.1743	.1797	.0986	.0743	.1170

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH7 - 1330 - 12/30/74)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	SW	NE	SE	WAVE GAGES TRAN 1	TRAN 2	INC.	REF.	ACCELEROMETERS N.VER.	HOR.	S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX,	12.7	70.3	51.65	259.79	50.95	162.78	.134	.181	1.047	1.182	.768	.731	1.587
7	5	.18	MIN.	-8.1	-150.2	-4.35	-212.21	-49.05	-112.14	-.138	-.140	-.643	-.917	-.828	-.917	-1.290
	10		MEAN	22.9	150.2	.00	1181.21	810.04	1104.56	5.670	5.452	4.035	4.668	13.223	13.720	12.965
			STDEV	3.50	37.11	10.657	82.997	14.872	46.791	.0395	.0422	.2216	.2427	.2034	.1959	.3221
			MAX,	6.8	27.0	7.84	291.23	37.67	173.79	.157	.137	1.188	1.457	.769	.660	1.925
8	5	.16	MIN.	-6.1	-67.5	-.16	-204.77	-42.33	-116.93	-.186	-.199	-.732	-.847	-.743	-.667	-1.797
	11		MEAN	22.8	160.9	.00	1143.02	733.83	1147.23	5.440	5.220	4.047	4.674	13.387	13.910	12.964
			STDEV	2.89	14.06	1.003	86.332	13.652	48.214	.0411	.0446	.2521	.2939	.1984	.1875	.3902
			MAX,	12.4	47.8	7.79	362.35	34.46	197.82	.161	.142	.961	1.043	.498	.542	.747
9	5	.20	MIN.	-8.1	-109.7	-.21	-177.65	-33.54	-107.12	-.159	-.170	-.550	-.596	-.636	-.357	-.860
	12		MEAN	22.3	161.4	.00	1094.26	804.04	1087.69	5.279	5.062	4.044	4.655	13.274	13.822	12.957
			STDEV	3.27	23.39	1.128	80.256	12.471	47.411	.0428	.0433	.2111	.2186	.1412	.1118	.1840
			MAX,	11.5	62.5	26.40	397.52	48.77	283.36	.248	.221	.962	1.086	.474	.401	.662
10	5	.24	MIN.	-8.4	-126.5	-1.60	-238.48	-47.23	-127.44	-.167	-.170	-.626	-.604	-.471	-.380	-.776
	13		MEAN	22.5	167.7	.00	1196.93	732.67	1176.63	5.514	5.305	4.094	4.687	13.221	13.836	12.959
			STDEV	4.83	24.85	5.188	131.584	19.011	82.184	.0481	.0510	.2037	.2414	.1242	.1006	.1763
			MAX,	13.4	58.3	88.55	305.94	43.06	195.54	.163	.148	.904	.931	.322	.306	.656
11	5	.26	MIN.	-11.0	-88.7	-19.45	-214.06	-44.94	-110.98	-.183	-.155	-.504	-.529	-.308	-.272	-.444
	14		MEAN	20.3	171.6	.00	1143.02	808.64	1102.61	3.196	6.015	4.102	4.689	13.257	13.767	12.965
			STDEV	4.24	17.36	20.866	86.769	15.340	52.033	.0483	.0486	.1891	.2138	.1000	.0821	.1344
			MAX,	13.1	54.1	72.79	306.05	41.58	191.57	.189	.186	.636	.603	.280	.266	.318
12	5	.44	MIN.	-7.1	-82.4	-99.21	-117.95	-86.42	-70.71	-.169	-.163	-.439	-.549	-.245	-.162	-.274
	15		MEAN	17.7	175.7	175.31	1036.93	826.09	1015.94	7.264	7.108	4.062	4.683	13.227	13.729	12.965
			STDEV	3.84	16.70	34.384	62.609	19.570	38.895	.0639	.0638	.1440	.1499	.0708	.0608	.0940

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH7 - 1330 - 12/30/74)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP. (MPH)	WIND DIR. (DEG.)	LOAD CELLS NW (LBS)	SW (LBS)	NE (LBS)	SE (LBS)	WAVE GAGES TRAN 1 (FT.)	TRAN 2 (FT.)	INC. (FT.)	REF. (FT.)	ACCELEROMETERS (FT/SEC/SEC) N.VER.	HOR.	S.VER.
			MAX,	8.5	43.2	46.32	199.03	39.26	130.43	.111	.117	.663	.733	.270	.276	.454
13	7	.21	MIN.	-6.3	-61.8	-101.68	-104.97	-60.74	-127.11	-.122	-.128	-.437	-.496	-.276	-.248	-.477
	21		MEAN	17.5	156.1	287.74	1299.86	983.14	1305.05	9.195	9.069	4.060	4.656	13.440	13.836	12.913
			STDEV	2.21	13.55	20.978	39.646	14.441	26.267	.0320	.0335	.1494	.1655	.0790	.0737	.1114
			MAX,	6.7	41.6	66.11	173.65	37.35	116.29	.150	.151	.768	.864	.420	.365	.795
14	7	.30	MIN.	-5.5	-84.4	-77.89	-86.35	-50.65	-55.93	-.378	-.434	-.512	-.544	-.420	-.320	-.728
	22		MEAN	18.3	147.0	200.76	1209.88	844.27	1185.52	8.776	8.652	4.160	4.730	13.316	13.779	12.910
			STDEV	2.41	18.08	21.201	40.827	12.534	24.107	.0493	.0520	.1670	.1955	.1123	.1027	.1617
			MAX,	8.1	54.2	108.73	195.61	57.30	109.47	.183	.231	.747	.669	.373	.288	.456
15	8	.44	MIN.	-4.4	-103.3	-67.27	-148.39	-38.70	-78.55	-.205	-.223	-.456	-.457	-.383	-.322	-.390
	0		MEAN	18.9	124.3	.00	1192.50	822.80	1022.38	7.214	7.056	7.027	4.643	13.274	13.617	12.911
			STDEV	2.05	27.92	24.710	54.314	14.292	31.875	.0714	.0759	.1630	.1816	.1051	.0865	.1330
			MAX,	12.6	39.2	33.70	328.02	44.49	193.38	.213	.233	.845	.877	.455	.396	.627
16	8	.51	MIN.	-7.0	-86.8	-2.30	-187.98	-47.51	-106.82	-.233	-.233	-.461	-.454	-.553	-.417	-.727
	1		MEAN	20.5	149.1	.00	1084.30	801.94	1070.00	5.437	5.227	4.057	4.640	13.228	13.868	12.909
			STDEV	3.39	18.73	6.606	82.334	15.615	49.404	.0868	.0903	.1713	.1993	.1205	.1025	.1574
			MAX,	9.2	34.8	33.70	224.20	38.81	118.01	.197	.171	.666	.659	.398	.334	.547
17	8	.44	MIN.	-6.8	-59.7	-2.30	-147.80	-25.19	-74.75	-.206	-.208	-.435	-.519	-.421	-.372	-.552
	3		MEAN	20.0	164.1	.00	1082.30	748.74	918.50	3.663	3.397	4.006	4.602	13.368	13.649	12.905
			STDEV	2.99	12.01	.000	71.200	9.615	36.055	.0692	.0717	.1587	.1730	.0909	.0795	.1218
			MAX,	8.3	56.8	33.70	162.23	20.87	93.13	.177	.139	.634	.612	.199	.195	.210
18	8	.31	MIN.	-7.2	-79.7	-2.30	-117.77	-27.13	-44.33	-.123	-.115	-.390	-.412	-.179	-.158	-.297
	4		MEAN	14.5	183.5	.00	913.56	721.19	697.64	2.339	2.040	4.013	4.547	13.342	13.626	12.903
			STDEV	3.26	15.83	.000	47.441	7.594	21.849	.0429	.0434	.1401	.1333	.0462	.0400	.0715

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH7 - 1330 - 12/30/74)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	SW	NE	SE	WAVE GAGES TRAN 1	TRAN 2	INC.	REF.	ACCELEROMETERS N.VER.	HOR.	S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX,	9.1	51.0	54.07	157.81	35.50	78.93	.262	.234	.644	.660	.283	.241	.488
19	8	.55	MIN.	-6.7	-64.5	-49.93	-182.19	-68.50	-66.43	-.176	-.179	-.405	-.440	-.305	-.209	-.527
	8		MEAN	14.7	179.4	117.10	956.60	848.57	789.76	5.050	4.829	4.105	4.677	13.361	13.744	12.879
			STDEV	3.01	13.88	21.840	41.588	14.847	20.752	.0837	.0845	.1515	.1669	.0908	.0640	.1067
			MAX,	1.4	38.4	23.66	216.09	98.24	69.67	.083	.380	.179	.162	.184	.111	.177
20	0	.46	MIN.	-1.8	-245.1	-.34	-15.91	-17.76	-36.19	-.070	-.140	-.128	-.171	-.488	-.061	-.246
	0		MEAN	2.9	245.1	.00	799.53	787.14	581.92	1.881	1.619	3.880	4.511	13.546	13.820	12.939
			STDEV	.64	57.29	2.534	16.865	20.600	11.112	.0170	.0303	.0369	.0475	.1152	.0143	.0511

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FHB - 2400 - 1/8/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	SW	NE	SE	WAVE GAGES TRAN 1	TRAN 2	INC.	REF.	ACCELEROMETERS N.VER.	HOR.	S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX,	1.8	32.9	24.96	49.37	80.24	8.72	.113	.109	.146	.078	.250	.089	.181
1	0	.19	MIN.	-2.1	-325.1	-107.04	-14.63	-15.76	-49.74	-.109	-.099	-.110	-.076	-.087	-.081	-.073
	0		MEAN	2.4	325.1	5099.04	761.01	794.73	4646.24	4.054	4.194	4.116	4.492	13.347	13.410	12.932
			STDEV	.79	65.65	23.966	10.425	16.246	10.748	.0075	.0073	.0407	.0235	.0963	.0446	.0535
			MAX,	8.9	37.3	55.20	300.52	24.71	154.79	.102	.086	.607	.751	.357	.311	.363
2	2	.17	MIN.	-6.8	-66.7	-76.80	-119.48	-27.29	-56.93	-.199	-.183	-.366	-.580	-.316	-.283	-.399
	18		MEAN	18.0	157.3	676.80	911.50	695.29	920.16	2.412	2.611	4.091	4.536	13.209	13.527	12.835
			STDEV	3.12	15.47	24.306	66.479	9.749	31.996	.0236	.0235	.1361	.1536	.1107	.0815	.0950
			MAX,	10.6	38.1	50.88	322.56	29.33	172.25	.097	.106	.701	.879	.358	.391	.619
3	2	.17	MIN.	-6.4	-70.8	-57.12	-201.44	-30.67	-94.77	-.093	-.097	-.451	-.606	-.484	-.288	-.565
	19		MEAN	20.2	165.3	625.12	917.44	666.67	987.93	.579	.826	4.049	4.433	13.209	13.532	12.833
			STDEV	3.17	13.98	19.813	99.539	11.028	53.237	.0266	.0269	.1607	.2025	.1411	.1017	.1393
			MAX,	13.6	48.1	48.64	660.25	26.83	382.88	.130	.094	.634	.903	.359	.374	.453
4	2	.19	MIN.	-10.5	-72.3	-71.36	-199.75	-45.17	-94.28	-.090	-.092	-.416	-.556	-.315	-.305	-.393
	20		MEAN	20.1	177.5	607.36	859.75	657.17	910.68	-.555	-.252	3.936	4.384	13.208	13.549	12.829
			STDEV	4.75	14.76	22.521	141.836	13.626	76.751	.0277	.0256	.1428	.1856	.1157	.0867	.1096
			MAX,	8.9	35.9	44.31	223.88	20.04	119.70	.078	.061	.576	.548	.362	.186	.284
5	2	.16	MIN.	-6.5	-77.9	-55.69	-124.12	-23.96	-55.68	-.062	-.060	-.448	-.476	-.311	-.154	-.223
	22		MEAN	17.1	171.8	623.69	808.12	675.96	812.97	-.073	.219	3.942	4.405	13.206	13.568	12.829
			STDEV	2.95	15.10	17.970	67.053	8.112	32.891	.0196	.0188	.1237	.1343	.1006	.0680	.0734
			MAX,	11.7	103.1	67.31	231.71	33.52	121.87	.174	.159	.618	.733	.372	.571	.794
6	2	.24	MIN.	-8.2	-94.0	-56.69	-104.29	-34.48	-42.45	-.245	-.239	-.534	-.650	-.470	-.532	-.898
	23		MEAN	15.6	191.5	704.69	804.29	726.48	779.46	2.223	2.427	4.105	4.426	13.201	13.522	12.826
			STDEV	3.08	20.09	22.001	53.054	11.192	24.474	.0400	.0367	.1676	.1853	.1398	.1212	.1840

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH9 - 2400 - 1/8/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP. MPH	WIND DIR. DEG.	LOAD CELLS NW LBS	SW LBS	NE LBS	SE LBS	WAVE GAGES TRAN 1 FT.	TRAN 2 FT.	INC. FT.	REF. FT.	ACCELEROMETERS (FT/SEC/SEC) N.VER.	HOR.	S.VER.
			MAX,	9.0	55.8	51.01	187.16	28.92	99.72	.136	.134	.637	.688	.427	.178	.278
1	13	.18	MIN.	-7.7	-71.2	-72.99	-104.84	-31.08	-53.54	-.134	-.142	-.361	-.387	-.246	-.162	-.314
	23		MEAN	16.7	191.3	832.60	935.54	758.91	820.28	5.236	5.378	4.034	5.033	13.174	13.831	12.834
			STDEV	3.49	14.92	18.110	50.773	9.177	27.526	.0245	.0246	.1348	.1455	.1042	.0650	.0824
			MAX,	7.1	52.9	36.08	72.69	35.36	47.05	.069	.062	.622	.569	.471	.286	.448
2	21	.15	MIN.	-5.7	-148.4	-39.92	-63.31	-28.64	-41.43	-.080	-.071	-.376	-.378	-.371	-.308	-.398
	7		MEAN	16.3	148.4	1031.91	1215.33	896.63	1292.90	9.180	9.141	4.204	5.152	13.321	13.892	12.919
			STDEV	2.37	40.81	13.179	23.756	10.432	15.784	.0207	.0197	.1364	.1379	.1301	.0907	.1158
			MAX,	6.1	148.8	36.96	132.15	25.85	81.35	.073	.063	.632	.571	.311	.201	.280
3	21	.15	MIN.	-5.7	-44.2	-51.04	-83.85	-30.15	-40.31	-.059	-.075	-.366	-.402	-.194	-.224	-.313
	10		MEAN	15.7	44.2	855.13	1027.85	782.20	10180.04	6.147	6.223	4.040	5.023	13.316	13.893	12.918
			STDEV	2.64	44.14	14.533	36.725	8.396	19.000	.0202	.0192	.1358	.1366	.1077	.0711	.0836
			MAX,	6.9	194.1	48.88	159.88	21.54	79.51	.058	.057	.692	.691	.312	.274	.286
4	21	.12	MIN.	-8.5	-36.9	-59.12	-112.12	-22.46	-51.63	-.069	-.063	-.383	-.461	-.362	-.235	-.306
	11		MEAN	17.8	36.9	767.12	1012.12	730.46	958.72	4.489	4.634	4.108	5.005	13.316	13.904	12.912
			STDEV	2.94	45.71	19.735	50.283	7.926	23.144	.0176	.0174	.1429	.1657	.1036	.0753	.0850
			MAX,	6.7	167.7	55.14	142.96	18.76	70.82	.094	.085	1.054	.641	.294	.270	.289
5	21	.10	MIN.	-5.9	-23.7	-56.86	-141.04	-21.24	-46.10	-.071	-.063	-.533	-.357	-.211	-.239	-.303
	14		MEAN	17.7	23.7	788.86	1009.04	737.24	964.70	4.703	4.841	4.207	4.979	13.325	13.908	12.909
			STDEV	2.57	34.64	17.808	45.376	7.724	22.556	.0205	.0190	.2137	.1405	.1021	.0753	.0795
			MAX,	7.5	172.1	54.69	173.78	28.03	91.16	.080	.064	.735	.604	.297	.264	.459
6	21	.15	MIN.	-6.7	-24.2	-69.31	-118.22	-27.97	-58.94	-.095	-.085	-.468	-.420	-.377	-.330	-.387
	15		MEAN	19.5	24.2	813.31	1062.22	747.97	1045.21	5.441	5.553	4.091	5.015	13.324	13.914	12.908
			STDEV	3.13	38.42	21.681	51.506	10.536	27.655	.0225	.0225	.1540	.1765	.1166	.0881	.1058

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH9 - 2400 - 1/8/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP. (MPH)	WIND DIR. (DEG.)	LOAD CELLS NW (LBS)	LOAD CELLS SW (LBS)	LOAD CELLS NE (LBS)	LOAD CELLS SE (LBS)	WAVE GAGES TRAN 1 (FT.)	WAVE GAGES TRAN 2 (FT.)	WAVE GAGES INC. (FT.)	WAVE GAGES REF. (FT.)	ACCELEROMETERS N.VER. (FT/SEC/SEC)	ACCELEROMETERS HOR. (FT/SEC/SEC)	ACCELEROMETERS S.VER. (FT/SEC/SEC)
			MAX,	7.9	165.3	45.00	99.02	29.56	52.12	.087	.106	.769	.781	.477	.441	.542
7	21	.14	MIN.	-5.3	-31.1	-51.00	-88.98	-30.44	-49.00	-.077	-.078	-.511	-.499	-.534	-.408	-.474
	16		MEAN	17.2	31.1	895.00	1072.98	798.44	1058.05	6.728	6.784	4.083	5.068	13.318	13.907	12.910
			STDEV	2.65	41.20	19.174	38.806	10.916	20.378	.0242	.0236	.1680	.1849	.1527	.1186	.1530
			MAX,	10.0	169.6	45.43	141.36	32.55	92.04	.112	.099	.944	.866	.646	.441	.713
8	21	.16	MIN.	-6.7	-23.4	-62.57	-82.64	-43.45	-58.06	-.097	-.133	-.592	-.618	-.533	-.408	-.725
	17		MEAN	18.6	23.4	938.57	1164.64	827.45	1170.98	7.614	7.642	4.291	5.162	13.317	13.907	12.908
			STDEV	3.08	35.43	19.020	40.774	13.595	25.726	.0303	.0301	.1949	.2155	.1575	.1246	.1770
			MAX,	6.5	163.9	38.76	111.78	26.36	73.25	.087	.096	.805	.726	.473	.361	.543
9	21	.16	MIN.	-5.4	-20.9	-41.24	-68.22	-33.64	-38.93	-.098	-.084	-.450	-.554	-.537	-.488	-.641
	18		MEAN	17.3	20.9	929.24	1168.22	817.64	1138.55	7.364	7.408	4.098	5.072	13.320	13.902	12.908
			STDEV	2.48	33.17	13.796	30.255	8.942	17.901	.0262	.0242	.1631	.1744	.1443	.1134	.1540
			MAX,	5.9	162.8	57.93	142.37	29.72	82.58	.104	.094	.695	.914	.639	.444	.878
10	21	.17	MIN.	-6.0	-25.3	-50.07	-113.63	-30.28	-53.30	-.096	-.105	-.508	-.571	-.539	-.575	-.814
	19		MEAN	18.2	25.3	870.87	1073.65	782.28	1086.94	6.436	6.510	4.054	5.039	13.321	13.904	12.911
			STDEV	2.29	37.61	16.768	42.001	10.086	24.075	.0293	.0305	.1716	.2082	.1683	.1454	.2101
			MAX,	6.9	143.6	55.55	198.81	27.28	105.90	.111	.138	.909	1.104	.814	.603	1.048
11	21	.19	MIN.	-5.7	-16.5	-64.45	-141.19	-24.72	-71.06	-.120	-.107	-.474	-.688	-.870	-.671	-1.067
	21		MEAN	21.7	17.2	772.45	1093.19	724.72	1107.90	4.855	4.993	4.096	5.052	13.317	13.915	12.910
			STDEV	2.69	28.57	21.662	56.483	9.020	32.725	.0349	.0358	.1829	.2278	.1860	.1549	.2169
			MAX,	8.2	111.7	61.49	242.35	20.76	129.85	.115	.098	.926	.863	.647	.438	.708
12	21	.16	MIN.	-10.7	-12.1	-62.51	-193.65	-31.24	-85.03	-.118	-.099	-.585	-.750	-.532	-.496	-.646
	22		MEAN	22.3	13.9	714.51	1017.65	699.24	1015.28	3.187	3.383	4.131	4.987	13.317	13.910	12.912
			STDEV	3.37	20.24	18.393	73.711	8.438	38.399	.0309	.0306	.1899	.2173	.1530	.1281	.1737

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH9 - 2400 - 1/8/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP. MPH	WIND DIR. DEG.	LOAD CELLS NW LBS	SW LBS	NE LBS	SE LBS	WAVE GAGES TRAN 1 FT.	TRAN 2 FT.	INC. FT.	REF. FT.	ACCELEROMETERS (FT/SEC/SEC) N.VER.	HOR.	S.VER.
			MAX,	9.0	110.6	41.47	222.02	16.95	119.11	.090	.101	.725	.949	.474	.359	.627
13	21	.16	MIN.	-6.7	-11.5	-54.53	-113.98	-27.05	-54.69	-.100	-.100	-.478	-.536	-.536	-.320	-.473
	23		MEAN	20.2	13.0	702.53	929.98	687.05	898.45	2.111	2.348	4.024	4.952	13.319	13.904	12.909
			STDEV	2.77	20.10	16.287	62.127	7.077	29.598	.0269	.0259	.1707	.1959	.1262	.1071	.1322
			MAX,	10.6	158.9	41.79	292.93	23.93	142.02	.116	.095	.900	.746	.475	.356	.539
14	21	.15	MIN.	-6.4	-19.3	-66.21	-163.07	-28.07	-90.24	-.089	-.092	-.610	-.687	-.367	-.323	-.561
	24		MEAN	21.2	19.3	698.21	967.07	686.07	952.44	2.240	2.473	4.054	4.951	13.319	13.907	12.912
			STDEV	3.59	33.11	17.753	76.333	8.323	38.727	.0281	.0282	.1822	.1940	.1358	.1112	.1399
			MAX,	7.9	47.9	65.96	212.45	22.99	114.64	.073	.102	.756	.697	.473	.271	.370
15	22	.16	MIN.	-7.5	-4.9	-58.04	-139.55	-29.01	-62.32	-.113	-.103	-.447	-.455	-.369	-.238	-.391
	1		MEAN	20.1	6.6	742.04	947.55	709.01	921.77	3.034	3.242	4.054	4.973	13.320	13.907	12.912
			STDEV	3.27	8.58	26.975	68.463	11.023	33.782	.0258	.0260	.1579	.1685	.1125	.0824	.0997
			MAX,	8.6	170.7	38.09	98.72	35.68	64.33	.074	.064	.456	.559	.306	.280	.452
16	22	.15	MIN.	-6.2	-25.6	-57.91	-65.28	-44.32	-43.11	-.081	-.056	-.363	-.388	-.368	-.314	-.394
	7		MEAN	14.2	25.6	1105.91	1241.28	936.32	1305.14	9.807	9.745	4.113	5.060	13.319	13.898	12.915
			STDEV	3.12	47.24	18.338	31.378	16.039	21.074	.0182	.0181	.1228	.1336	.1086	.0791	.1032
			MAX,	8.3	189.4	49.89	121.44	43.84	76.55	.080	.062	.629	.703	.302	.264	.279
17	22	.16	MIN.	-6.4	-18.5	-62.11	-78.56	-52.16	-53.01	-.079	-.076	-.369	-.500	-.372	-.245	-.313
	8		MEAN	17.4	18.5	1074.11	1266.56	904.16	1358.19	9.711	9.656	4.095	5.044	13.321	13.914	12.918
			STDEV	3.14	38.72	20.233	38.920	16.823	25.271	.0213	.0206	.1298	.1511	.1143	.0757	.0920
			MAX,	10.5	187.0	47.56	240.43	27.45	148.56	.064	.069	.631	.644	.472	.257	.370
18	22	.15	MIN.	-8.1	-25.8	-88.44	-99.57	-36.55	-53.68	-.083	-.090	-.393	-.431	-.202	-.338	-.307
	10		MEAN	18.4	25.8	880.44	1067.57	756.55	1047.89	6.175	6.272	4.093	5.027	13.320	13.922	12.912
			STDEV	3.32	43.71	21.148	55.706	11.080	32.035	.0206	.0209	.1412	.1585	.1090	.0785	.0927

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH9 - 2400 - 1/8/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	LOAD CELLS SW	LOAD CELLS NE	LOAD CELLS SE	WAVE GAGES TRAN 1	WAVE GAGES TRAN 2	WAVE GAGES INC.	WAVE GAGES REF.	ACCELEROMETERS N.VER.	ACCELEROMETERS HOR.	ACCELEROMETERS S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX,	7.8	148.8	62.45	164.06	26.25	94.19	.077	.075	.779	.693	.488	.342	.460
19	22	.14	MIN.	-6.3	-14.6	-57.55	-123.94	-21.75	-62.23	-.074	-.083	-.398	-.485	-.354	-.252	-.470
	13		MEAN	18.8	15.7	813.55	999.94	729.75	953.55	4.658	4.816	4.072	5.003	13.312	13.921	12.907
			STDEV	2.77	28.91	21.472	50.908	8.997	26.494	.0227	.0220	.1583	.1758	.1145	.0856	.1067
			MAX,	7.3	173.6	40.32	130.44	14.50	61.50	.048	.053	.553	.524	.315	.182	.205
20	22	.14	MIN.	-7.4	-16.1	-59.68	-69.56	-21.50	-26.98	-.053	-.058	-.318	-.346	-.190	-.243	-.218
	14		MEAN	15.5	16.3	819.68	921.56	733.50	856.29	4.129	4.298	4.017	4.967	13.315	13.912	12.908
			STDEV	2.87	36.97	16.001	33.948	6.131	14.763	.0169	.0158	.1181	.1200	.0960	.0641	.0711
			MAX,	6.2	170.3	39.14	92.39	21.00	37.50	.070	.067	.434	.583	.300	.261	.200
21	22	.15	MIN.	-5.4	-26.0	-44.86	-83.61	-19.00	-32.02	-.057	-.059	-.334	-.339	-.205	-.248	-.307
	16		MEAN	16.3	26.0	860.86	971.61	755.00	921.06	5.022	5.165	4.033	4.960	13.322	13.917	12.913
			STDEV	2.33	40.57	14.684	32.971	6.941	15.069	.0166	.0157	.1082	.1203	.0874	.0672	.0675
			MAX,	6.8	171.5	43.29	109.51	22.46	57.98	.096	.080	.690	.743	.634	.429	.538
22	22	.15	MIN.	-6.1	-23.2	-44.71	-110.49	-25.54	-52.62	-.094	-.069	-.411	-.614	-.376	-.250	-.478
	17		MEAN	17.9	23.2	904.71	1058.49	785.54	1049.22	6.298	6.388	4.058	5.055	13.323	13.919	12.913
			STDEV	2.47	40.66	14.200	32.860	8.144	17.977	.0240	.0228	.1588	.1750	.1368	.0874	.1169
			MAX,	11.5	139.6	59.44	237.32	45.55	150.06	.093	.106	.861	1.029	.632	.423	.537
23	22	.15	MIN.	-8.7	-81.5	-88.56	-146.68	-46.45	-80.62	-.104	-.092	-.444	-.737	-.715	-.426	-.732
	18		MEAN	20.3	81.5	924.56	1130.88	790.45	1144.09	7.105	7.168	4.143	5.102	13.324	13.926	12.915
			STDEV	3.32	65.59	24.902	62.139	14.784	36.615	.0282	.0299	.1943	.2164	.1493	.1134	.1532
			MAX,	9.7	57.9	56.46	222.09	32.20	136.19	.103	.123	.904	1.126	.629	.432	.960
24	22	.15	MIN.	-7.0	-159.9	-87.54	-133.91	-43.80	-64.47	-.118	-.128	-.606	-.922	-.718	-.587	-.901
	19		MEAN	18.9	159.9	939.54	1125.91	795.80	1151.21	7.261	7.309	4.101	5.108	13.326	13.916	12.915
			STDEV	3.46	41.48	21.917	54.967	13.017	32.035	.0341	.0360	.2233	.2373	.1563	.1303	.2024

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH9 - 2400 - 1/8/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	LOAD CELLS SW	LOAD CELLS NE	LOAD CELLS SE	WAVE GAGES TRAN 1	WAVE GAGES TRAN 2	WAVE GAGES INC.	WAVE GAGES REF.	ACCELEROMETERS N.VER.	ACCELEROMETERS HOR.	ACCELEROMETERS S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX.	7.6	31.9	61.65	135.64	36.11	80.27	.078	.101	.733	.947	.795	.775	1.210
25	22 20	.11	MIN.	-6.8	-103.4	-46.35	-132.36	-27.89	-71.41	-.060	-.088	-.598	-.589	-.552	-.838	-1.159
			MEAN	20.0	160.3	918.35	1120.36	783.89	1140.79	6.934	6.990	4.093	5.082	13.327	13.913	12.918
			STDEV	2.41	20.23	18.545	46.342	10.659	27.186	.0215	.0234	.1992	.2218	.2070	.1984	.2826

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH10 - 1345 - 2/9/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP. MPH	WIND DIR. DEG.	LOAD CELLS NW LBS	SW LBS	NE LBS	SE LBS	WAVE GAGES TRAN 1 FT.	TRAN 2 FT.	INC. FT.	REF. FT.	ACCELEROMETERS (FT/SEC/SEC) N.VER.	HOR.	S.VER.
			MAX,	3.9	54.4	10.24	10.75	9.29	9.15	.072	.075	.155	.115	.156	.159	.165
1	0	.52	MIN.	-2.2	-176.6	-23.93	-19.79	-15.51	-17.71	-.157	-.154	-.152	-.130	-.349	-.197	-.089
	0		MEAN	3.5	184.9	1132.65	1108.29	930.21	1035.99	8.611	8.653	3.980	4.965	13.310	13.848	12.948
			STDEV	.86	37.62	3.957	5.271	3.182	3.632	.0174	.0148	.0333	.0266	.0778	.0417	.0443
			MAX,	9.1	63.6	94.83	168.74	67.48	73.97	.497	.558	.835	.753	.560	.415	.539
2	2	.25	MIN.	-13.7	-99.7	-91.17	-111.26	-48.08	-50.85	-.301	-.213	-.547	-.527	-.450	-.519	-.561
	11		MEAN	15.0	188.0	995.47	951.26	816.33	848.72	5.722	5.834	4.425	5.378	13.444	13.933	12.998
			STDEV	3.72	19.53	24.742	50.725	15.561	22.265	.0485	.0460	.1912	.1939	.1360	.1119	.1480
			MAX,	8.9	47.9	52.32	197.75	54.18	129.15	.137	.128	.799	.907	.448	.326	.500
3	5	.24	MIN.	-6.5	-61.0	-67.68	-206.25	-33.82	-150.51	-.380	-.329	-.379	-.501	-.394	-.351	-.431
	19		MEAN	14.8	181.0	892.12	1102.25	789.82	1161.04	6.747	6.819	4.078	5.045	13.416	13.935	13.035
			STDEV	2.54	12.26	21.037	61.374	11.987	36.717	.0386	.0398	.1621	.1884	.1355	.0974	.1139
			MAX,	11.8	45.3	93.12	389.26	43.28	208.18	.124	.113	.717	.880	.453	.239	.420
4	5	.23	MIN.	-7.4	-63.6	-106.88	-170.74	-40.72	-84.12	-.112	-.113	-.358	-.604	-.389	-.270	-.342
	21		MEAN	16.4	178.2	739.13	1039.06	791.55	973.00	4.355	4.606	3.981	4.969	13.414	13.939	13.032
			STDEV	3.30	12.02	27.303	78.380	11.272	42.955	.0350	.0363	.1519	.2194	.1165	.0855	.1063

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH11 - 0900 - 3/1/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	SW	NE	SE	WAVE GAGES TRAN 1	TRAN 2	INC.	REF.	ACCELEROMETERS N.VER.	HOR.	S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX,	2.4	128.3	4325.99	8340.80	120.04	19.86	1.604	7.637	.274	.309	.135	.087	.166
1	0	5.09	MIN.	-3.1	-53.2	-36.01	-71.09	-22.68	-56.34	-5.417	-25.254	-.213	-.213	-.314	-.339	-.292
	0		MEAN	3.1	139.2	1669.67	2156.21	962.04	1082.58	7.584	4.338	3.993	5.063	5.066	5.259	5.069
			STDEV	1.30	28.78	187.585	361.436	8.115	7.520	.2352	1.0975	.0462	.0441	.0283	.0269	.0306
			MAX,	8.9	55.4	56.11	202.38	37.07	123.87	.055	.064	.831	1.049	.611	.459	.853
2	0	.10	MIN.	-5.8	-150.8	-67.89	-157.62	-36.93	-88.13	-.125	-.146	-.296	-.615	-.598	-.490	-.736
	25		MEAN	19.0	150.8	903.89	1129.62	808.93	1124.13	6.992	7.209	3.868	4.980	5.201	5.405	5.198
			STDEV	3.36	42.43	22.494	65.805	13.598	37.841	.0169	.0177	.1680	.2166	.1235	.1094	.1707
			MAX,	8.9	98.0	48.01	189.99	17.95	109.74	.068	.091	.563	.628	.230	.365	.345
3	4	.16	MIN.	-7.8	-105.0	-59.99	-114.01	-24.05	-50.26	-.084	-.079	-.308	-.293	-.274	-.279	-.364
	16		MEAN	19.6	105.0	721.99	1002.01	716.05	1046.26	4.111	4.540	4.135	5.119	5.247	5.364	5.230
			STDEV	2.90	62.24	22,328	56.817	7.509	28.550	.0227	.0236	.1399	.1339	.0677	.0831	.0874
			MAX,	12.3	103.8	63.31	182.54	40.74	122.53	.148	.147	.770	.759	.422	.420	.629
4	7	.25	MIN.	-8.6	-115.7	-78.69	-111.46	-45.26	-67.47	-.150	-.128	-.254	-.368	-.452	-.427	-.757
	12		MEAN	18.2	115.7	920.69	1125.46	827.26	1137.47	7.847	8.100	4.107	5.219	5.290	5.377	5.252
			STDEV	3.98	55.66	24.406	53.350	14.372	33.448	.0400	.0406	.1620	.1781	.1337	.1113	.1605
			MAX,	8.9	148.9	58.27	271.12	28.51	134.52	.119	.118	.553	.862	.425	.516	.634
5	7	.26	MIN.	-7.5	-52.4	-91.73	-132.88	-31.49	-67.48	-.176	-.155	-.240	-.393	-.482	-.331	-.549
	14		MEAN	20.3	52.4	797.73	1032.88	755.49	1087.48	5.684	6.041	4.043	5.168	5.287	5.382	5.248
			STDEV	3.12	48.10	22.882	59.094	10.775	32.883	.0354	.0366	.1364	.1753	.1217	.1047	.1496
			MAX,	12.6	151.0	54.02	246.45	27.25	117.61	.123	.121	.594	.694	.435	.309	.407
6	7	.25	MIN.	-7.3	-38.8	-67.98	-139.55	-28.75	-68.39	-.169	-.149	-.251	-.330	-.372	-.267	-.471
	15		MEAN	21.1	38.8	727.98	965.55	724.75	1054.39	4.167	4.596	4.002	5.106	5.277	5.386	5.237
			STDEV	3.61	41.15	24.054	63.906	8.467	30.352	.0343	.0332	.1395	.1549	.0988	.0937	.1172

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH11 - 0900 - 3/1/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP. MPH	WIND DIR. DEG.	LOAD CELLS NW LBS	SW LBS	NE LBS	SE LBS	WAVE GAGES TRAN 1 FT.	TRAN 2 FT.	INC. FT.	REF. FT.	ACCELEROMETERS (FT/SEC/SEC) N.VER.	HOR.	S.VER.
			MAX.	12.0	103.7	69.54	201.55	21.21	82.84	.118	.084	.643	.734	.386	.333	.427
7	7	.23	MIN.	-9.2	-13.4	-64.46	-164.45	-22.79	-63.16	-.116	-.101	-.202	-.341	-.320	-.378	-.418
	16		MEAN	19.4	15.4	688.46	898.45	710.79	1029.16	2.907	3.413	3.953	5.065	5.259	5.396	5.218
			STDEV	3.58	18.97	23.151	66.432	6.436	29.896	.0311	.0279	.1338	.1495	.0956	.0888	.1092
			MAX.	10.6	198.4	64.00	254.24	33.13	124.01	.118	.116	.728	.728	.432	.375	.666
8	9	.23	MIN.	-10.9	-47.4	-100.00	-141.76	-40.87	-71.99	-.119	-.122	-.270	-.398	-.543	-.405	-.585
	5		MEAN	18.9	47.4	803.99	1023.79	762.86	1078.01	5.602	5.977	4.020	5.123	5.314	5.388	5.248
			STDEV	4.14	48.68	28.009	68.262	13.612	37.728	.0347	.0341	.1539	.1648	.1153	.0965	.1368
			MAX.	11.5	172.1	75.53	333.18	40.17	205.59	.127	.192	.906	.781	.433	.362	.699
9	9	.22	MIN.	-8.7	-50.7	-100.47	-192.82	-45.83	-98.41	-.153	-.143	-.323	-.396	-.407	-.384	-.686
	7		MEAN	22.8	50.7	786.47	1088.82	749.83	1122.41	5.745	6.118	4.101	5.120	5.312	5.401	5.249
			STDEV	4.16	48.49	34.270	93.910	16.206	53.663	.0401	.0409	.1823	.1583	.1316	.1041	.1445
			MAX.	10.0	173.3	76.09	254.25	45.26	156.35	.195	.184	.852	.857	.469	.361	.631
10	9	.25	MIN.	-8.0	-46.1	-85.91	-175.75	-38.74	-105.65	-.148	-.172	-.325	-.371	-.472	-.384	-.754
	8		MEAN	23.4	46.1	868.75	1145.72	774.24	1147.39	6.072	6.385	4.101	5.171	5.311	5.402	5.250
			STDEV	3.59	44.60	28.525	77.068	14.429	46.228	.0432	.0442	.1709	.1821	.1212	.1104	.1518
			MAX.	10.9	112.1	79.21	236.06	53.39	147.27	.645	.598	.824	.948	.600	.528	.934
11	9	.36	MIN.	-7.4	-90.8	-88.79	-187.94	-42.61	-114.73	-.259	-.233	-.328	-.435	-.543	-.387	-.655
	9		MEAN	23.8	90.8	912.49	1206.49	800.65	1217.61	7.101	7.388	4.079	5.158	5.314	5.404	5.251
			STDEV	3.19	59.15	30.270	77.342	17.305	48.061	.0630	.0625	.1744	.1911	.1464	.1324	.1894
			MAX.	10.7	112.9	114.20	290.57	72.66	187.48	.640	.632	1.006	1.195	.835	.914	1.648
12	9	.40	MIN.	-8.6	-91.7	-113.80	-199.43	-63.34	-122.52	-.364	-.266	-.350	-.495	-.912	-1.052	-1.461
	10		MEAN	25.0	91.7	930.52	1234.76	827.45	1206.81	8.011	8.353	4.050	5.193	5.314	5.392	5.249
			STDEV	4.32	55.19	35.451	87.205	20.977	53.710	.0857	.0812	.2137	.2437	.2267	.2238	.3575

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH11 - 0900 - 3/1/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	SW	NE	SE	WAVE GAGES TRAN 1	TRAN 2	INC.	REF.	ACCELEROMETERS N.VER.	HOR.	S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX,	13.1	128.1	109.04	235.47	80.71	163.28	.451	.364	.985	1.191	.700	.837	1.474
13	9	.41	MIN.	-7.5	-79.8	-104.96	-194.53	-67.29	-118.72	-.389	-.393	-.398	-.525	-.812	-.892	-1.568
	11		MEAN	21.9	79.8	981.86	1241.07	903.97	1192.33	8.837	8.995	4.122	5.248	5.314	5.367	5.255
			STDEV	4.03	54.05	34.954	68.446	22.771	44.982	.1015	.1081	.2449	.2493	.2242	.2045	.3181
			MAX,	14.4	177.1	110.99	309.13	59.98	153.69	.307	.272	1.097	1.172	.806	.985	1.542
14	9	.40	MIN.	-11.9	-57.2	-121.01	-212.87	-58.02	-120.31	-.317	-.349	-.388	-.544	-.840	-1.049	-1.331
	12		MEAN	21.6	57.2	970.40	1215.72	862.61	1214.26	8.609	8.708	4.113	5.241	5.309	5.353	5.253
			STDEV	4.70	51.46	39.062	84.688	22.362	50.437	.0892	.0926	.2244	.2564	.2097	.2117	.3334

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH12 - 2230 - 3/20/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	SW	NE	SE	WAVE GAGES TRAN 1	TRAN 2	INC.	REF.	ACCELEROMETERS N.VER.	HOR.	S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX.	8.4	140.0	62.20	99.15	44.33	48.56	.074	.069	.496	.501	.215	.193	.208
1	0	.17	MIN.	-5.7	-99.2	-39.80	-48.85	-19.67	-23.44	-.083	-.076	-.272	-.241	-.222	-.146	-.197
	0		MEAN	12.8	99.2	871.85	937.28	832.65	1007.27	5.990	5.305	4.201	5.220	5.329	5.333	5.234
			STDEV	2.62	69.47	13.971	21.354	9.562	11.443	.0179	.0194	.1084	.1173	.0585	.0503	.0653
			MAX.	9.1	135.4	21.49	64.59	14.20	34.85	.057	.046	.545	.488	.189	.183	.261
2	0	.14	MIN.	-7.3	-115.4	-24.51	-43.41	-15.80	-21.15	-.051	-.056	-.275	-.229	-.214	-.156	-.314
	0		MEAN	11.8	115.4	884.51	949.42	827.80	1013.15	6.513	6.799	4.179	5.183	5.321	5.343	5.215
			STDEV	2.76	65.96	9.098	19.909	5.368	11.137	.0159	.0156	.1130	.1069	.0545	.0508	.0681
			MAX.	8.6	94.7	40.25	138.96	34.40	85.85	.112	.144	.636	.780	.483	.462	.782
3	0	.21	MIN.	-6.2	-104.9	-65.75	-69.04	-39.60	-42.15	-.093	-.114	-.260	-.321	-.525	-.352	-.874
	1		MEAN	18.1	104.9	923.75	1111.04	843.60	1114.15	7.924	8.157	4.036	5.172	5.330	5.369	5.234
			STDEV	2.73	60.15	18.660	35.685	10.805	22.129	.0301	.0327	.1449	.1649	.1431	.1226	.1788
			MAX.	13.1	95.2	58.23	178.02	45.47	103.88	.156	.163	.827	.955	.615	.631	1.360
4	0	.24	MIN.	-7.1	-104.5	-83.77	-117.98	-48.53	-66.12	-.147	-.194	-.350	-.401	-.661	-.691	-1.175
	2		MEAN	21.3	104.5	941.77	1179.99	850.53	1158.12	8.542	8.746	4.152	5.227	5.332	5.369	5.231
			STDEV	3.26	58.38	22.653	43.195	14.695	26.162	.0460	.0484	.1957	.2147	.1900	.1898	.2938
			MAX.	7.6	151.9	50.92	153.14	31.67	87.41	.093	.122	.738	.796	.484	.364	.748
5	0	.19	MIN.	-6.5	-34.6	-75.08	-94.86	-36.33	-58.59	-.102	-.094	-.286	-.330	-.491	-.517	-.705
	3		MEAN	20.6	34.6	935.08	1174.86	846.33	1156.59	8.516	8.718	4.087	5.207	5.329	5.365	5.235
			STDEV	2.93	41.42	19.137	39.018	11.795	25.009	.0288	.0280	.1513	.1705	.1370	.1097	.1568
			MAX.	7.2	115.9	46.85	107.50	27.83	55.02	.086	.114	.668	.813	.319	.272	.549
6	0	.19	MIN.	-4.7	-14.4	-53.15	-72.50	-22.17	-44.98	-.080	-.094	-.279	-.339	-.353	-.270	-.431
	7		MEAN	18.8	16.2	911.15	1116.50	836.17	1120.98	7.988	8.207	4.107	5.216	5.326	5.355	5.231
			STDEV	2.13	22.31	14.011	26.324	7.753	15.326	.0264	.0270	.1363	.1646	.1143	.0971	.1315

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH12 - 2230 - 3/20/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = .500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	SW	NE	SE	WAVE GAGES TRAN 1	TRAN 2	INC.	REF.	ACCELEROMETERS N.VER.	HOR.	S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX,	10.2	138.0	50.55	150.86	35.35	98.39	.073	.079	.532	.703	.287	.339	.381
7	0	.17	MIN.	-6.9	-17.1	-77.45	-85.14	-46.65	-59.61	-.069	-.080	-.236	-.270	-.284	-.272	-.328
	9		MEAN	18.4	18.2	931.45	1107.14	840.65	1117.61	8.087	8.306	4.115	5.223	5.324	5.357	5.229
			STDEV	3.20	27.26	19.667	36.519	11.697	22.201	.0221	.0226	.1285	.1431	.0876	.0816	.1025
			MAX,	10.4	114.0	72.43	196.27	40.01	129.16	.125	.120	.703	.833	.422	.457	.757
8	0	.20	MIN.	-7.6	-16.3	-83.57	-129.73	-53.99	-74.84	-.098	-.099	-.270	-.319	-.552	-.390	-.663
	10		MEAN	22.1	16.8	907.57	1159.72	823.99	1152.84	8.224	8.439	4.148	5.248	5.323	5.373	5.226
			STDEV	3.33	22.59	26.255	53.094	14.696	32.887	.0288	.0285	.1447	.1750	.1282	.1153	.1603
			MAX,	9.0	108.0	49.65	143.41	32.26	100.63	.105	.115	.671	.741	.324	.334	.554
9	0	.20	MIN.	-6.1	-88.3	-72.35	-82.59	-39.74	-53.37	-.103	-.096	-.251	-.309	-.416	-.344	-.426
	11		MEAN	19.2	88.3	936.35	1138.59	841.74	1133.37	8.376	8.581	4.105	5.237	5.321	5.361	5.226
			STDEV	3.48	61.75	23.462	44.187	13.576	29.269	.0282	.0306	.1395	.1522	.1040	.0886	.1147
			MAX,	11.1	140.5	100.80	296.82	54.69	170.49	.129	.148	.844	.993	.573	.550	.841
10	0	.22	MIN.	-9.5	-17.9	-123.20	-175.18	-59.31	-91.51	-.127	-.142	-.283	-.338	-.603	-.636	-.849
	13		MEAN	24.5	18.8	893.20	1187.18	809.31	1177.51	8.147	8.365	4.085	5.216	5.607	5.382	5.210
			STDEV	3.94	28.18	36.376	77.993	19.146	45.590	.0376	.0349	.1709	.2003	.1388	.1285	.1790
			MAX,	11.5	146.0	95.24	256.21	57.20	145.45	.204	.246	.909	.922	.789	1.112	1.832
11	0	.27	MIN.	-12.9	-53.6	-100.76	-247.79	-46.80	-132.55	-.178	-.219	-.320	-.409	-.959	-1.160	-1.616
	14		MEAN	27.7	53.6	810.76	1205.79	772.80	1192.55	7.398	7.656	4.097	5.158	5.292	5.396	5.203
			STDEV	4.37	52.33	29.763	83.770	17.150	48.104	.0569	.0599	.2077	.2283	.2424	.2613	.4286
			MAX,	10.8	103.5	67.14	250.15	38.58	168.48	.171	.198	.860	.960	.724	.896	1.747
12	0	.26	MIN.	-8.5	-13.6	-82.86	-189.85	-39.42	-107.52	-.150	-.180	-.318	-.397	-.822	-1.036	-1.667
	15		MEAN	25.2	14.9	770.86	1121.85	751.42	1141.52	6.172	6.508	4.068	5.146	5.291	5.375	5.181
			STDEV	3.95	19.45	25.076	69.811	12.488	41.639	.0492	.0527	.1874	.2182	.2228	.2191	.3833

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH12 - 2230 - 3/20/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	SW	NE	SE	WAVE GAGES TRAN 1	TRAN 2	INC.	REF.	ACCELEROMETERS N.VER.	HOR.	S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX.	12.0	63.8	55.36	183.38	20.98	102.58	.136	.122	.638	.843	.466	.467	.803
13	0	.23	MIN.	-7.3	-8.0	-64.64	-124.62	-29.02	-63.42	-.109	-.118	-.233	-.309	-.475	-.448	-.718
	16		MEAN	20.8	9.5	726.64	960.62	727.02	1045.42	4.630	5.046	3.958	5.085	5.280	5.364	5.180
			STDEV	4.36	11.27	24.012	66.572	9.373	36.446	.0328	.0364	.1416	.1707	.1370	.1225	.1779
			MAX.	10.4	64.4	58.40	184.95	21.44	88.24	.095	.094	.625	.622	.404	.339	.604
14	0	.20	MIN.	-8.5	-8.2	-65.60	-109.05	-22.56	-51.76	-.085	-.102	-.194	-.300	-.402	-.305	-.545
	17		MEAN	20.1	9.3	693.60	867.05	704.56	1007.76	3.202	3.672	3.945	5.050	5.274	5.356	5.176
			STDEV	3.75	12.01	21.781	54.227	7.195	24.182	.0264	.0291	.1316	.1453	.1061	.0896	.1237
			MAX.	13.9	80.8	136.21	110.20	139.25	49.16	.135	.131	.367	.397	.278	.169	.190
15	6	.36	MIN.	-11.5	-318.5	-79.79	-157.80	-66.75	-58.84	-.116	-.126	-.273	-.243	-.260	-.170	-.216
	14		MEAN	20.2	318.5	1011.89	851.69	964.82	960.82	7.768	7.985	4.254	5.274	5.401	5.357	5.218
			STDEV	5.06	103.60	40.126	51.751	39.679	20.837	.0371	.0357	.1018	.0852	.0579	.0486	.0585
			MAX.	13.5	110.9	233.84	218.92	109.24	80.79	.504	.468	.293	.286	.177	.182	.183
16	6	.63	MIN.	-20.8	-290.0	-112.16	-137.08	-56.76	-43.21	-.181	-.155	-.142	-.149	-.192	-.157	-.188
	18		MEAN	20.8	290.0	833.51	642.61	795.57	919.64	2.661	3.097	3.922	5.054	5.328	5.338	5.152
			STDEV	4.62	107.69	51.112	54.756	26.527	16.088	.0389	.0338	.0613	.0657	.0539	.0444	.0550
			MAX.	8.7	109.1	49.50	161.30	29.34	83.70	.114	.092	.529	.615	.239	.186	.284
17	10	.20	MIN.	-7.7	-143.4	-60.50	-96.70	-36.66	-52.30	-.093	-.077	-.214	-.255	-.265	-.187	-.257
	[illegible]		MEAN	15.7	143.4	782.50	1040.70	788.66	1078.31	6.362	6.644	4.143	5.185	5.406	5.408	5.226
			STDEV	3.35	59.27	22.067	52.260	11.290	26.120	.0232	.0245	.1189	.1312	.0678	.0557	.0783
			MAX.	8.1	120.5	43.59	166.82	25.81	82.68	.089	.089	.349	.525	.171	.153	.183
18	10	.23	MIN.	-5.1	-143.5	-68.41	-91.18	-30.19	-49.32	-.081	-.075	-.163	-.217	-.198	-.152	-.256
	[illegible]		MEAN	15.7	143.5	778.41	1027.18	784.19	1071.32	6.106	6.399	4.094	5.145	5.406	5.407	5.225
			STDEV	2.64	53.90	19.434	47.133	9.794	23.689	.0208	.0242	.0894	.1136	.0441	.0467	.0545

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH13 - 2230 - 3/20/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP. (MPH)	WIND DIR. (DEG.)	LOAD CELLS NW (LBS)	SW (LBS)	NE (LBS)	SE (LBS)	WAVE GAGES TRAN 1 (FT.)	TRAN 2 (FT.)	INC. (FT.)	REF. (FT.)	ACCELEROMETERS N.VER. (FT/SEC/SEC)	HOR.	S.VER.
			MAX,	9.7	59.3	107.60	340.36	31.81	133.56	.170	.209	.675	.812	.429	.578	.799
1	23	.37	MIN.	-12.4	-130.4	-101.34	-133.64	-38.19	-66.44	-.377	-.255	-.272	-.366	-.479	-.507	-.790
	23		MEAN	20.8	171.0	705.89	1141.38	794.16	1147.37	3.519	4.586	4.177	5.243	5.516	5.490	5.015
			STDEV	3.36	26.69	28.223	74.717	9.644	29.630	.0497	.0491	.1359	.1803	.1346	.1251	.1997
			MAX,	12.8	76.4	57.60	307.88	24.96	132.10	.124	.118	.500	.651	.386	.353	.441
2	24	.35	MIN.	-9.0	-136.5	-76.40	-136.12	-37.04	-49.90	-.113	-.113	-.166	-.322	-.387	-.291	-.404
	6		MEAN	20.6	136.5	476.40	888.12	727.04	985.90	2.434	3.055	4.122	5.173	5.494	5.477	5.001
			STDEV	4.10	49.30	25.606	73.194	10.994	30.246	.0380	.0346	.1088	.1428	.1093	.0916	.1298
			MAX,	9.2	76.1	79.26	289.34	36.66	134.10	.191	.176	.745	.936	.624	.880	.912
3	24	.32	MIN.	-7.2	-136.8	-90.74	-160.66	-39.34	-77.90	-.178	-.147	-.279	-.446	-.620	-.951	-.642
	7		MEAN	20.7	136.8	520.74	1042.66	743.34	1063.90	4.157	4.686	4.236	5.246	5.492	5.493	5.003
			STDEV	3.69	46.94	30.135	78.112	13.818	37.252	.0549	.0515	.1707	.2079	.1816	.1923	.1914
			MAX,	11.3	86.0	71.05	306.89	41.42	199.86	.250	.250	.932	1.105	.793	1.001	1.119
4	24	.30	MIN.	-8.3	-121.9	-94.95	-171.11	-50.58	-96.14	-.228	-.211	-.348	-.559	-.820	-.999	-.808
	8		MEAN	22.4	121.9	578.95	1157.11	770.58	1124.14	5.926	6.361	4.303	5.360	5.490	5.506	5.000
			STDEV	3.83	49.11	35.103	96.943	17.090	53.806	.0645	.0641	.2117	.2435	.2229	.2187	.2349
			MAX,	9.0	127.2	76.65	186.45	36.81	107.21	.183	.173	.694	.923	.525	.684	.570
5	24	.32	MIN.	-8.1	-80.7	-81.35	-123.55	-41.19	-68.79	-.159	-.192	-.253	-.433	-.483	-.672	-.512
	9		MEAN	19.9	80.7	685.35	1171.55	823.19	1160.79	7.735	8.070	4.260	5.361	5.490	5.485	5.007
			STDEV	3.03	48.88	24.136	47.125	12.540	27.668	.0504	.0457	.1575	.1972	.1405	.1492	.1574
			MAX,	6.7	56.5	56.83	142.38	36.66	77.08	.171	.165	.754	.972	.595	.919	.577
6	24	.32	MIN.	-5.5	-151.4	-67.17	-97.62	-35.34	-62.92	-.165	-.165	-.244	-.462	-.715	-.912	-.640
	10		MEAN	19.6	151.4	787.17	1245.62	873.34	1204.92	9.161	9.407	4.200	5.338	5.487	5.486	5.000
			STDEV	2.67	36.45	24.240	40.460	13.459	24.938	.0507	.0476	.1600	.2124	.1767	.1960	.1822

SUMMARY OF STATISTICAL DATA FOR FRIDAY HARBOR FLOATING BREAKWATER (FH13 - 2230 - 3/20/75)
(MAX. AND MIN. VALUES MEASURED FROM ZERO MEAN)
SAMPLING PERIOD = 500 MS
NUMBER OF SAMPLES = 2047

REC. NO.	TIME IN DAYS AND HOURS	TRANS. COEF.		WIND SP.	WIND DIR.	LOAD CELLS NW	LOAD CELLS SW	LOAD CELLS NE	LOAD CELLS SE	WAVE GAGES TRAN 1	WAVE GAGES TRAN 2	WAVE GAGES INC.	WAVE GAGES REF.	ACCELEROMETERS N.VER.	ACCELEROMETERS HOR.	ACCELEROMETERS S.VER.
				MPH	DEG.	LBS	LBS	LBS	LBS	FT.	FT.	FT.	FT.	(FT/SEC/SEC)		
			MAX.	13.8	125.5	91.92	346.20	48.48	198.64	.198	.218	.811	.656	.386	.446	.551
7	24	.32	MIN.	-10.3	-123.6	-118.08	-231.80	-49.52	-117.36	-.167	-.183	-.264	-.394	-.454	-.571	-.463
	17		MEAN	22.8	123.6	596.09	1135.77	767.51	1137.36	6.385	6.800	4.271	5.272	5.494	5.486	5.026
			STDEV	4.74	49.67	40.252	111.057	17.216	58.518	.0551	.0572	.1696	.1708	.1153	.1147	.1383
			MAX.	10.4	111.9	83.84	460.62	42.06	207.33	.089	.082	.765	.891	.863	1.370	1.140
8	24	.14	MIN.	-10.1	-125.7	-114.16	-223.38	-43.94	-130.67	-.073	-.079	-.259	-.415	-.918	-1.308	-1.192
	18		MEAN	24.9	125.7	548.16	1193.38	741.94	1168.67	5.945	6.388	4.240	5.267	5.486	5.512	5.010
			STDEV	4.00	48.06	38.769	114.883	16.219	61.259	.0235	.0234	.1644	.2069	.2075	.2559	.2450

APPENDIX H

INCIDENT AND TRANSMITTED WAVE SPECTRAL PLOTS

Appendix H contains the incident and transmitted wave spectral plots along with the corresponding transmission response curve for 11 representative records. The data for the first nine were recorded at Friday Harbor, Washington, during the winter of 1975. Figures H-11 and H-12 were computed from similar data collected in Alaska during the winters of 1974 and 1975.

The original time series were high-pass filtered at a cutoff frequency of 0.05 hertz to remove tidal drift. Each series consisted of 2,048 data samples and were sampled at a period of 0.5 second for the Friday Harbor data and 0.44 second for the Alaska data.

The standard deviations and corresponding overall transmission coefficients for each of the Friday Harbor plots are given in Appendix G.

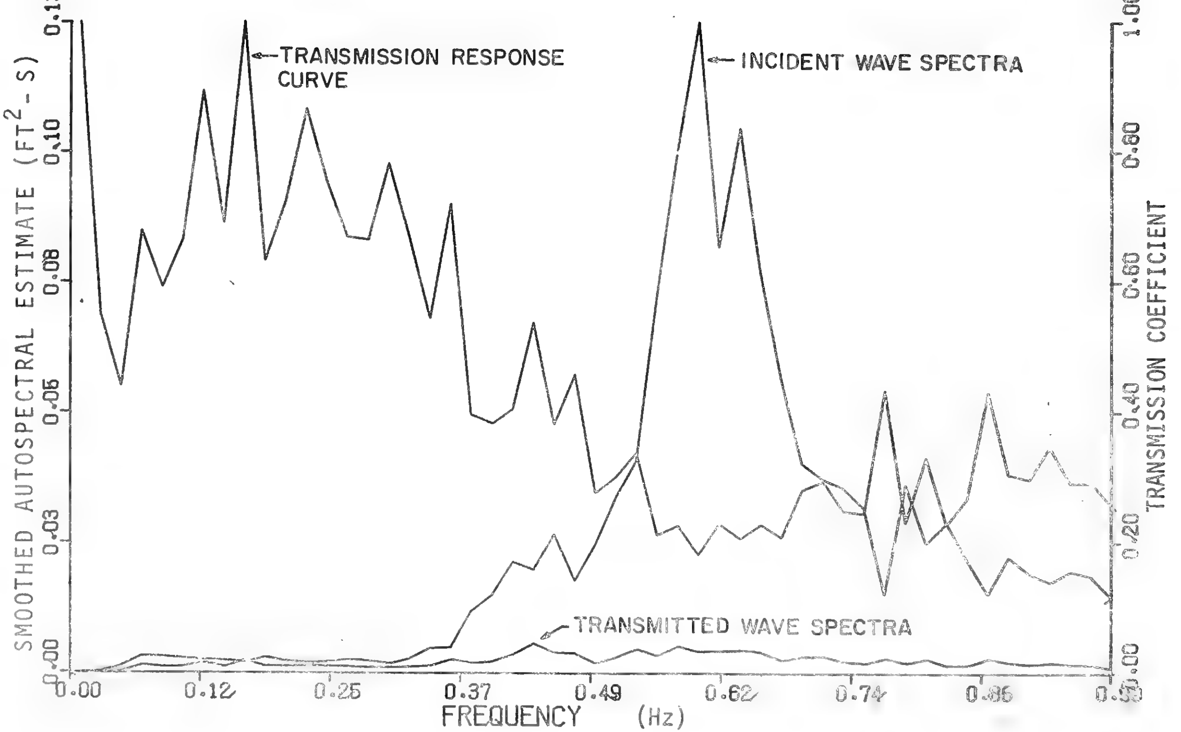


Figure H-1. Incident and transmitted wave spectral data (FH7-6)

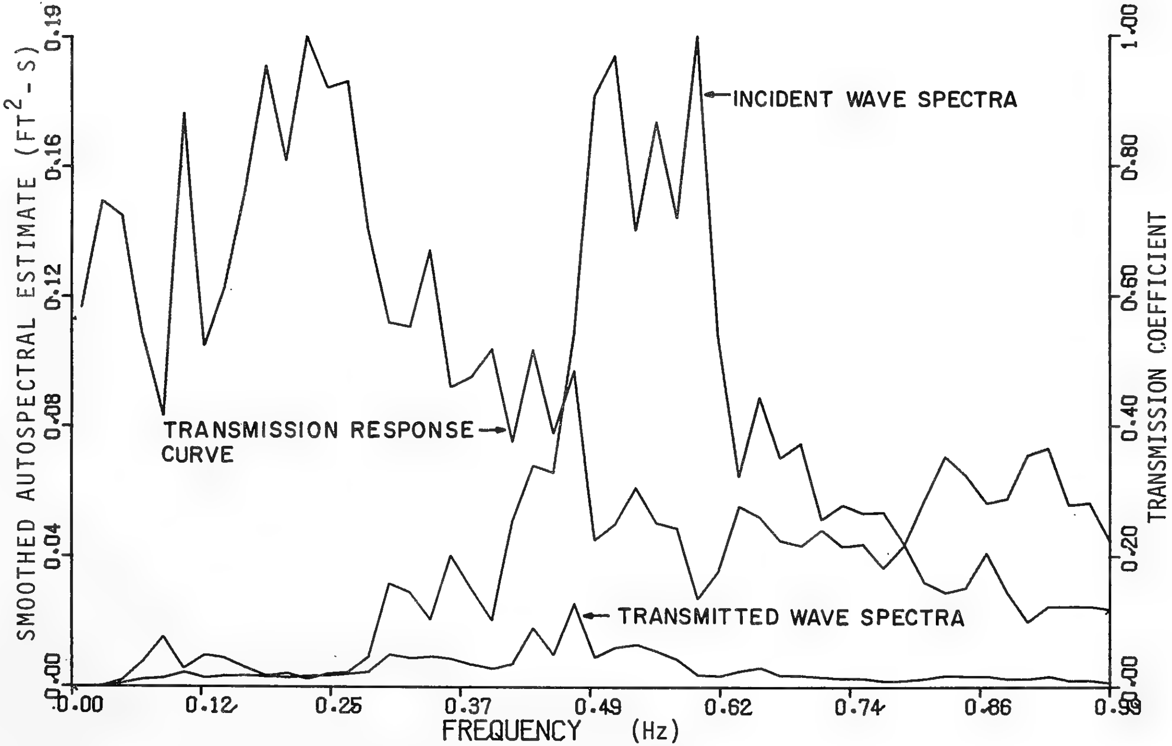


Figure H-2. Incident and transmitted wave spectral data (FH7-7)

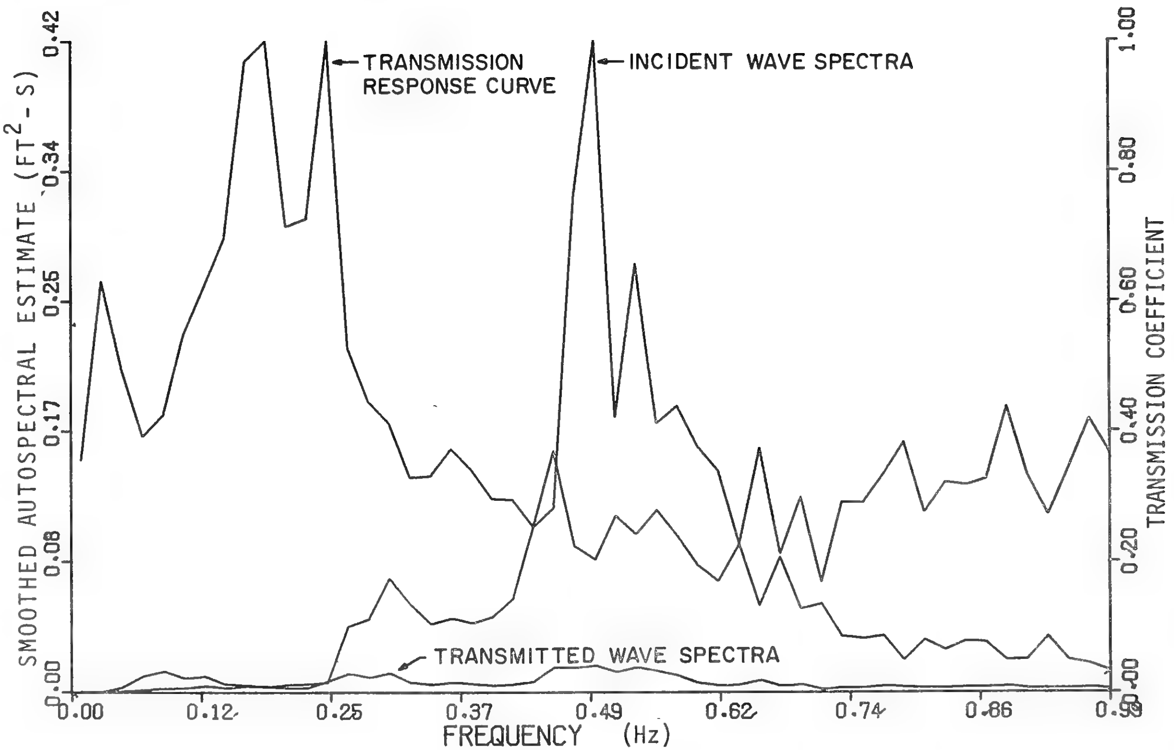


Figure H-3. Incident and transmitted wave spectral data (FH7-8).

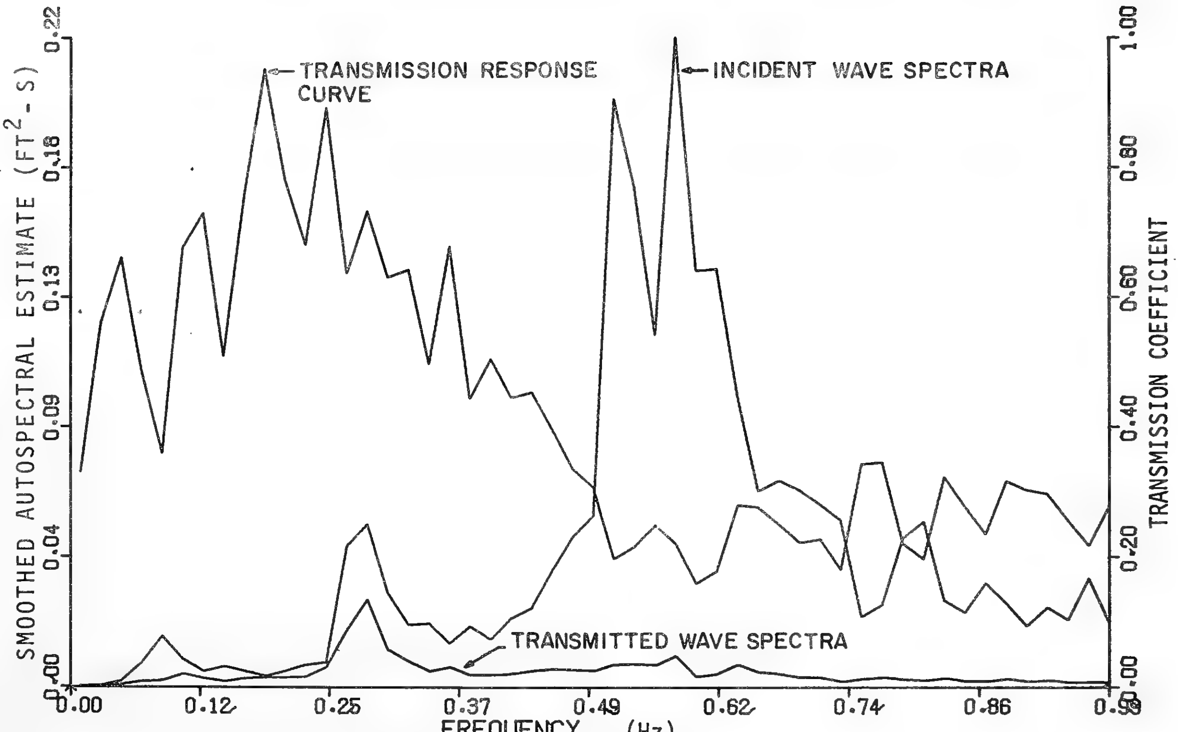


Figure H-4. Incident and transmitted wave spectral data (FH7-9).

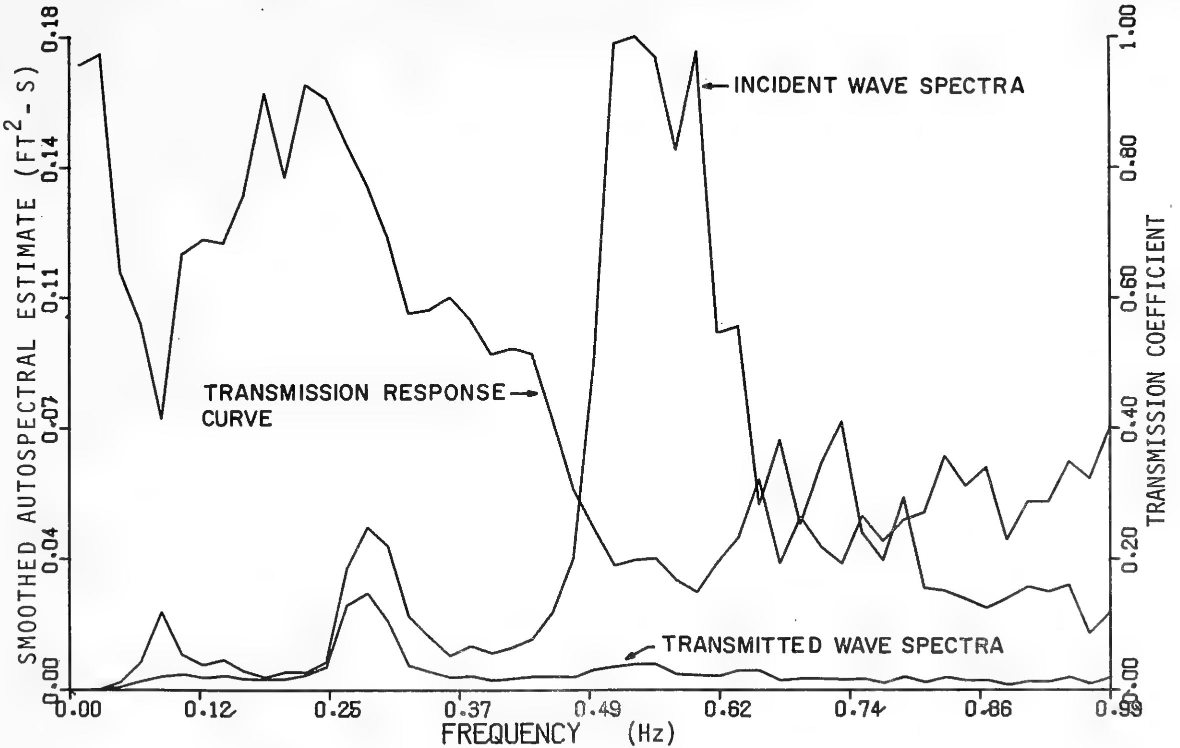


Figure H-5. Incident and transmitted wave spectral data (FH7-10).

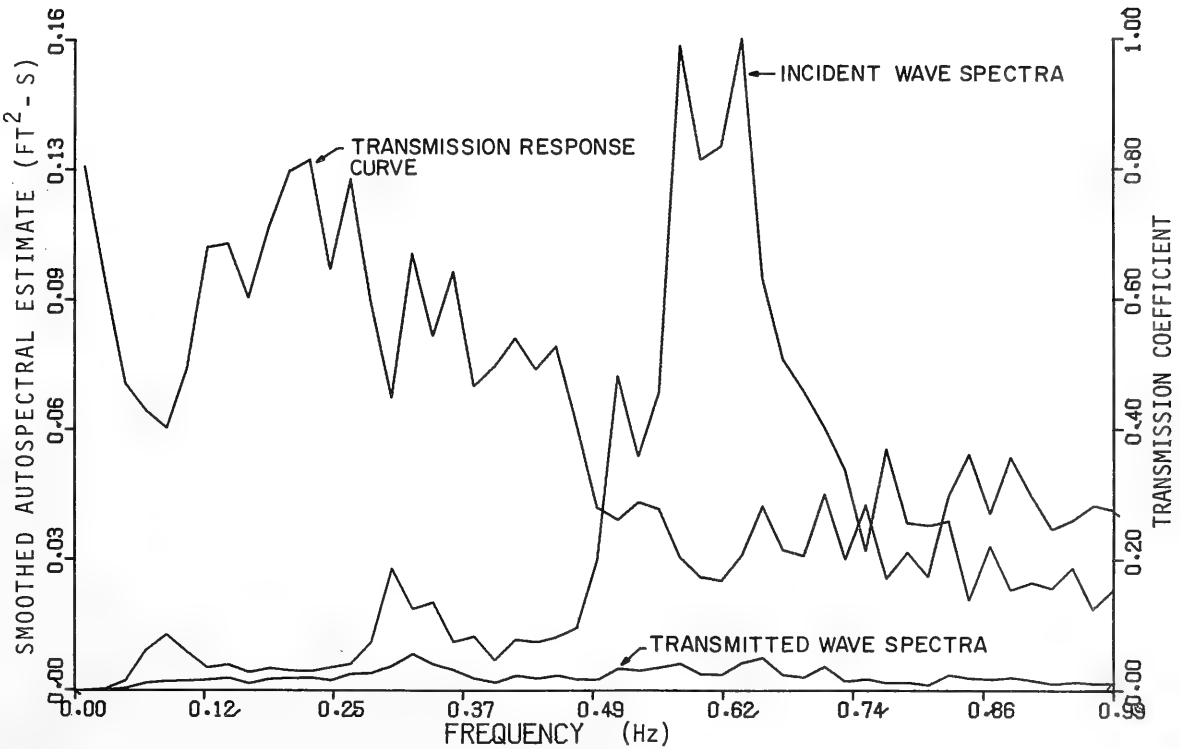


Figure H-6. Incident and transmitted wave spectral data (FH7-11).

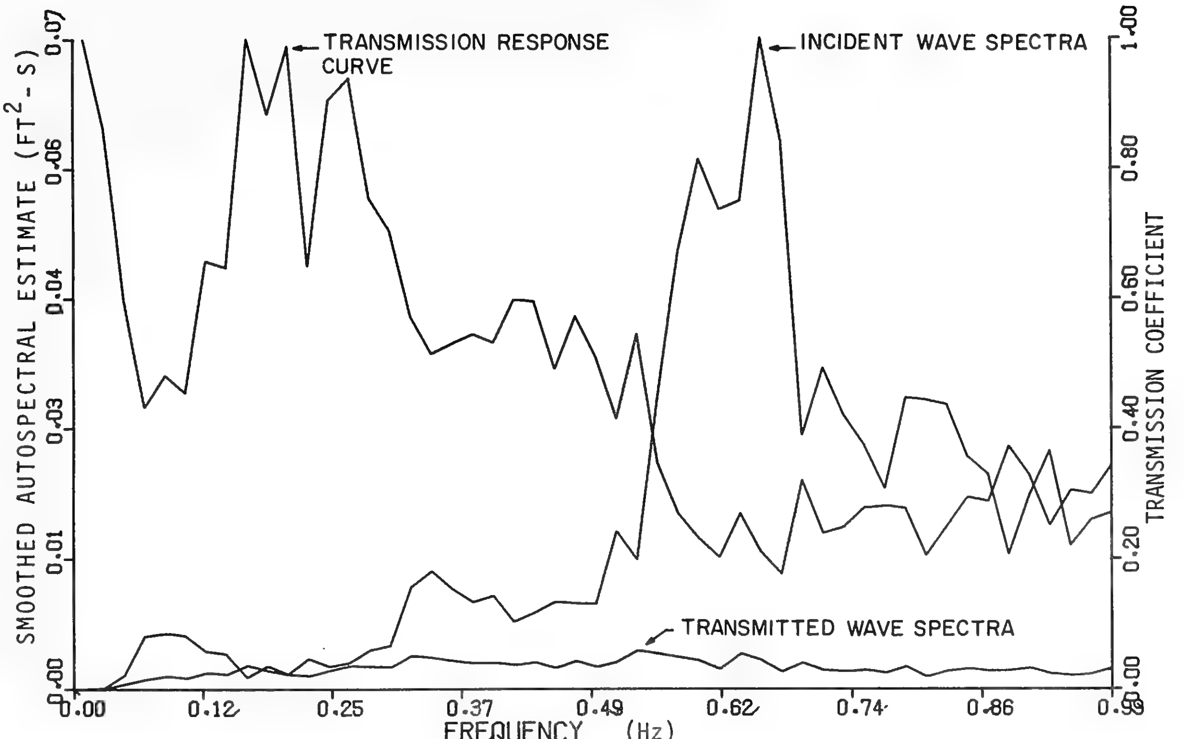


Figure H-7. Incident and transmitted wave spectral data (FH7-12).

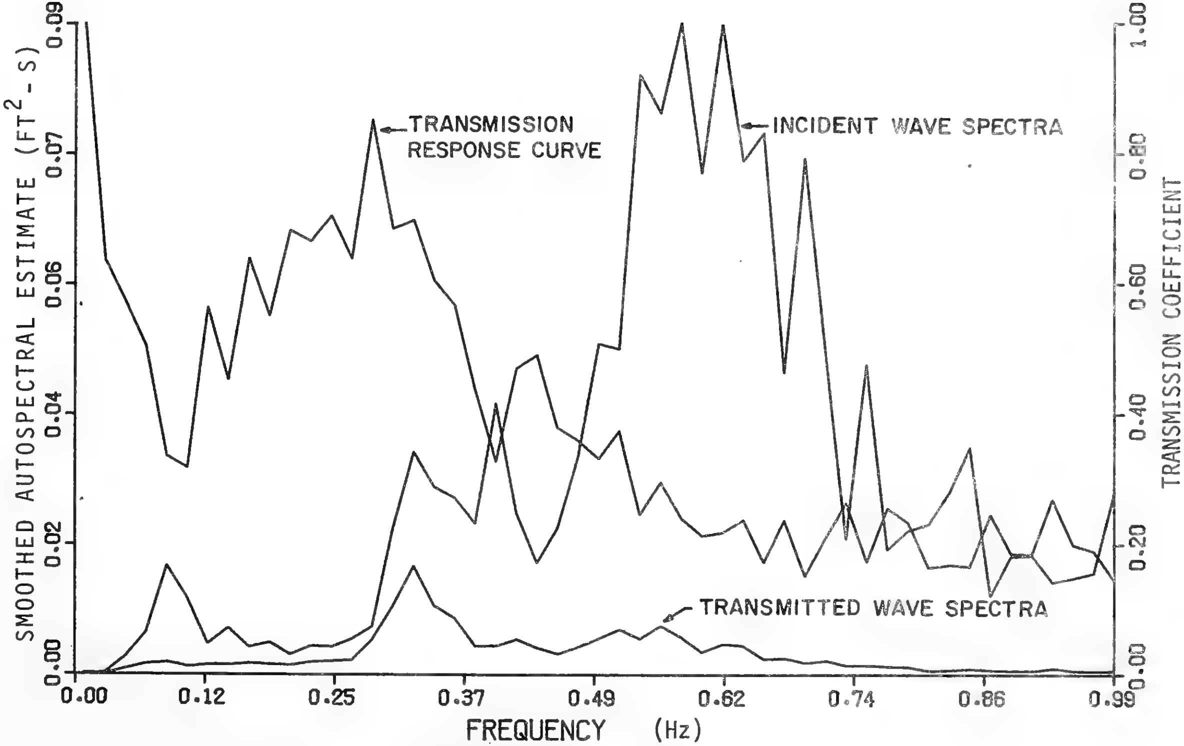


Figure H-8. Incident and transmitted wave spectral data (FH11-11).

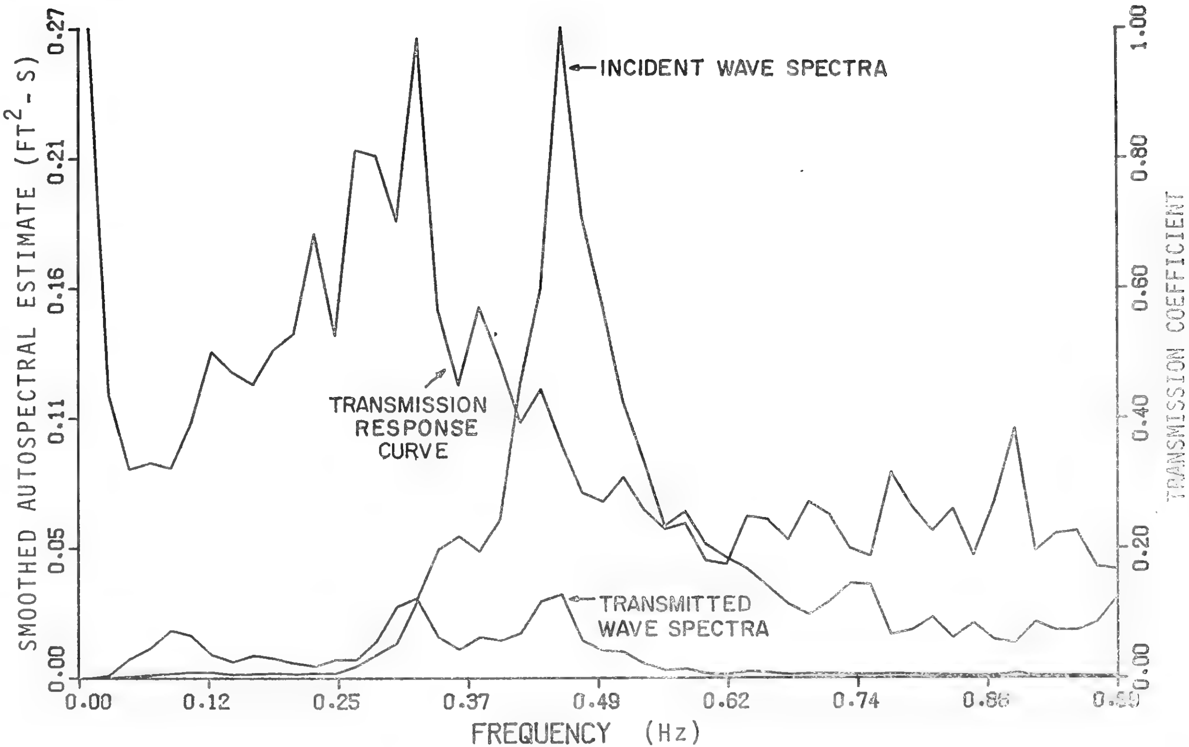


Figure H-9. Incident and transmitted wave spectral data (FH11-12).

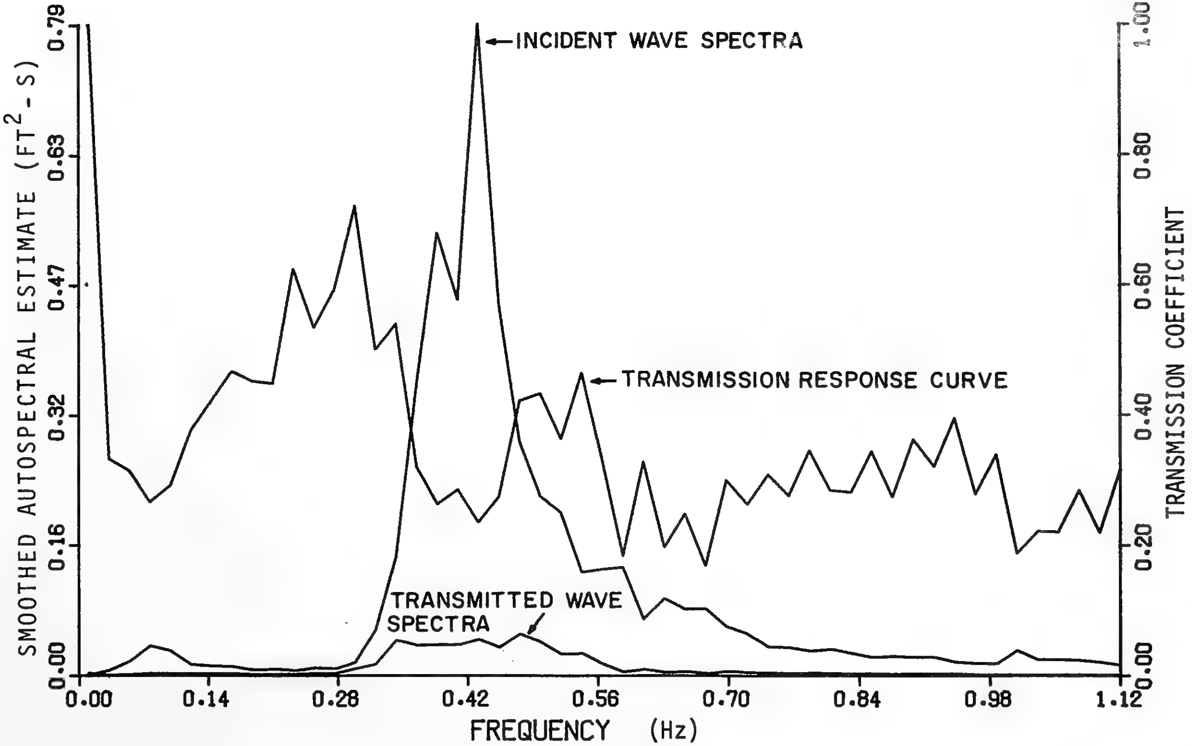


Figure H-10. Incident and transmitted wave spectral data (TK7-1), Tenakee Springs, Alaska.

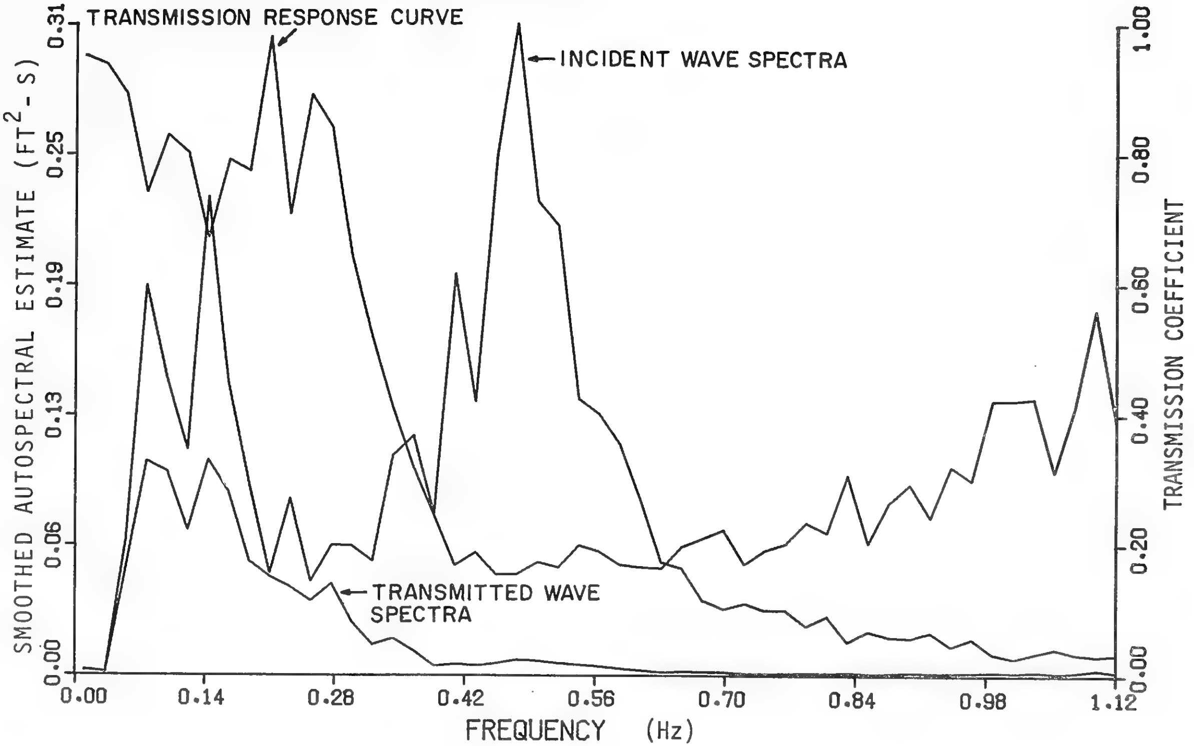


Figure H-11. Incident and transmitted wave spectral data (SK4-10), Sitka, Alaska.

APPENDIX I

LOW-FREQUENCY SPECTRAL ANALYSIS OF FORCE DATA

Appendix I contains the low-frequency autospectral and cross-spectral plots for record FH7-8. The data were recorded at Friday Harbor, Washington, on 6 January 1975 at 0030 hours.

The original time series were low-pass filtered at a cutoff frequency of 0.2 hertz and every eighth data point used to generate a new time series. This gives 256 points with a sampling period of 4 seconds.

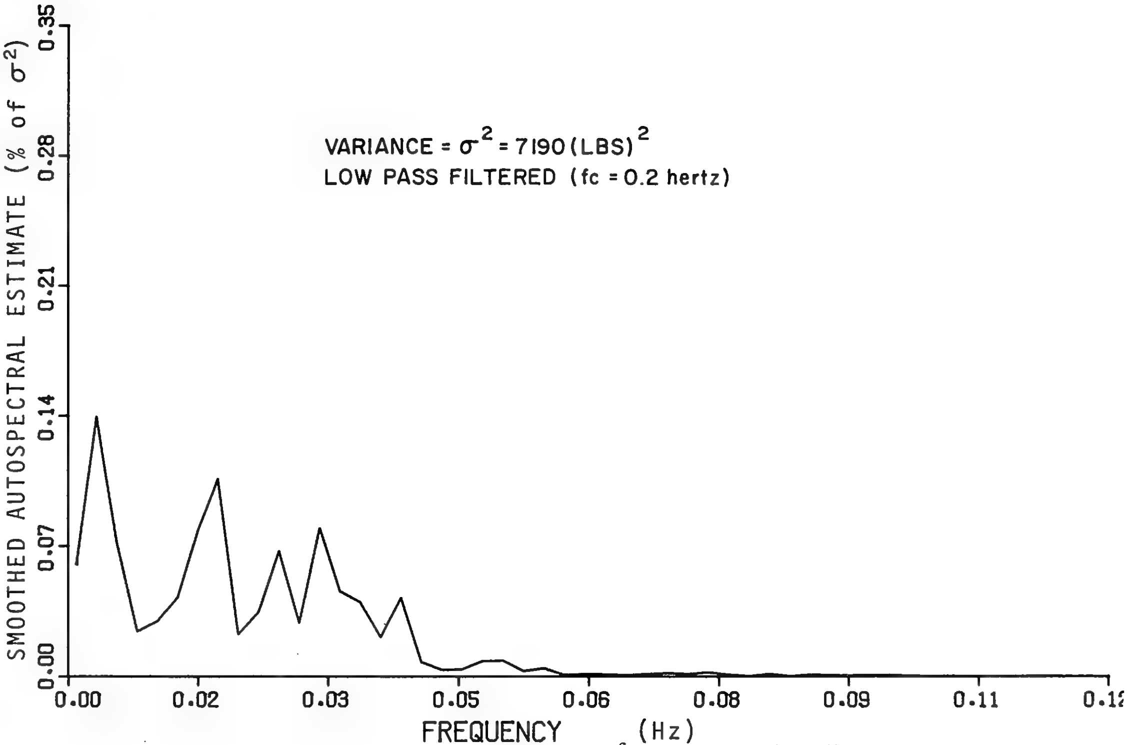


Figure I-1. Southwest force spectra (FH7-8).

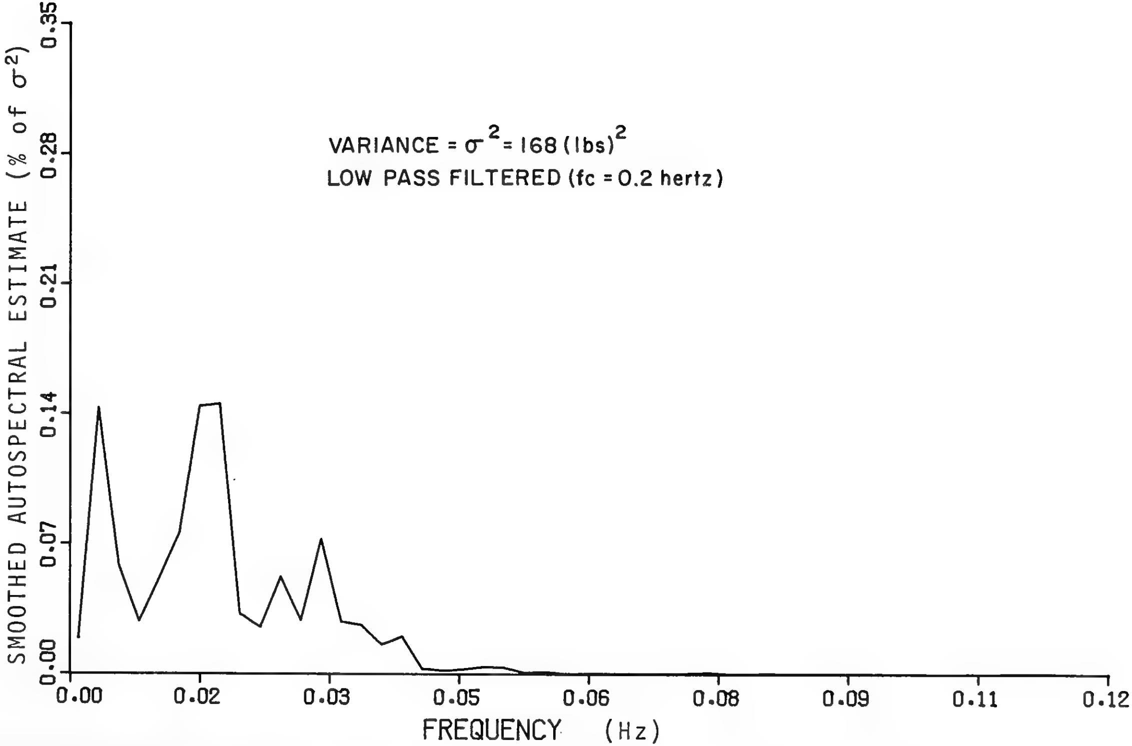


Figure I-2. Northeast force spectra (FH7-8).

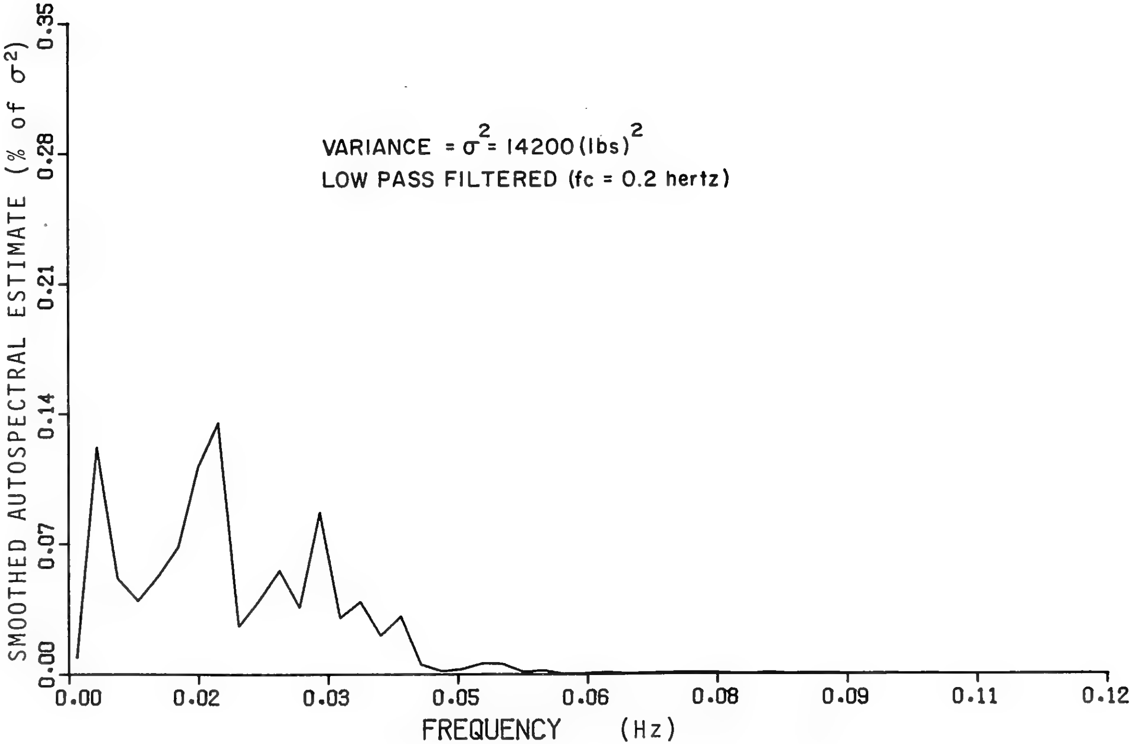


Figure I-3. Southeast force spectra (FH7-8).

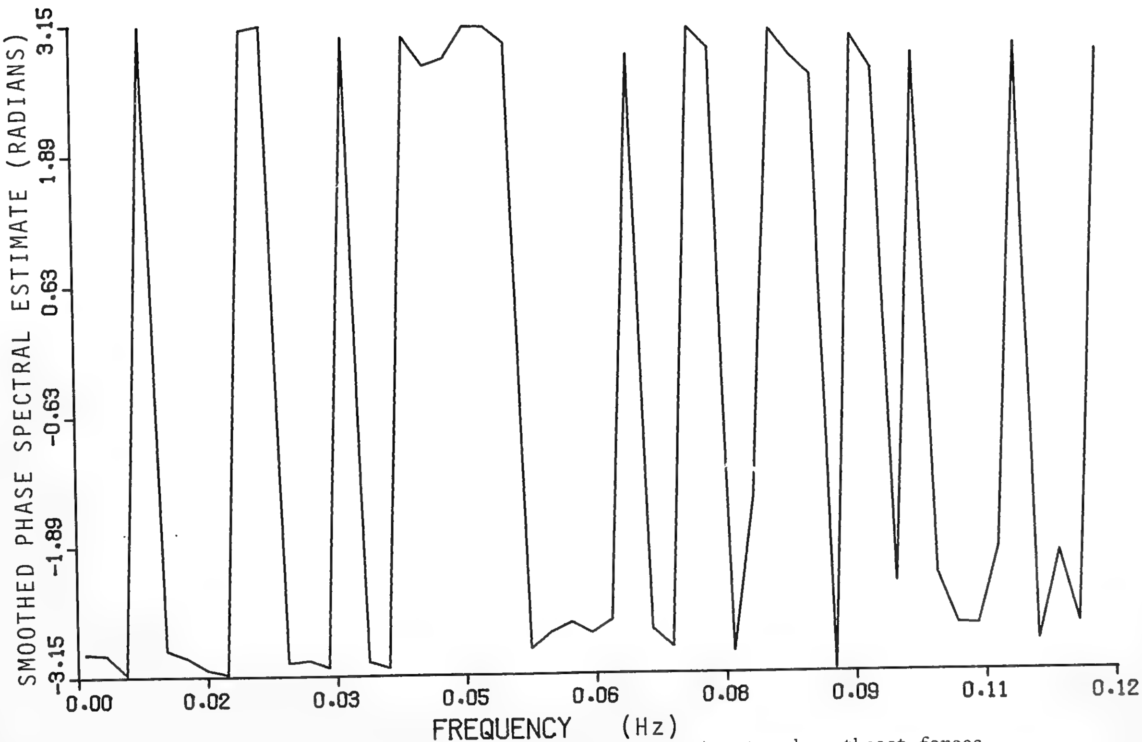


Figure I-4. Phase between northeast and southeast forces.

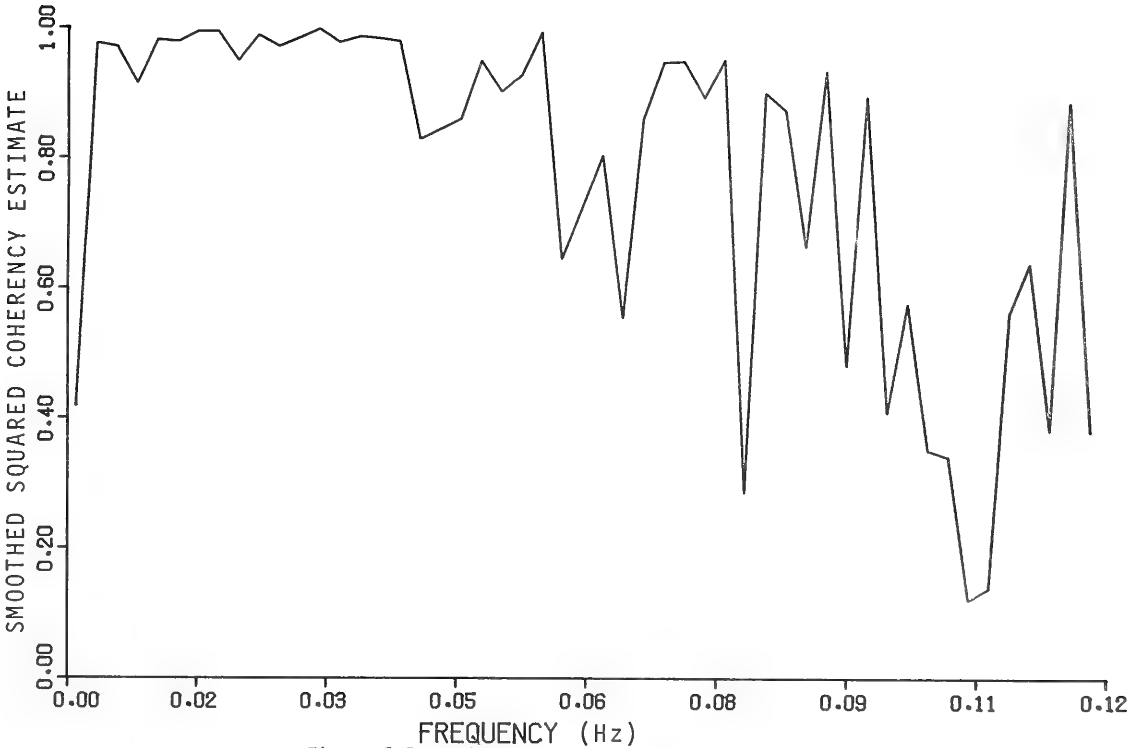


Figure I-5. Coherency between northeast and southeast forces.

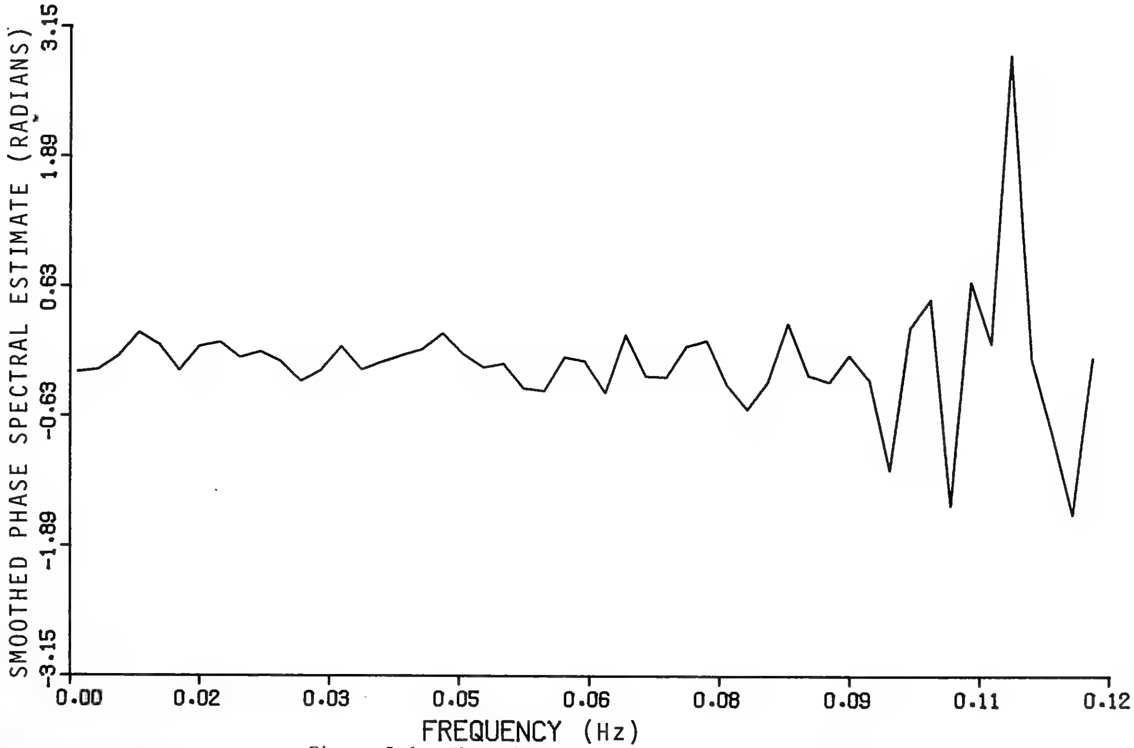


Figure I-6. Phase between the southeast and southwest forces.

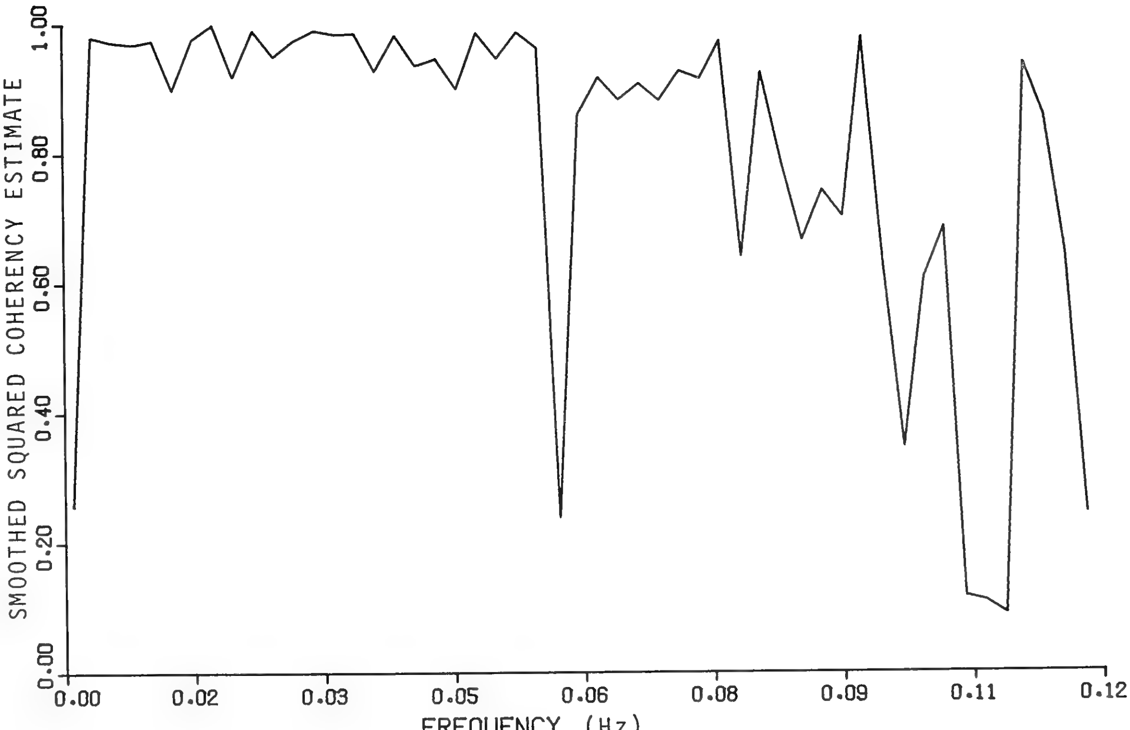


Figure I-7. Coherency between the southeast and southwest forces.

APPENDIX J

HIGH-FREQUENCY SPECTRAL ANALYSIS OF FORCE AND MOTION DATA

Appendix J contains the incident wave spectral plot along with the autospectral and cross-spectral plots for the force and motion data for record FH7-8. The data was recorded at Friday Harbor, Washington, on 6 January 1975 at 0030 hours.

The incident wave spectra was unfiltered. All the force and motion spectral data were digitally high-pass filtered at a cutoff frequency of 0.1 hertz. The autospectral data is plotted as a percent of the variance, i.e., the total area under the spectra. Wave heights, forces, and motions were measured in feet, pounds, and feet per second square, respectively.

All spectra were computed from 2,048 data points sampled at 0.5-second intervals.

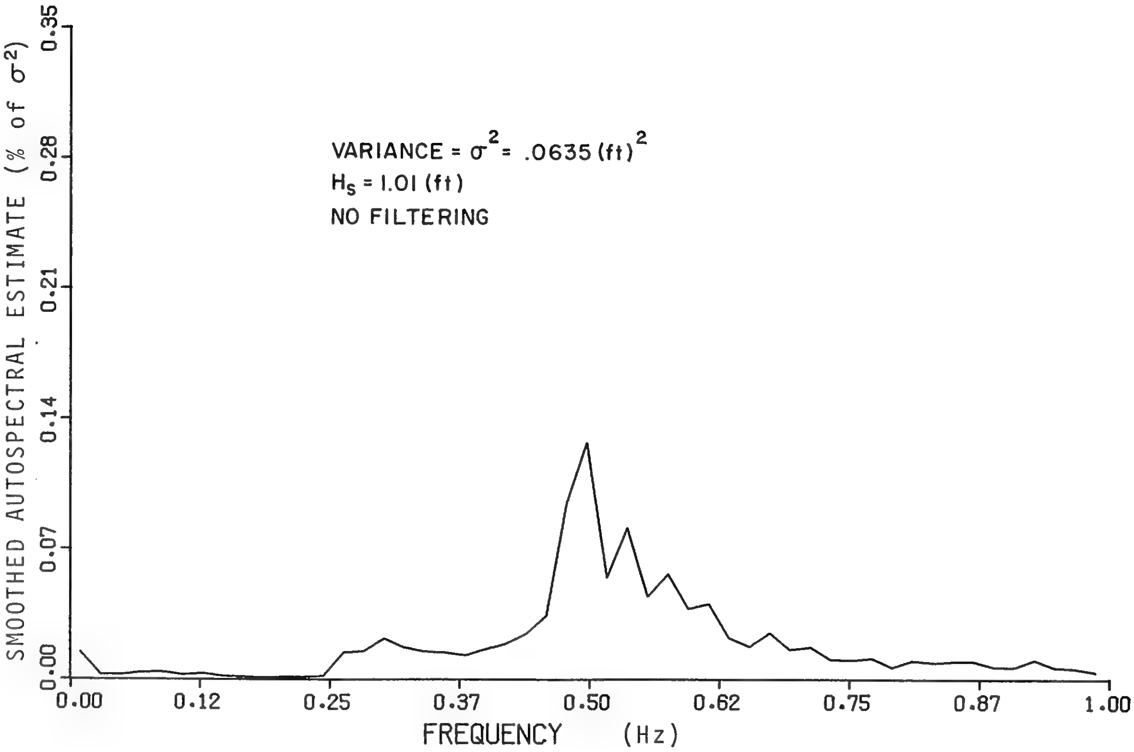


Figure J-1. Incident wave spectra (FH7-8).

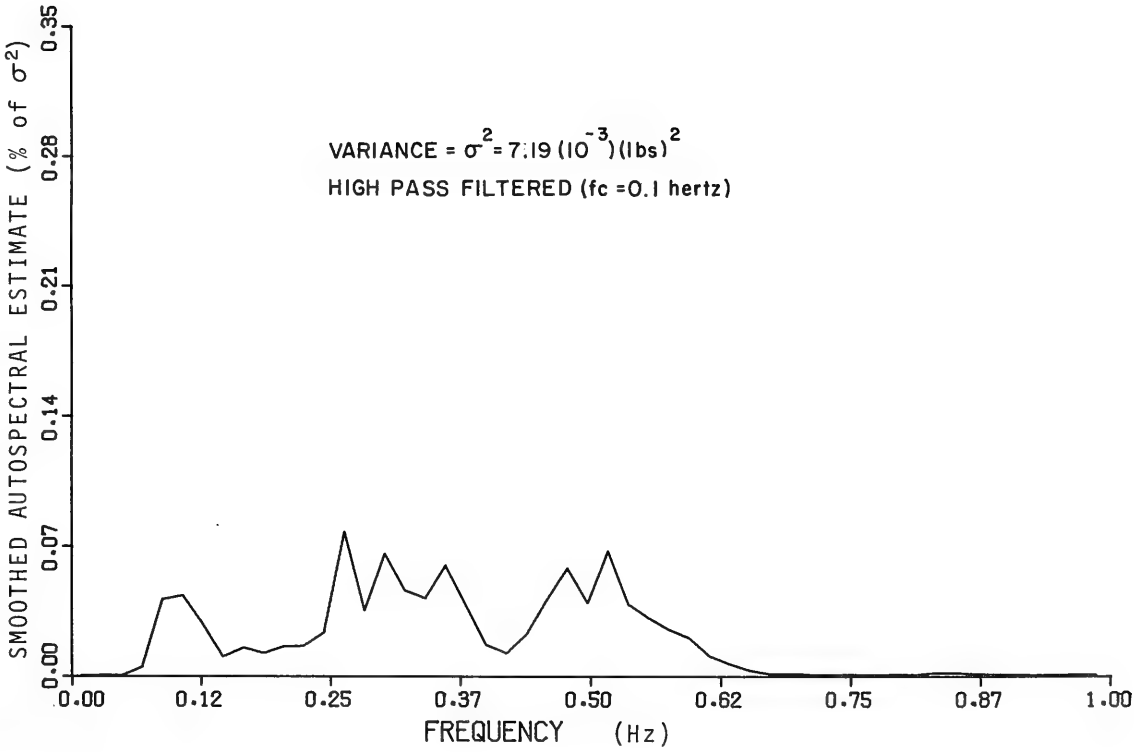


Figure J-2. Southeast force spectra (FH7-8).

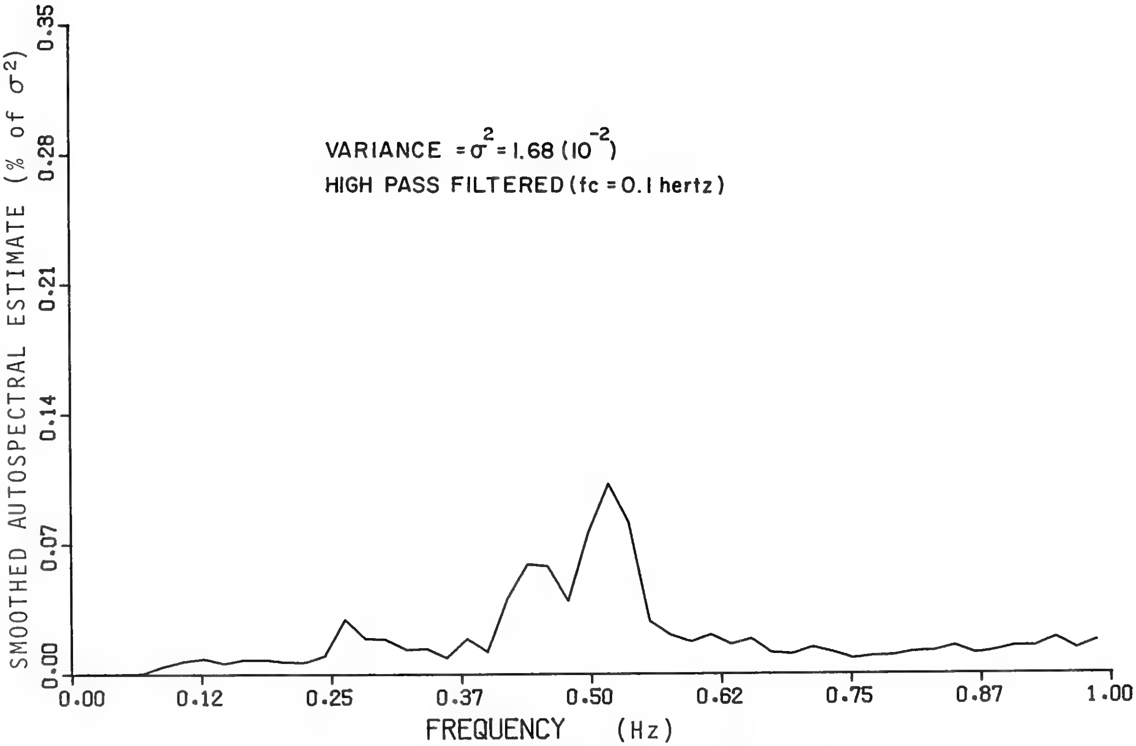


Figure J-3. Northeast force spectra (FH7-8).

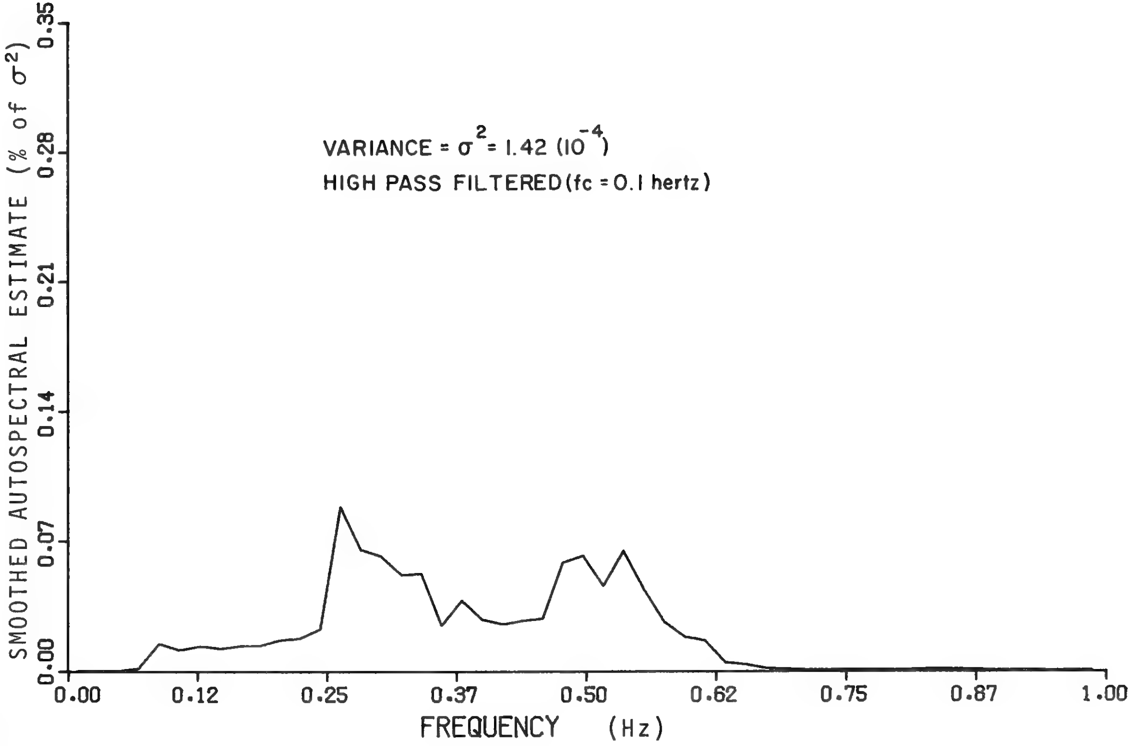


Figure J-4. Southeast force spectra (FH7-8)

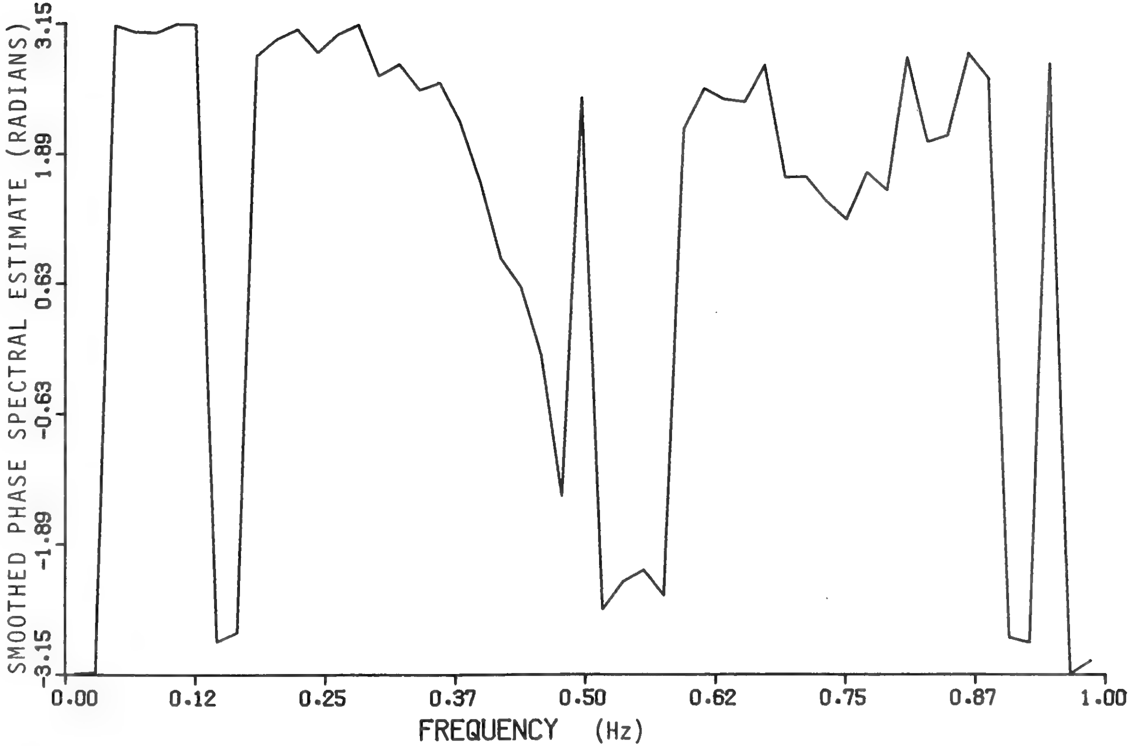


Figure J-5. Phase between the northeast and southeast forces.

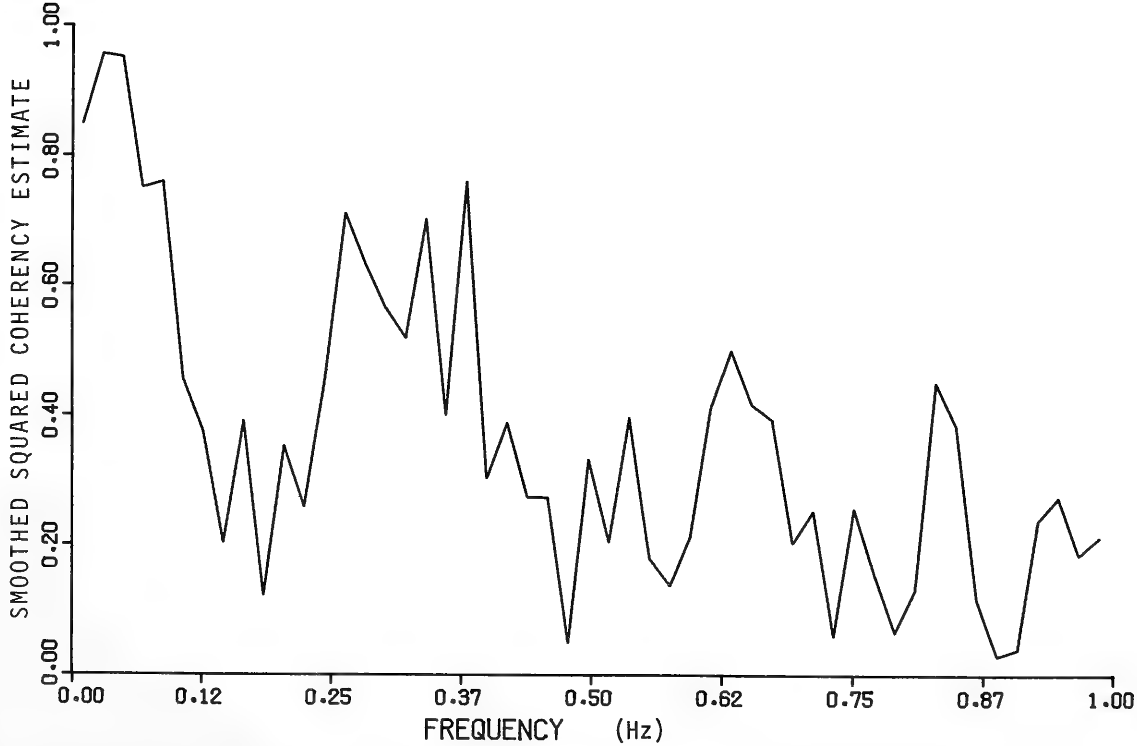


Figure J-6. Coherency between the northeast and southeast forces.

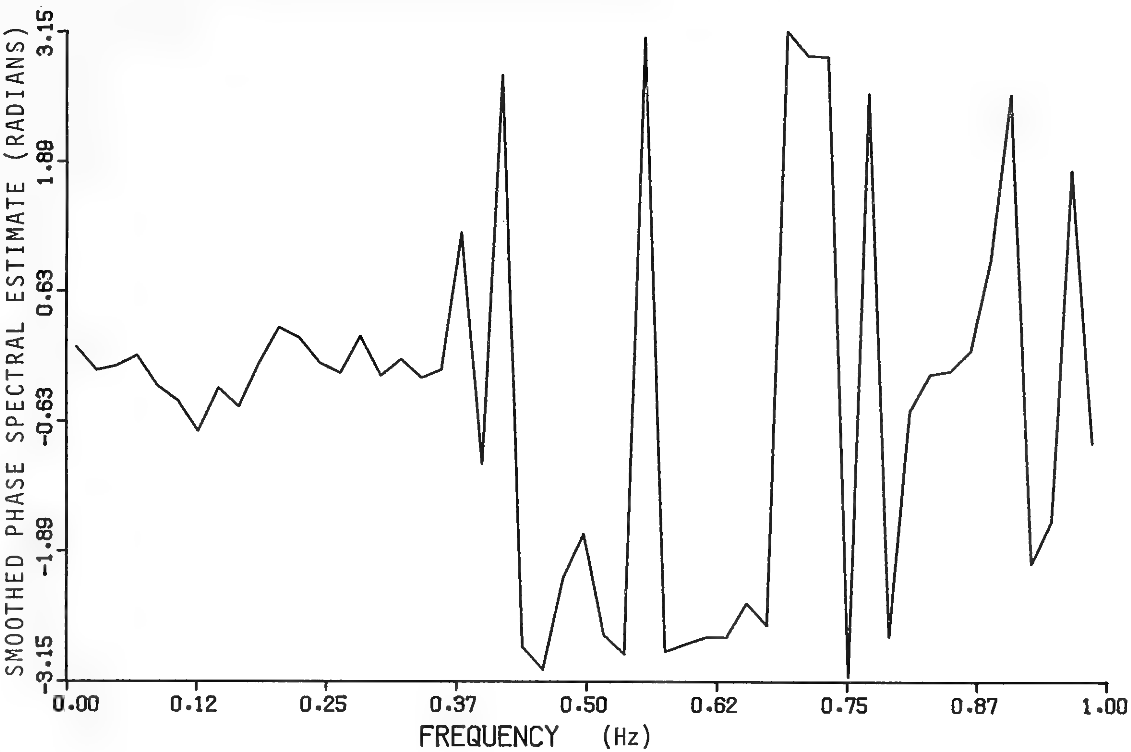


Figure J-7. Phase between the southeast and southwest forces.

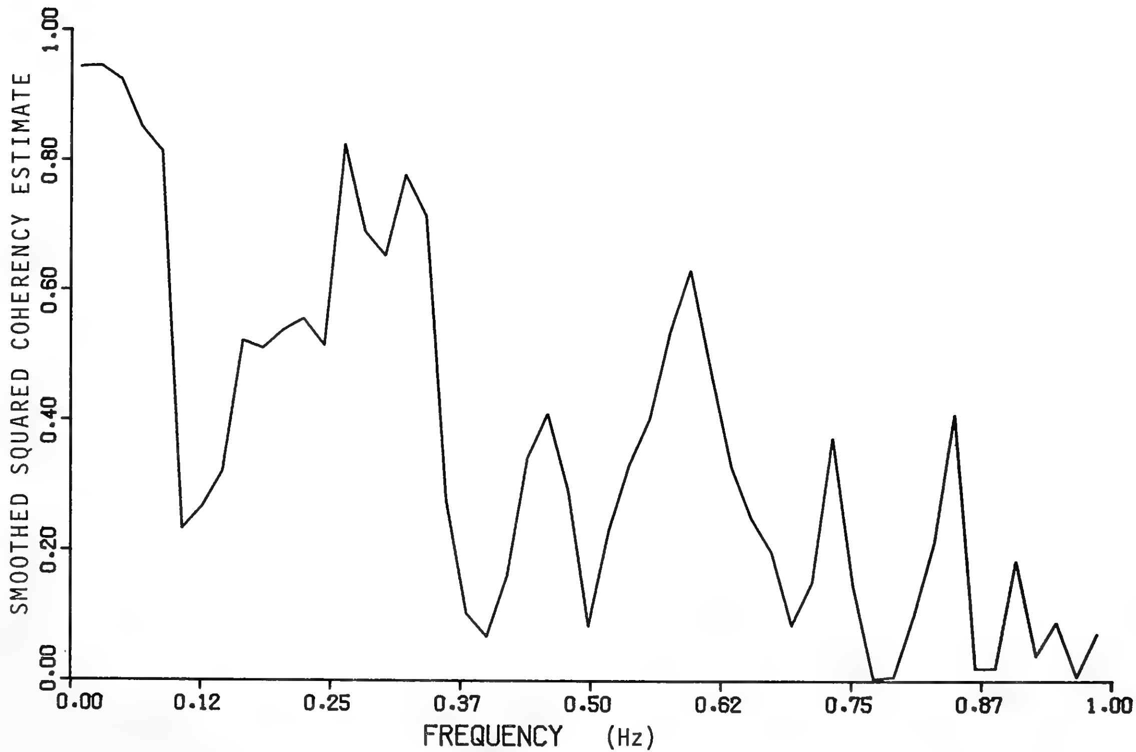


Figure J-8. Coherency between the southeast and southwest forces.

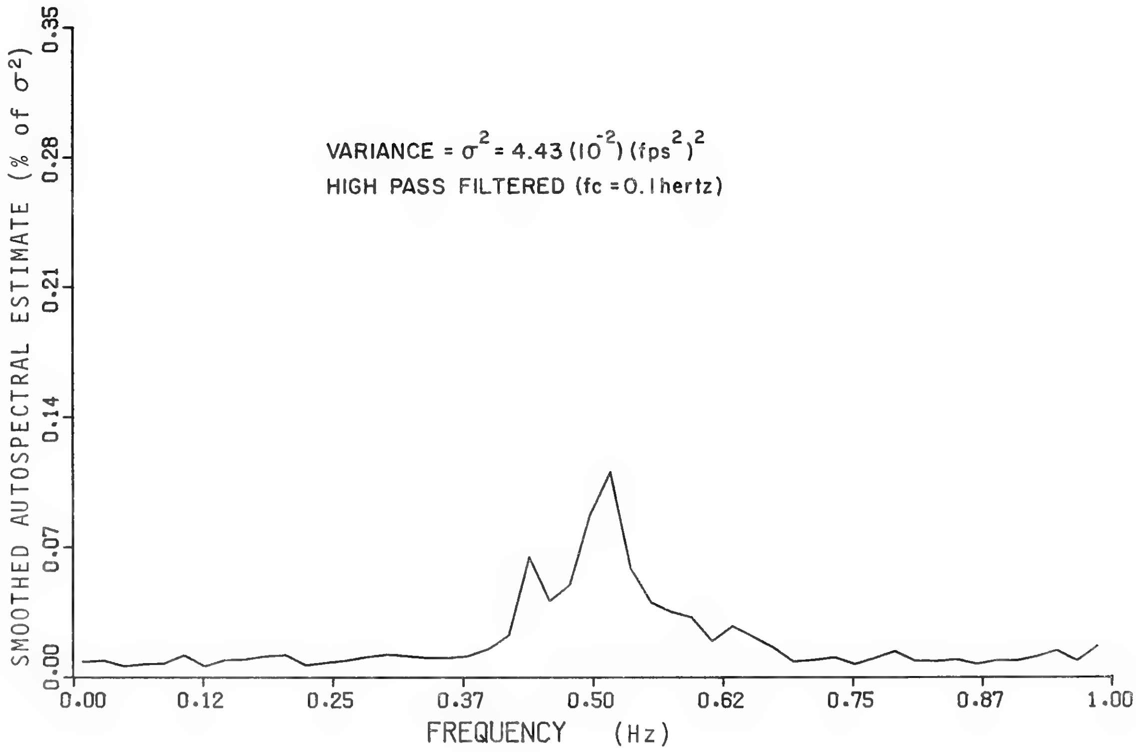


Figure J-9. Heave motion spectra (FH7-8).

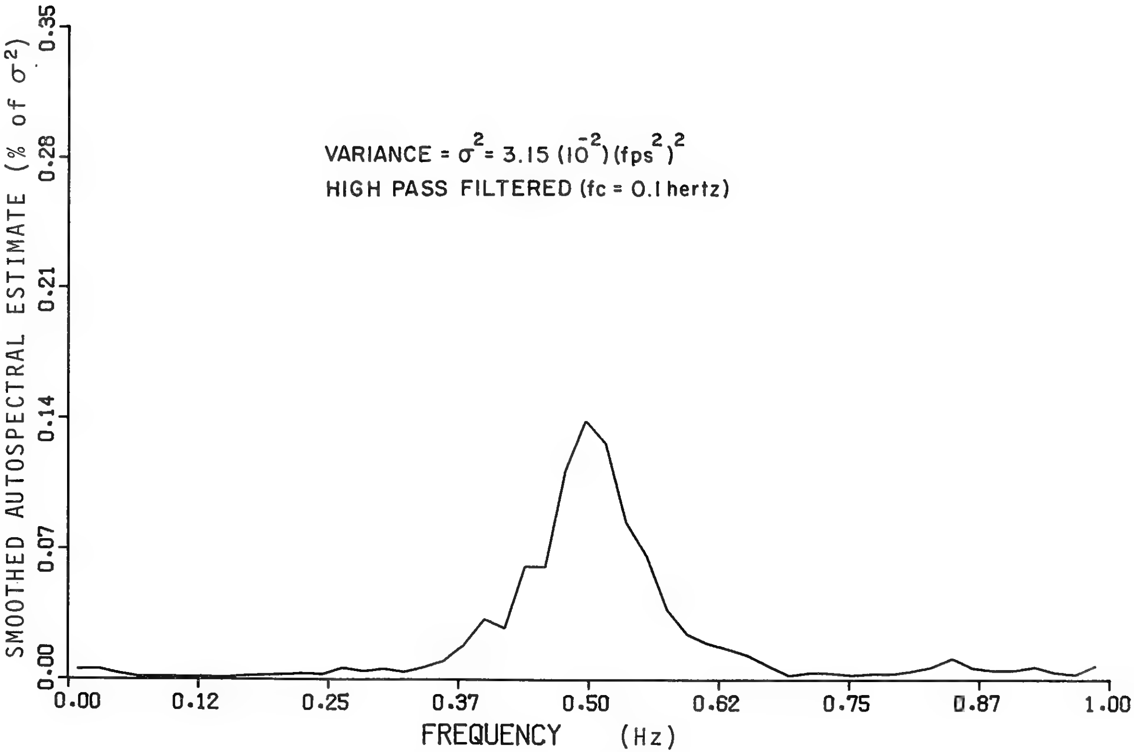


Figure J-10. Sway motion spectra (FH7-8).

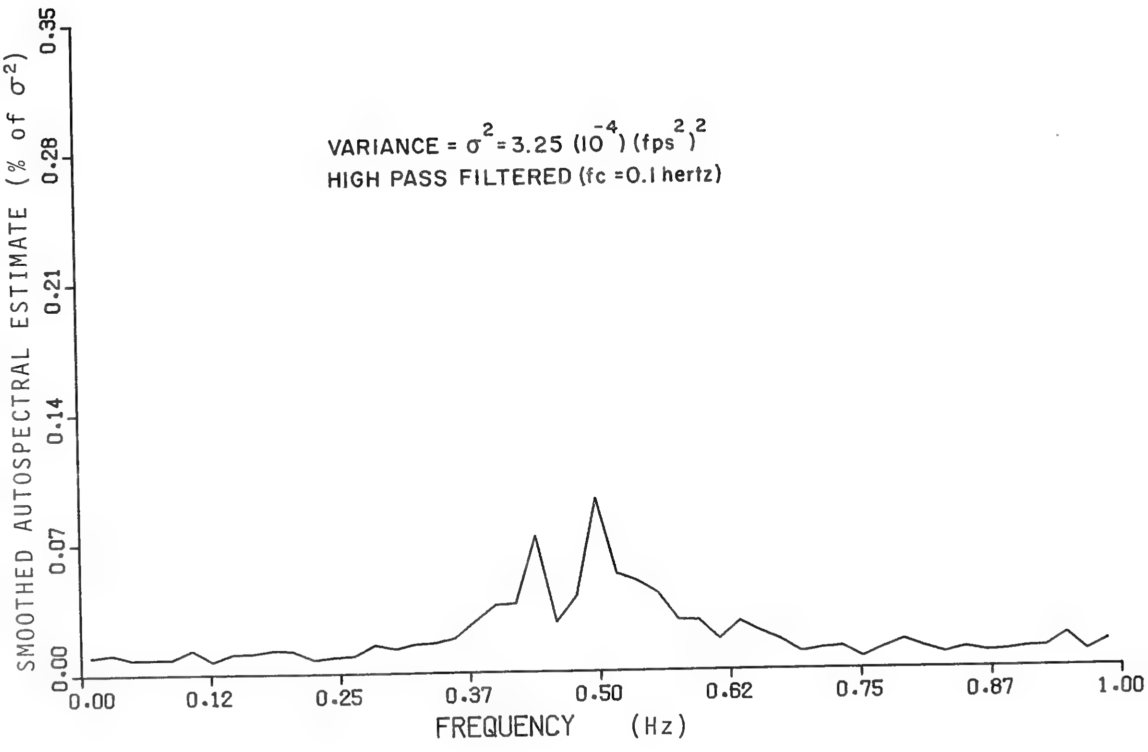


Figure J-11. Roll motion spectra (FH7-8).

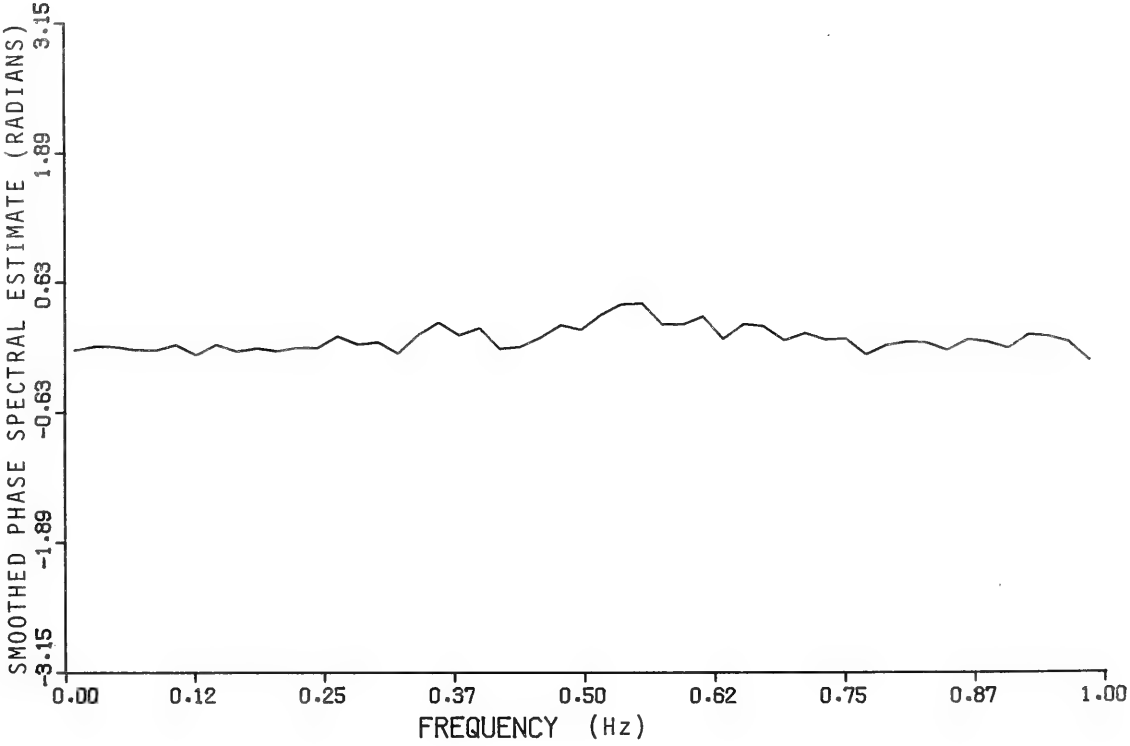


Figure J-12. Phase between heave and roll.

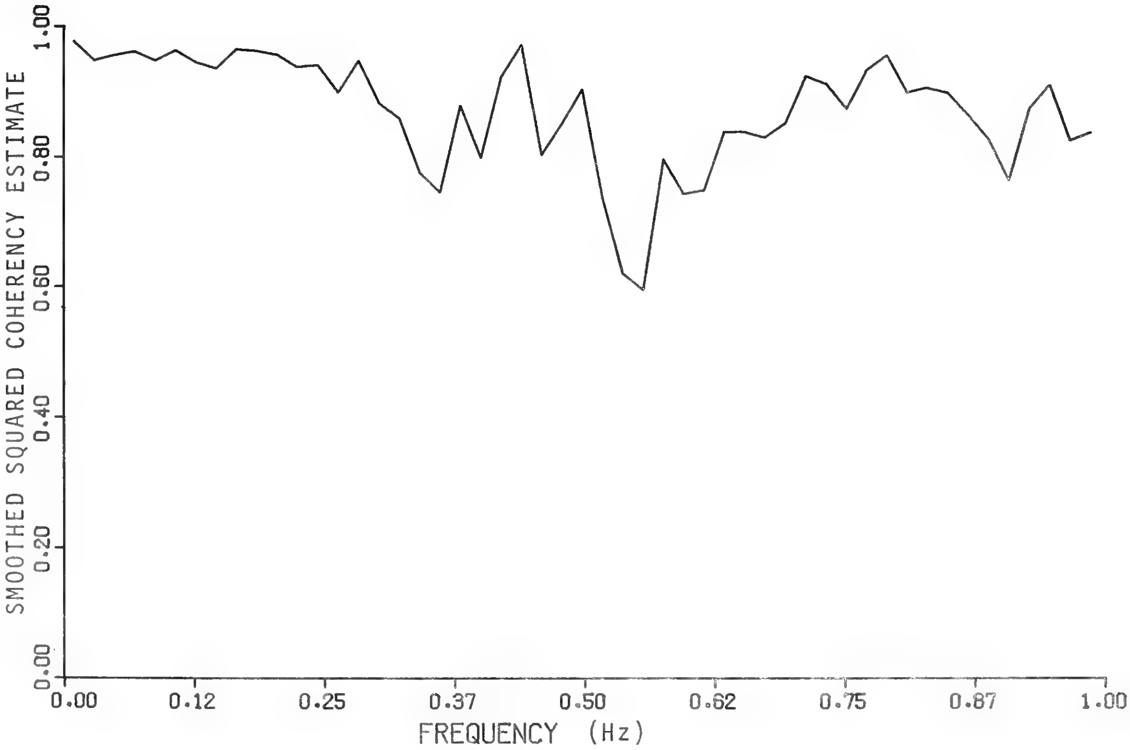


Figure J-13. Coherency between heave and roll.

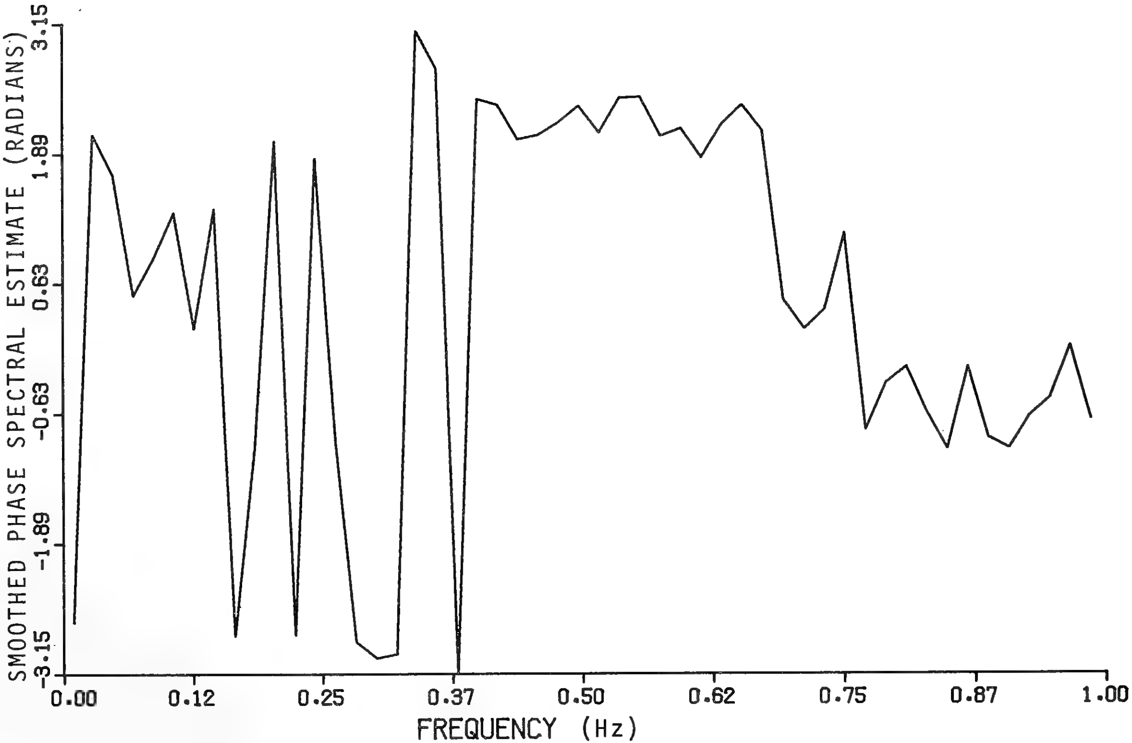


Figure J-14. Phase between sway and roll.

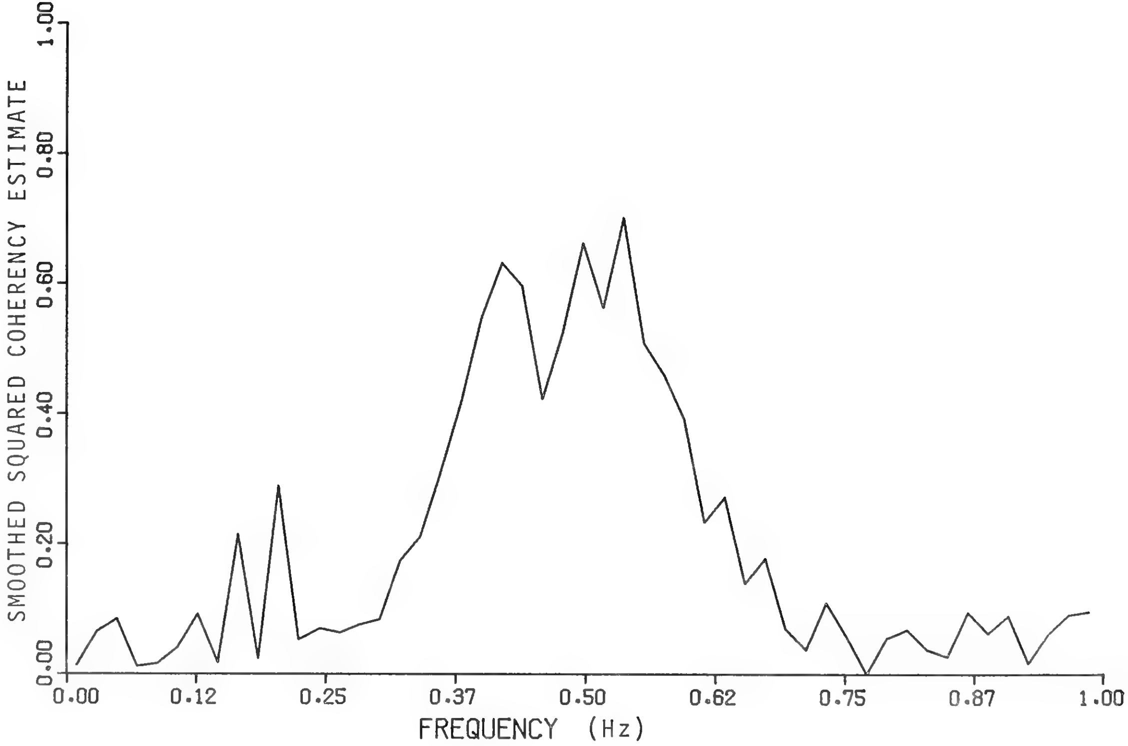


Figure J-15. Coherency between sway and roll.

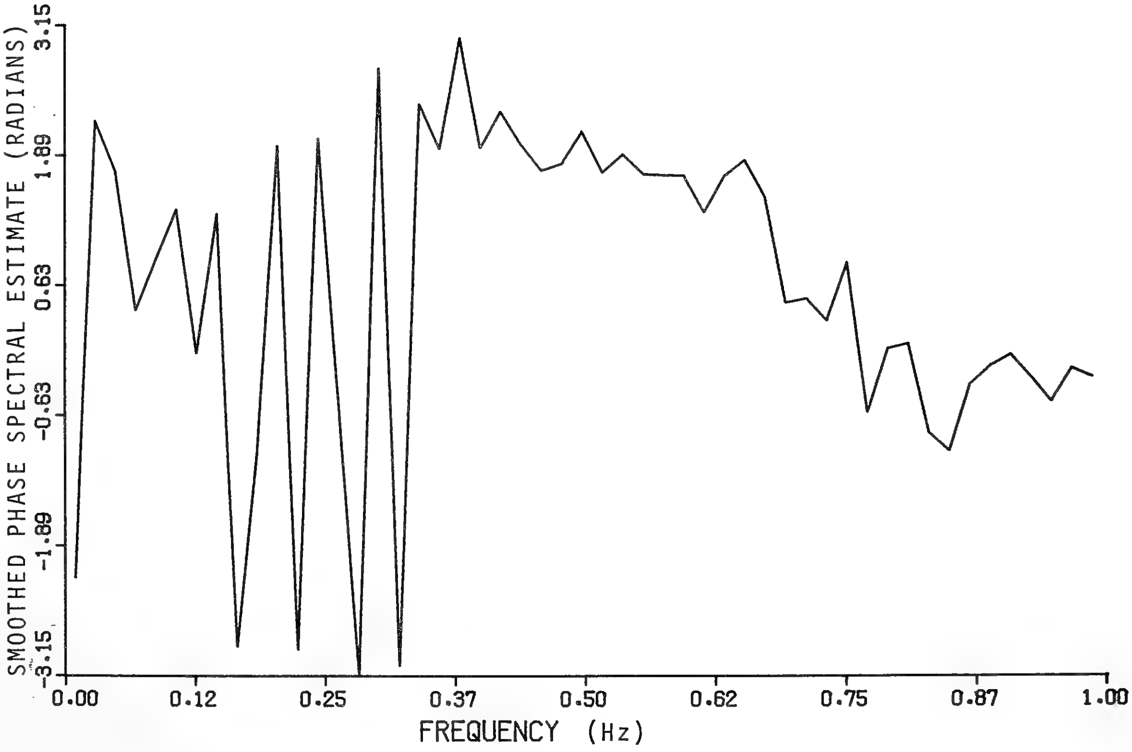


Figure J-16. Phase between sway and heave.

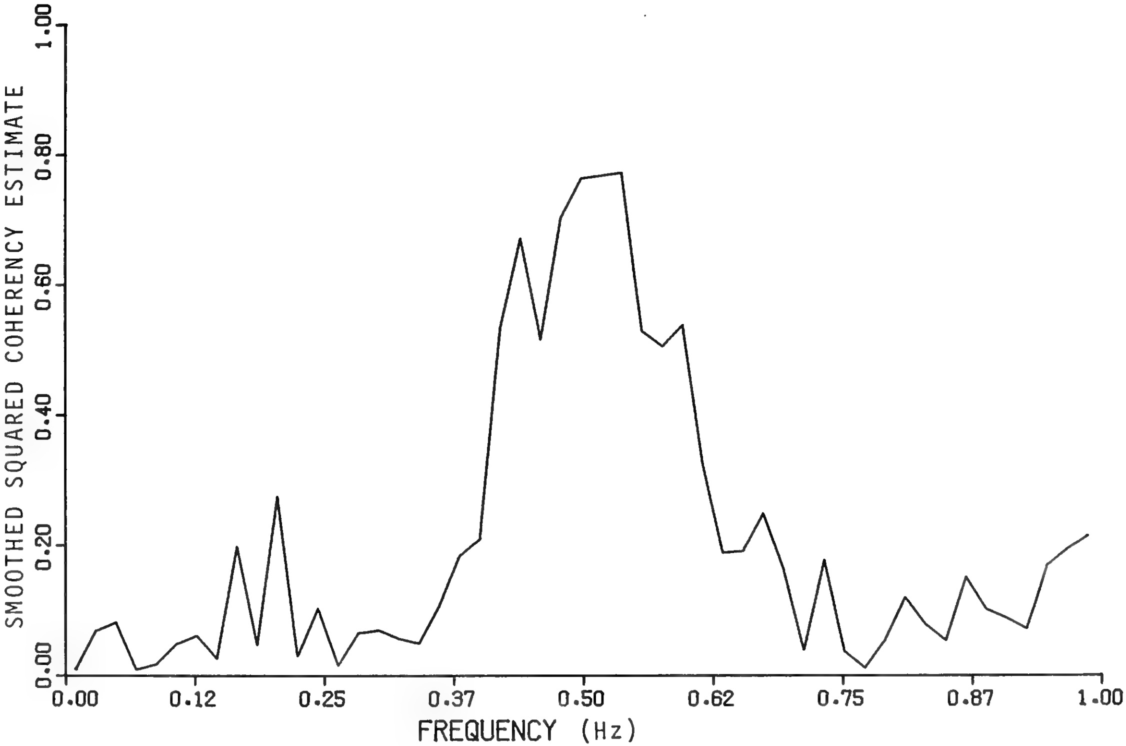


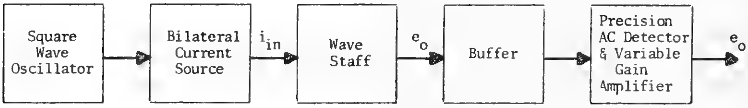
Figure J-17. Coherency between sway and heave.

APPENDIX K

WAVE MEASUREMENT

1. Wave Staff Design.

A block diagram of the wave staff and associated electronic circuits is shown below:



The wave staff itself consists of a length of PVC tubing which is spirally wound with a resistance wire, such that when it is immersed in seawater, the electrical resistance varies in direct proportion to the length of the exposed staff.

The electronic circuits driving the wave staff consist of a fixed frequency square wave oscillator (having a precisely controlled output amplitude) driving a precision bilateral current source with an output current directly proportional to the input voltage. Thus, the wave staff is driven by a current source of constant magnitude, but one which changes direction with each one-half cycle of the square wave oscillator. The output of the wave staff then is a square wave voltage with a magnitude (peak to peak) that is directly proportional to the length of the exposed wave staff. This output is fed to a high input impedance voltage follower circuit which serves as a buffer between the wave staff and the ac detector circuit. The precision ac detector circuit uses two operational amplifiers in conjunction with two diodes to form a precision full-wave rectifier circuit that is capable of operating at very low input voltages. Ordinary diode detector circuits cannot operate on ac signals of peak magnitude less than the forward voltage drop of the diodes and produce large conversion errors unless the signal magnitude is large with respect to the diode voltage drop. A gain control has been incorporated in the detector circuit so that full-scale output can be set at any positive value up to +10 volts with a wave staff resistance of 300 ohms up to 3,000 ohms.

Alternating current is used to drive the wave staff to avoid both the corrosion effects that would occur if direct current were used and the dc offset which occurs as a result of the use of dissimilar metals in a conducting solution. The latter is eliminated by use of ac coupling in the output from the wave staff.

Bench tests of the wave staff electronic circuits were made using a 1,000-ohm variable precision resistor in place of the wave staff. The circuit was adjusted to produce an output range of 0 to 10 volts with the resistor varied from 0 to 1,000 ohms. Linearity was determined to be 0.1 percent of full scale over this range.

Tests were also made to determine the effect of temperature on sensitivity and zero drift. A decrease in sensitivity was noted with decreasing temperature of about 0.03 percent of reading per °Celsius over the temperature range of 0 to 24°Celsius. A zero drift of 2 millivolts was also noted over the same temperature range. A ±10 percent change in supply voltage from the nominal ±15 volts produced no observable change in output. If we assume an operating temperature range of ±5°Celsius, the maximum error in the wave staff electronics due to the combined effects of nonlinearity and sensitivity variations with temperature is ±0.2 percent of reading. Since the primary interest is in a dynamic measurement of waves, the zero drift noted will have negligible effect on the experiment since temperature variations of any appreciable magnitude will only occur over long periods of time compared to the wave periods.

Further calibration tests were conducted using actual wave staffs of 1-inch diameter and 20-foot lengths, and 3.5-inch diameter and 8-foot lengths at various depths of immersion in saltwater. These tests were conducted from a dock at Shilshole Bay on Puget Sound. Because of ripples and waves on the water of the order of 1 inch (peak-to-valley) it was difficult to obtain a highly precise measurement. The output was recorded on a strip chart recorder and it was therefore possible to average these variations to some degree. The readout resolution of the strip chart (and accuracy) is about ±1/4 of a minor division. Full scale across the chart is 50 minor divisions and, thus, the resolution is about 0.5 percent of full scale. Some nonlinearity is noted near full immersion (see calibration curve). Some offset was expected because of the finite resistance of the saltwater path in the ground return which is not taken into account during initial calibration of the wave staff unit. The initial calibration is made with the wave staff on the dock where full scale and zero are set by making actual contact between the ground wire and the wave staff resistance element at the corresponding ends. However, measurements were made of the resistance of the saltwater path to ground in the same location where the wave staffs were immersed and the value of resistance measured (on the order of 10 ohms) does not account for the offset observed at full immersion. In addition, the offset should occur at all readings and it does not. Therefore, it is believed that the nonlinearity observed is a result of some other phenomenon as yet undetermined. Both units produced highest accuracy near center scale with decreasing accuracy toward either end. Overall accuracy including end points is about ±3 percent. If the range of operation is reduced so as not to use the last 1 foot on each end of the wave staff, the accuracy is improved to about ±1 percent.

The output from the wave staff electronic circuit is fed directly into a voltage to frequency converter; the frequency output is then counted and stored on separate storage registers, once every 50 milliseconds. If an 8-bit register is used for the wave staff measurement, the maximum count that can be stored is 255; therefore, the sample time must be on the order of 25.5 milliseconds (maximum count divided by maximum frequency output from voltage to frequency converter). The wave buoys use an 8-bit register with a 32.5-millisecond sample time while the wave staffs use a 16-bit register with a 250-millisecond sample time.

The error due to gain instability and nonlinearity of the voltage to frequency converter is of such low magnitude that it can be neglected and the overall accuracy of the recording is essentially the same as given for the wave staff unit by itself (i.e., between ± 1 and ± 3 percent depending on the range of operation on wave staff).

2. Spar Buoy Design.

Spar buoys were used at two of the sites because of their advantage in handling and transport and because they minimized the placement difficulties due to navigational hazards, water depth, and tidal conditions. The spar buoys were made of two PVC pipes coupled together near the center of the buoy. The lower section is a 15 foot by 6 inch pipe filled with styrofoam. The top section is 12 feet by 3 inches wherein the upper 8 feet is wound with a resistance wire which measures wave elevation. The wave staff electronics are mounted inside the top section, above the waterline, with the remainder being filled with a wood core to add stiffness. The buoys also have a 2.5-foot diameter damping plate mounted on the bottom and are anchored using a dual point mooring system with the anchor lines attached at the center of drag on the buoy to prevent it from being pulled underwater in strong currents. One of these buoys was tested in the Puget Sound just north of Seattle. Its performance exceeded expectations both in terms of minimized response to the waves and accuracy of wave height measurement. Figure K-1 gives a sample of the output from the buoy's wave staff in saltwater for a plus and minus 1 foot excitation of the buoy in heave. This was accomplished by pushing the buoy up and down by hand. Some distortion results from this approach which shows up in the output of the accelerometer mounted at the center of the response of the buoy in heave and roll in calm water. The natural periods for heave and roll taken from these plots are approximately 18 and 14 seconds, respectively. These are well out of the range of the 3-to-4-second wave periods expected at the site. Visual observations of the buoy in waves in excess of 1.5 feet indicated no observable heave or roll motion, but some yaw about the anchor line caused by the current and wind. This motion resulted in less than a 1 foot variation from the buoy's horizontal position in calm water and appeared to have periods in excess of 30 to 60 seconds. For comparative measurements, the buoy was located about 30 feet from an existing four-gage array of 1-inch diameter Oceanographic Services, Inc. resistance wire wave staffs. A comparison of simultaneous output from the two wave staffs (buoy mounted and stationary) is shown in Figure K-4. The autospectras computed from data obtained from one of the stationary wave staffs and from the spar buoy, in a 25-miles per hour storm with

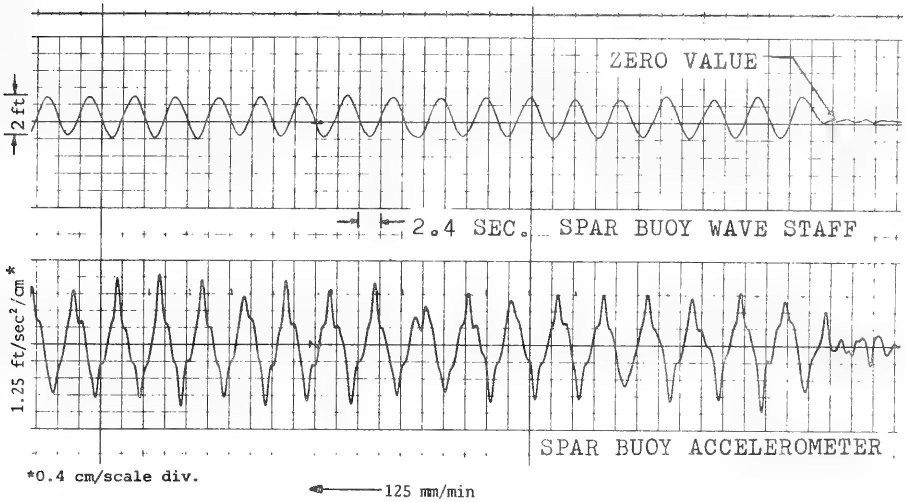


Figure K-1. Wave and acceleration data for par uoy.

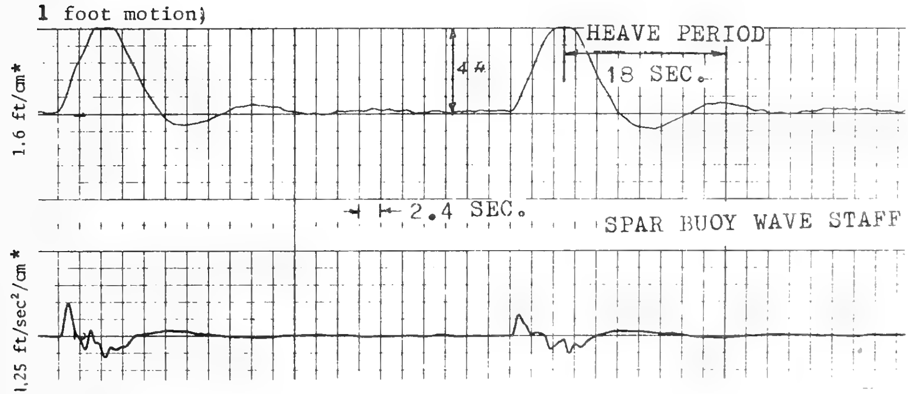


Figure K-2. Spar buoy heave response.

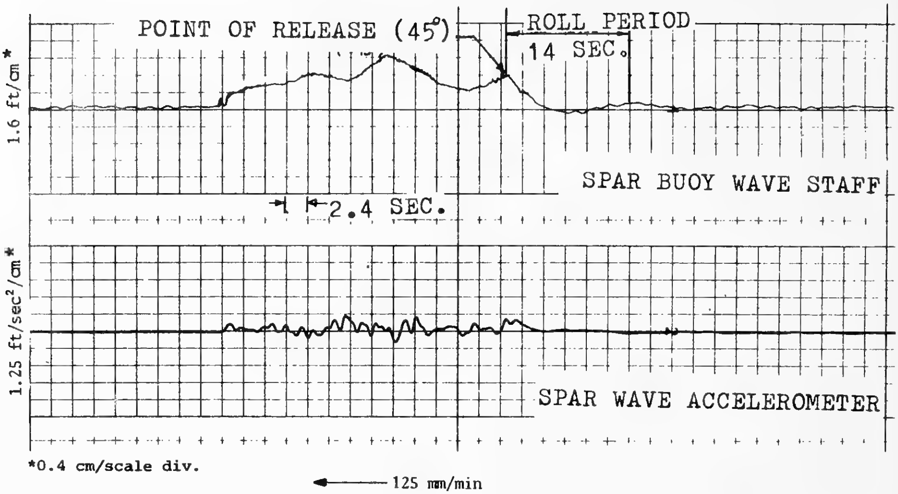


Figure K-3. Spar buoy roll response.

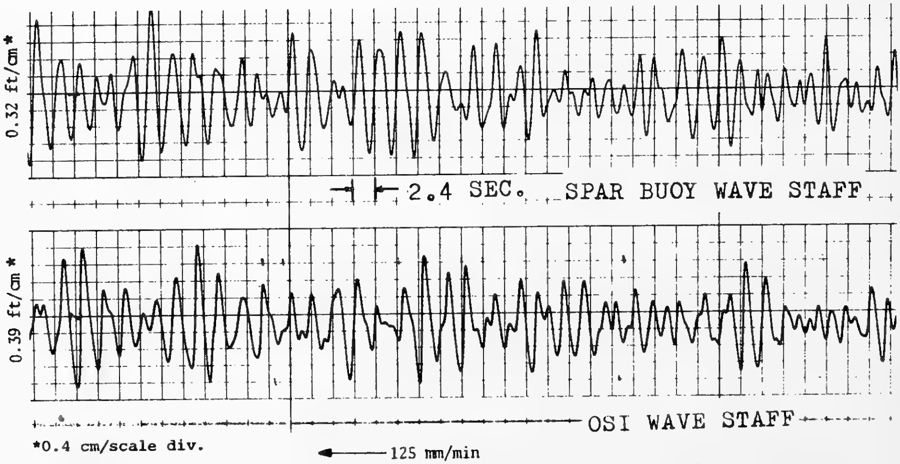


Figure K-4. Wind wave data for spar buoy and stationary staff.

maximum wave heights in excess of 1.5 feet are shown in Figure K-5. These spectra were computed from simultaneous records of 20 minutes in length.

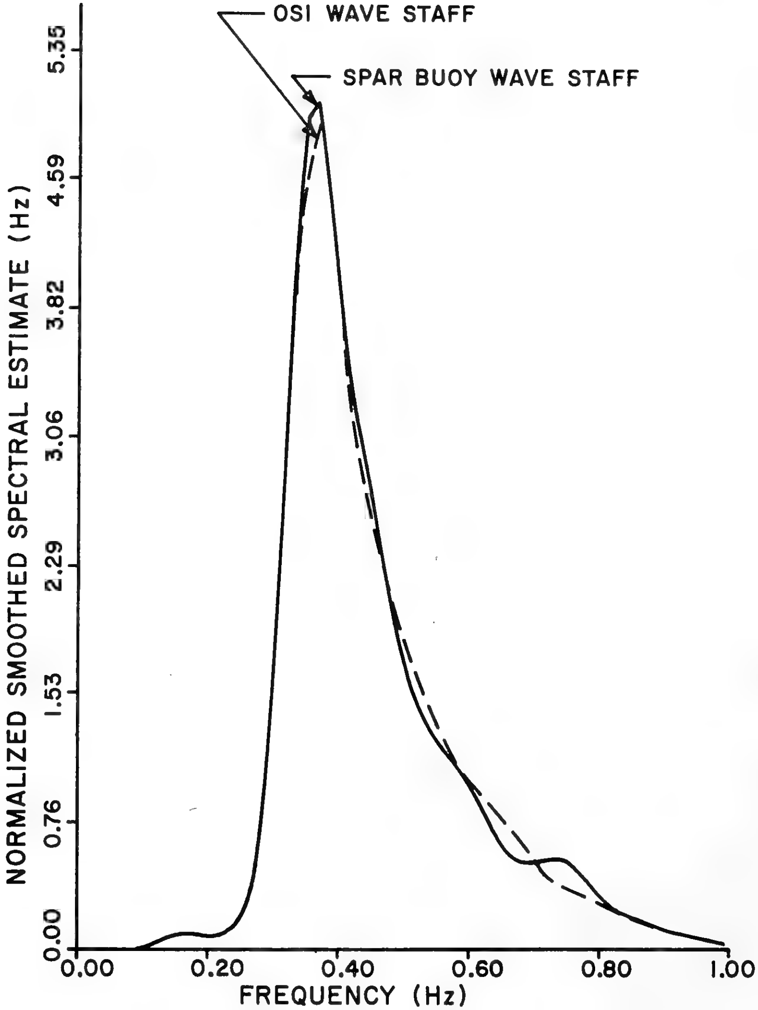


Figure K-5. Wave spectra from spar buoy and stationary staff.

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