A COMPUTER PROGRAM TO ESTIMATE THE COMBINED EFFECT OF REFRACTION AND DIFFRACTION OF WATER WAVES

Prepared by

HENRY W. WORTHINGTON
JOHN B. HERBICH
Coastal and Ocean Engineering Division
Texas Engineering Experiment Station

August 1970

TAMU – SG – 70 – 219 COE Report No. 127

A COMPUTER PROGRAM TO ESTIMATE THE COMBINED EFFECT OF REFRACTION AND DIFFRACTION OF WATER WAVES

by

Henry W. Worthington and John B. Herbich
Coastal and Ocean Engineering Division
Texas A&M University

Partially Supported by the National Science Foundation
Sea Grant Program
Institutional Grant GH-59 to
Texas A&M University

Sea Grant Publication No. 219
Coastal and Ocean Engineering Division
Report No. 127 - C.O.E.

August 1970

ABSTRACT

This study reviews the phenomena which generally affect water waves entering a harbor, and discusses the traditional methods of calculating the effects of the three principal phenomena - refraction diffraction and shoaling. The utility of harnessing the capability of the computer to make the required calculations is illustrated.

A computer program is presented which estimates the effects of refraction and diffraction as they combine to change the direction and height of water waves. A unique feature of the program, referred to as "REDSEA", is that it considers the degree of reflection from the breakwater in calculating the diffraction coefficients.

The validity of the predicted results is established by comparin them to experimental data obtained in connection with this study as well as data from a similar study conducted previously. Applications of the program to design and analysis problems are discussed.

PREFACE

Research described in this report was conducted as part of the continuing research program in Coastal and Ocean Engineering at Texas A&M University.

The report was written primarily by the senior author in partial fulfillment of the requirements for a Master of Science Degree in Civil Engineering. The research and this report on the research were supervised by the junior author.

This study was partially supported by the National Science Foundation Sea Grant Program Institutional Grant 59 to Texas A&M University.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Dr. Schiller, Mr. Jim Young, Miss Loretta Bayer, and the other staff and faculty members of the Coastal and Ocean Engineering Division at Texas A&M University, whose assistance was most valuable. A special expression of apprecia-tion is also extended to the Chicago Bridge and Iron Company of Oak Brook, Illinois, whose financial support provided the wave tank facility used in this study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The Coastal Engineer is charged with the task of evaluating the nature of the sea and designing his structures and facilities in such a manner that both the coastal environment and his products may coexist in harmony. While history records the efforts of Coastal Engineers as long ago as 2000 B.C. with the construction of the port of A-ur, it is repleat with the failures and shortcomings of the men involved in the discipline. One of the early failures involved the construction of the port of Ostia, Italy, about 43 A.D. Soon after its completion, engineers were confronted by unexpected silt which began accumulating in the port, and within 75 years the port was closed by the silt.[17]

It is not necessary to go so far back into history to find an example of such a failure, for one of the classic examples of inadequate engineering along the coast occurred on the California coast at Santa Barbara. Here beginning in 1927, a breakwater was constructed to create a harbor for pleasure craft. The breakwater interrupted the littoral drift of sand, however, and not only caused the harbor to fill with sand, but caused serious erosion of the beaches downcoast. Undoubtedly the Santa Barbara harbor would

---

The citations on the following pages follow the style of the Journal of the Waterways and Harbors Division, American Society of Civil Engineers.

have long since met the same fate as Ostia but for the ability of modern dredges to keep the harbor open by a process of continuous dredging.[17]

Countless other examples are readily available, but need not be cited, for the point to be made is that throughout history, the Coastal Engineer has been plagued by the difficulty in forecasting precisely the effects his structures will have on the balance of forces which nature has established. Waves, winds, tides, currents, beach materials, storms, hurricanes, and many other factors interpla in such a complex fashion that their effects on a structure, and conversely the effect of a structure on the balance of these forces, cannot generally be calculated with great accuracy. Furthermore, the calculations that have traditionally been used to give approximations are often tedious and time consuming.

To overcome the inability of mathematical calculations to accurately predict a result, modern planners have resorted to the extensive use of physical models. These models are often quite elaborate and are themselves governed by various model laws. In general, these models give very good results, provided they are properly designed and carefully constructed. However on the debit side, models are costly, difficult, and slow to build. A thorough model study of a harbor construction plan may take months or even years.

In the last decade the digital computer has emerged as a most powerful tood in countless fields of endeavor, and certainly the

Coastal Engineer can be counted as one of its benefactors. By harnessing the power of the computer, the engineer is able to make almost instantly the myriad of calculations that formerly were very painstaking or even out of the question due to their complexity. He is able to investigate a large number of possibilities in a mere fraction of the time formerly required to analyze a single design. While the computer cannot by any stretch of the imagination replace the sound engineering judgement or experience of the Coastal Enginee , nor can it replace completely the physical model, it does have many applications in the field of Coastal Engineering and may complement engineering judgement and physical model studies. The paragraphs that follow will discuss one such application of the digital computer to Coastal Engineering.

CHAPTER II

HARBORS, BREAKWATERS, AND WAVES

General

A harbor is a protected part of a body of water where vessels may take refuge from heavy seas. More specifically it is a place where waves coming from the open seas will be sufficiently reduced in height that vessels will not be endangered. Where natural harbors are inadequate in size or number, artificial harbors may be created by constructing breakwaters to protect a body of water, but regardless of whether a harbor is natural or artificial, the waves approaching the harbor are not usually stopped altogether, but instead are merely reduced in height. The problem to be submitted to the digital computer for solution is "How much will the wave height and direction be changed under these circumstances?"

The degree of reduction is a function of many things: water depths within the harbor, water depth contours at the harbor entrance, the direction of approach of the incident wave, the period of the wave, water currents, the entrance width, the degree of wave reflection from the breakwater, and the particular area of interest within the harbor, to mention only the most important. Even if all of the variables named are given specific values, it is a very involved task to arrive at an approximation of the wave height. If the wave height for a number of points within the and breakwater designs, the effort required is multiplied accordingly. Prior to the advent of the digital computer, the calculations required might have taken thousands of man-hours, with a correspondingly large possibility for human error. However the incredible speed of the computer in making the same calculations reduces the time required to a few minutes, and virtually eliminates the possibility for error. A brief review of the phenomena of wave transformation will serve to illustrate the point.

<u>Propagation of Waves into Shoaling Water</u>

The Linear Wave Theory relates the velocity of a progressive wave to other variables by the formula

$$C = \sqrt{\frac{gL}{2\pi} \tanh \frac{2\pi d}{L}} \qquad (1)$$

where:

L = wave length

C = wave celerity

g = acceleration of gravity

T = wave period

d = water depth

In relatively shallow water ($\frac{d}{L} < \frac{1}{2}$) this equation reduces to

$$C = \sqrt{gd} \quad . \qquad (2)$$

It is seen that the wave velocity (or celerity) in conditions of shallow water is dependent only upon the depth of the water at the point in question. Now if a wave approaches shallow water at an angle to the bottom contours, then part of the wave will be slowed down before the rest of the wave which is in deeper water, causing the wave to be bent, or "refracted". If orthogonals are constructed perpendicular to the wave fronts, these orthogonals will be seen to converge or diverge depending on the bottom contours.

If these orthogonals diverge, the energy contained within a wave is redistributed along a wider front and intuitively it is recognized that the height of the wave should be decreased under these conditions. The energy of one wave per unit width can be determined by the equation

$$E = \frac{\gamma H^2 L}{8} \qquad (3)$$

and the energy between two orthogonals a distance b_o apart is given by

$$E = \frac{\gamma H_o^2 L b_o}{8} \qquad (4)$$

where:

E = energy

H = wave height

b = distance between orthogonals

γ = specific weight of water

subscript "o" denotes deep water

The assumption is generally made that during the process of refraction there is no energy transfer between orthogonals, and this

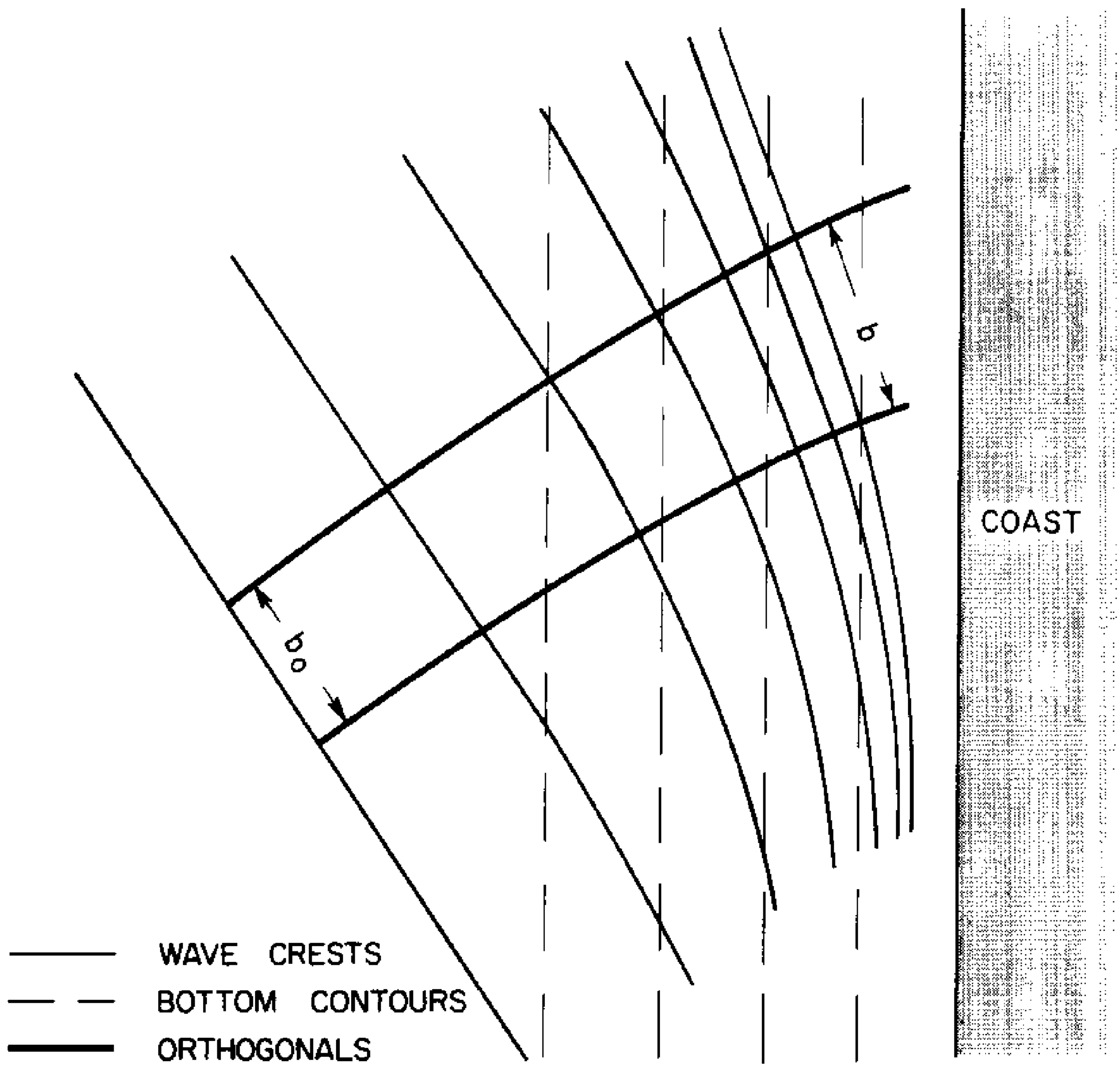

FIG. I WAVE REFRACTION DEFINITION SKETCH

$$\frac{\gamma H_o^2 L b_o}{8} = \frac{\gamma H^2 L b}{8} \quad (5)$$

From this can be obtained the ratio

$$\frac{H}{H_o} = \sqrt{\frac{b_o}{b}} \quad (6)$$

which is called the refraction coefficient, C_r.[17]

As the wave moves into shallow water, it is also subjected to a second transformation in addition to refraction, called "shoaling." The power transmitted by a wave is proportional to the energy of the wave and the group celerity of the wave. If the celerity becomes less in shallow water, but the rate of shoreward energy transfer remains constant, then the wave height must change. The ratio of the wave height in shoaling water to the deep-water height is given by

$$\frac{H}{H_o'} = \left[\frac{1}{\left(1 + \frac{2Kd}{\sinh 2Kd}\right) \tanh Kd} \right]^{1/2} \quad (7)$$

where:

$$K = \frac{2\pi}{L} .$$

This ratio is known as the shoaling coefficient, C_s.[5]

The evaluation of the shoaling coefficient is simplified by tables contained in References 2 and 17, which give H/H_o' as a function of d/L or d/L_0. The evaluation of the refraction coefficient, however, is much more involved. For several decades two to engineers. The first method, known as the "wave front method", is essentially a chart showing successive wave crests, with each crest separated from the preceeding one by a distance proportional to the wave celerity. Orthogonals to the crests are then drawn, which determines the distances b and b_o. (See Fig. 1). The second method is similarly a graphical method, except that the orthogonals are constructed initially, without the necessity of first drawing the wave fronts. Both of these methods are discussed in more detail in References 2, 3, 5 and 17. But regardless of which method is used, the process is time consuming and the accurac obtained is dependent on the skill of the draftsman.

Diffraction of Waves

The third and final change in wave form as it might enter a harbor is due to the phenomenon called diffraction. Wave diffraction occurs as part of a wave is "cut off" as it moves past an obstruction such as a breakwater. The portion of the wave passing beyond the obstruction and any wave reflected back from the obstruction act as an energy source and cause waves of a circular pattern in the lee of the obstruction. The classical treatment of this phenomenon, which owes its origin to the study of polarized light, is described by Putnam and Arthur[14] and Wiegel[17]. Their analysis shows

$$\eta = (a\ i\ K\ C/g)e^{ikCt} \cosh kd \cdot F(r, \theta) \qquad (8)$$

where:

$$F(r, \Theta) = f(\sigma)\, e^{-ikr \cos(\Theta-\Theta_o)} + f(\sigma')\, e^{-ikr \cos(\Theta+\Theta_o)} \tag{9}$$

$$\sigma = \sqrt{4kr/\pi} \quad \sin[(\Theta_o+\Theta)/2] \tag{10}$$

$$\sigma' = - \sqrt{4kr/\pi} \; \sin[(\Theta_o-\Theta)/2] \tag{11}$$

$$f(\sigma) = \frac{1+i}{2} \int_{-\infty}^{\sigma} e^{\frac{-i\pi t^2}{2}} dt \tag{12}$$

$$f(\sigma') = \frac{1+i}{2} \int_{-\infty}^{\sigma} e^{\frac{-i\pi t^2}{2}} dt \tag{13}$$

and

η = distance from still water level to surface

a = wave amplitude

i = $\sqrt{-1}$

r, Θ = radius vector and vectorial angle respectively of polar coordinate system

t = time

Equation (12) may be rewritten (Ref. 4)

$$f(\sigma) = \frac{1+i}{2} \left[\int_{-\infty}^{o} e^{\frac{-i\pi t^2}{2}} dt + \int_{o}^{\sigma} e^{\frac{-i\pi t^2}{2}} dt \right]$$

$$= \frac{1+i}{2} \left[\frac{1-i}{2} + \int_{o}^{\sigma} \cos \pi\, 1/2\, t^2\, dt - i \int_{o}^{\sigma} \sin 1/2\, \pi\, t^2 dt \right] \quad (14$$

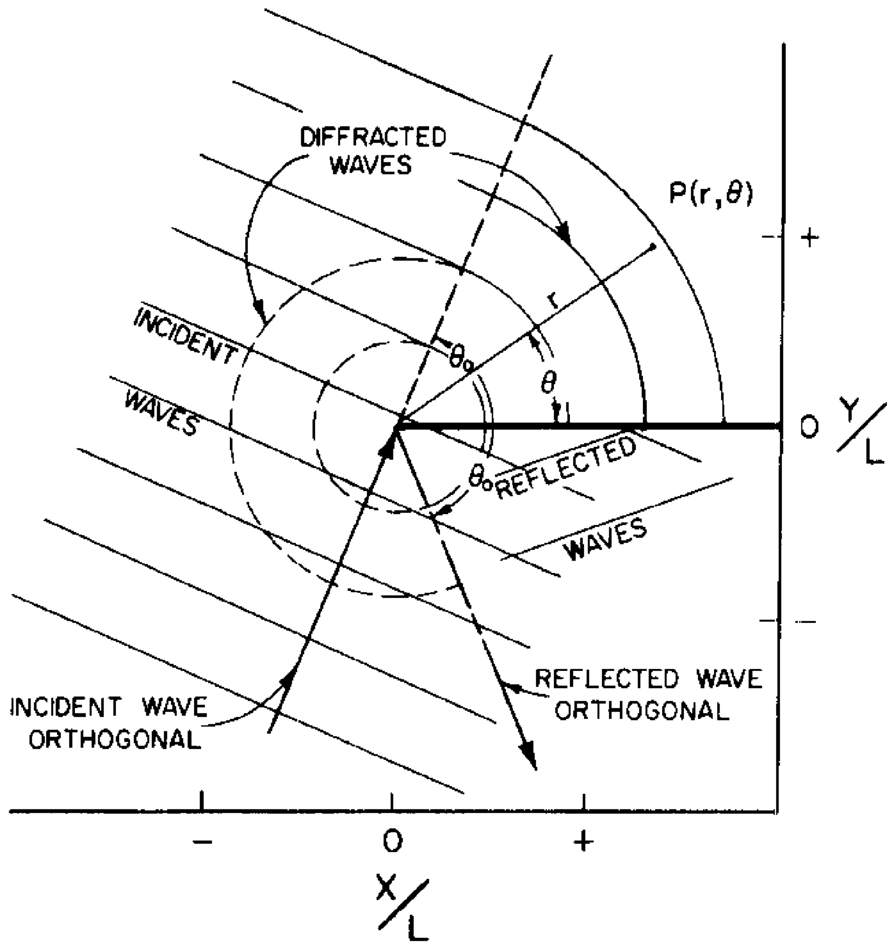

FIG. 2 WAVE DIFFRACTION DEFINITION SKETCH

Useful functions in solving this equation are the Fresnel integrals which are defined[8] as

$$C(x) = \int_0^x \cos(u^2)du \quad (15$$

and

$$S(x) = \int_0^x \sin(u^2)du \quad (16$$

Tabulated values of these Fresnel integrals then permit the evaluation of (12) and (13), which in turn permit the calculation of the wave height at any point in the vicinity of the breakwater.

The second term of equation (9) represents that portion of the diffracted wave which is caused by the reflected wave from the breakwater. In general, tables of diffraction coefficients C_d have been calculated assuming 100% reflection from the breakwater.[2, 4, 13] Yet the experiments that have been conducted to verify the diffraction theory[14] as well as breakwater construction practice, use structures that probably come closer to 0% reflection than 100%. This discrepancy is pointed out and discussed by Silvester and Lim[15] although there is no single instance in the literature where the degree of reflection is used to determine the diffraction coefficient.

Several practical considerations have probably dictated this rather careless treatment of the reflected portion of the diffracted wave in the past. First, this term is significant only in the zones immediately in front of the breakwater and near the tip of the breakwater. Further inside the harbor this term generally becomes insignificant as can be demonstrated with the computer program to be presented in this study. Secondly, diffraction coefficients traditionally have been determined by design engineers from charts and tables such as those in References 2, 4 and 17. These charts and tables are of necessity somewhat unwieldy as they stand. If many sets of these were to be constructed, with each set representing a different coefficient of reflection from the breakwater, the result would be a disproportionate increase in the volume of published diffraction tables, with little increase in accuracy. However where the diffraction coefficient is calculated mathematically, as it is readily done by computer, it is a simple matter to include a percentage of this term equal to the percent reflection from the breakwater. Detailed discussions of the theory of water wave diffraction are contained in References 3, 4, 7, 10, 14 and 17.

Combined Effects - Diffraction of Waves in Shoaling Water

The theory of wave diffraction is based on the assumption that the water depth in the region of diffraction is constant. As one might imagine, it would be a rare harbor indeed that might have water of a constant depth throughout its reach. If the theory does not apply to actual conditions, then how do we estimate wave attenuation under actual conditions? The U.S. Army Coastal Engineering Research Center describes what has been done in practice for several decades.[2]

1. Construct a refraction diagram shoreward to the breakwater.
2. Construct a diffraction diagram carrying the successive crests shoreward three or four wave length
3. With the wave crest and wave direction indicated by the last shoreward wave crest determined from the diffraction diagram, construct a new refraction diagram to the breaker line.

This procedure represents the state of the art today. Considering the work that would be involved to estimate wave height and direction under conditions of varying tides, varying wave periods, varying wave directions, varying breakwater locations and varying breakwater reflection coefficients, it becomes obvious that a thorough investigation represents a monumental task. And yet such an investigation is often warranted because the safety of harbored vessels, currents within the harbor, littoral drift, equilibrium harbor shorelines, and conditions of seiche are all influenced by the wave height and direction within the harbor.

Furthermore, the question arises as to the validity of this technique of evaluating the combined effects, since it does seem to lack somewhat in precision. The literature describes only one study which has been done to evaluate the combined effects. This study was done by Mobarek in 1962 in a wave tank 6 feet by 12 feet. Even though Mobarek notes the serious limitations imposed by his equipment and strongly suggested that more experiments on a larger scale be conducted, there do not seem to have been any further experiments.

Summary

In summary there are three principal phenomena which affect the height of water waves entering a harbor: refraction, shoaling, and diffraction. Of these three, two also affect wave direction: refraction and diffraction. Any one of these three can be readily evaluated using techniques that have been available to engineers for a number of years. However, it is a very time consuming proces to evaluate the combination of these effects simultaneously, and furthermore there is a need of further evidence that the method currently employed by engineers does give good predictions. If the digital computer could eliminate the tedious, time consuming task of predicting wave attenuation in a harbor, and if the compute predictions could be verified in a large scale model, it would be a worthwhile effort. This was precisely the objective of the study to be described in the paragraphs to follow.

CHAPTER III

A COMPUTER PROGRAM

General

The task of assembling a computer program to solve the simultaneous refraction-diffraction problem does not entail any concepts or theories that are new. On the contrary, the problem will be attacked much as it had been before the age of the computer. The same principles discussed in the previous chapter will constitute the basis for the computer solution. The computer program will be referred to by the acronym REDSEA, derived from "refracion and diffracion - simultaneous effects approximation."

Fortunately REDSEA did not have to be written without the benefit of the work of others who had found applications of the computer to wave phenomena. In 1967, Fan, Cumming, and Wiegel[4] published "Computer Solution of Wave Diffraction by Semi-Infinite Breakwater," which included a computer program that would evaluate the diffraction coefficient based on the theory previously discussed except that 100% reflection was assumed. A second computer program which would calculate the effects of refraction and shoaling was published in 1969 by Orr and Herbich[12] in "Numerical Calculation of Wave Refraction by Digital Computer." REDSEA represents essentially a combination of these two programs, along with a provision to include the effects of wave reflection from the breakwater. Both of these older programs, as well as REDSEA, are written in the FORTRAN IV computer language.

Refraction Program

The refraction program of Orr and Herbich begins with the establishment of a rectilinear coordinate system superimposed over the body of water, with the origin of the coordinates to the seaward side of the area of interest. A grid of evenly spaced lines is then oriented with the grid lines parallel to the coordinate axes, and the bottom topography is registered by noting the water depth at each grid line intersection. Other information submitted to the computer includes the angle of wave approach and wave period.

The second step in the refraction calculation is to compute and record within the computer memory bank the celerity of the given wave at each of the grid intersections. With this information the computer is caused to calculate the path of a wave orthogonal from a given starting point and with a given starting direction. This is done by calculating the grid coordinates of the intersection of the wave crest and the orthogonal at a given time increment which must be specified by the program user. A single orthogonal is traced in this manner until it reaches the limits of the grid system or the shoreline. At each of the points thus plotted along the orthogonal trace, the coefficients of refraction and shoaling as well as the wave direction are calculated using mathematical techniques described in the refraction portion of REDSEA (Appendix 1) and in Reference 12. The useful information which the computer may be called upon to deliver are a series of points along an orthogonal, with the coordinates, wave height, and wave direction for each of these points. Th program user may specify as many orthogonal starting points as may be desired, and this will cause the computer to give the complete trace of each orthogonal, so that the wave pattern in the area of interest may be determined.

Diffraction Program

The program to calculate the diffraction coefficient presented by Fan follows very closely the mathematical theory which was discussed briefly in the previous chapter, and which is discussed in greater detail in Reference 17. The original program by Fan however not only involves some computer techniques which have since been superceded, but is partly written in MAP computer language which is not generally used by engineers. For these reasons the diffraction program was rewritten for this study, although many of the mathematical procedures presented in Reference 4 were retained.

This newer diffraction program is presented as Subroutine "DIFFR" in the REDSEA program, and requires as input information a wave length, a wave angle with the breakwater, a coefficient of reflection from the breakwater, and the transposed rectilinear coordinates of the point for which the diffraction coefficient is desired. From this information, the parameters for diffraction calculations are determined. The Fresnel integral values are evaluated through the use of a series expansion.[13] The variables used in subroutine DIFFR are acronyms from the mathematical procedures previously mentioned, and the steps involved in Subroutine DIFFR may be readily related to the steps in the mathematical procedures.

REDSEA

REDSEA is a combination of the Orr and Herbich refraction program and subroutine DIFFR. In the simplest terms, the technique use in REDSEA is to initiate orthogonals as in the refraction program. Then as each point along an orthogonal is located, the refraction and shoaling coefficients are calculated as before. Following this the coordinates of the point are transformed into coordinates used in the diffraction coefficient calculations, (see Fig. 2) and a wave length at that point is calculated according to the relationship

$$L = CT \qquad (18)$$

With this information a diffraction coefficient is calculated and the wave height at that point becomes the product of the shoaling, refraction, and diffraction coefficients. A wave orthogonal is terminated when it reaches the breakwater, the limits of the grid, or the shore. The orthogonals thus plotted are termed "primary" orthogonals for future reference.

Once all of the primary orthogonals have been plotted, the computer program initiates a second series of orthogonals in the lee of the breakwater, which will be termed "radial" orthogonals.

The orthogonals of this series all start at the breakwater tip but differ from each other in the direction each takes initially.

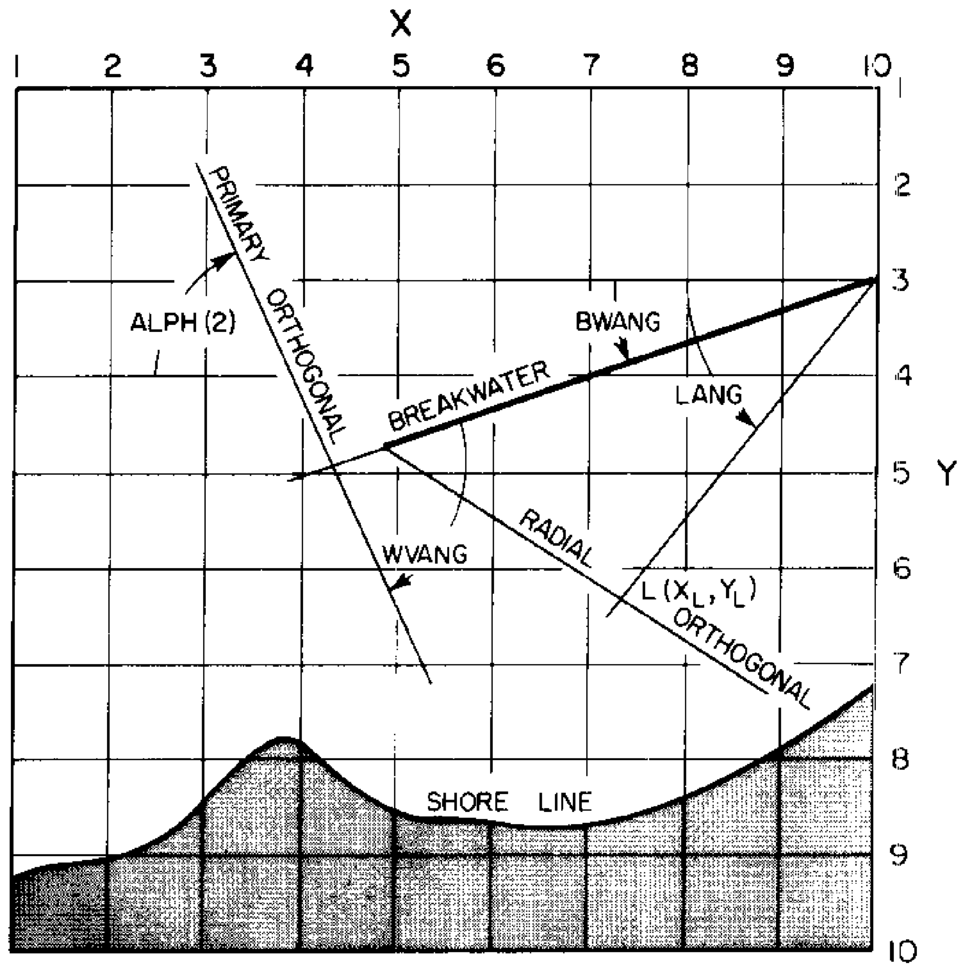

FIG. 3 REDSEA DEFINITION SKETCH

first radial orthogonal a direction fifteen degrees clockwise from the breakwater line. Each successive radial orthogonal is assigned an initial direction fifteen degrees clockwise from the preceeding one, and the initiation of radial orthogonals is continued until finally an orthogonal is propagated out of the lee of the breakwater, at which point the problem is stopped.

Several problems are encountered in implementing the basic plan for REDSEA however. First, in order to calculate a diffraction coefficient, the angle between the wave orthogonal and the breakwater must be known, and yet if refraction takes place between the orthogonal origin and the breakwater, the angle will not be known until the orthogonal is propagated to the breakwater. To overcome this problem, an approximation is made in REDSEA. For all of the primary orthogonals, the angle between the breakwater and the wave orthogonal is taken as the value of that angle at the orthogonal origin. In other words, any change in direction due to refraction between the origin and the breakwater is neglected. The error introduced by making this assumption is small since diffraction coefficients will generally be near unity except in the lee of the breakwater, and a small variation in the angle of incidence will have little effect. However in the lee of the breakwater, this angle is very important, and for this reason the assumption is not carried on to the radial orthogonals. Instead, the wave angle of the last orthogonal passing the breakwater tip is taken as the angle of incidence for the breakwater. A similar problem is encountered in calculating the wave height in the protected zone, for if the wave height was changed by refraction before a wave reached the breakwater tip, then this change would influence the wave height in the lee. Since the radial orthogonals are initiated at the tip of the breakwater with an initial refraction coefficient of unity, any changes that might have previously occurred in the height would not be accounted for unless specific provision were made. In this case the refraction coefficient of the last orthogonal passing the breakwater is recorded, and all wave heights in the breakwater lee are increased or decreased in proportion to this value.

REDSEA was written with as few limitations as possible within the established framework, and has been used to simulate conditions in a 6 ft x 12 ft wave tank, as well as a bay half a mile wide. A thorough understanding of the program may be gained by a study of the complete program in Appendix II, along with the description of the variables in Appendix III and Figure 3.

As is illustrated in the REDSEA printout in Appendix III, the program produces information which is divided into two sections. The first section is a recapitulation of the water depth data as it was recorded within the computer, and it is included in the data printout primarily to facilitate the detection of any errors in this information. The second section is a detailed account of the REDSEA prediction for the conditions given, and is self-explanitory. It should be noted that as many problems as are desired may be run at one time by adding a separate problem data card for each set of wave conditions following the Water Depth Cards. (See Appendix II)

CHAPTER IV

LABORATORY INVESTIGATION

General

Although REDSEA is capable of predicting wave height and direction, the only data available to check these predictions is that from Mobarek's small tank. Since equipment is now available at Texas A&M University to conduct better tests on a larger scale, it was decided to conduct experiments with waves under conditions of simultaneous diffraction and refraction which would permit the comparison of predicted wave heights and directions with actual conditions.

Equipment Description

The wave tank used in the experiment (Fig. 4) is 86 feet long, 32 feet wide, and has a water depth of 2 feet. The wave generator is capable of producing waves of heights ranging up to 6 inches, and periods ranging from 1.28 to over 12 seconds. For ease of measuring, however, all testing was conducted at the maximum height and minimum period. The wave generator consists of a metal plate, hinged at the bottom and extending the width of the tank, which is driven by an electric motor through a variable diameter pulley transmission.

Wave absorbers in the breakwater lee consisted of horsehair

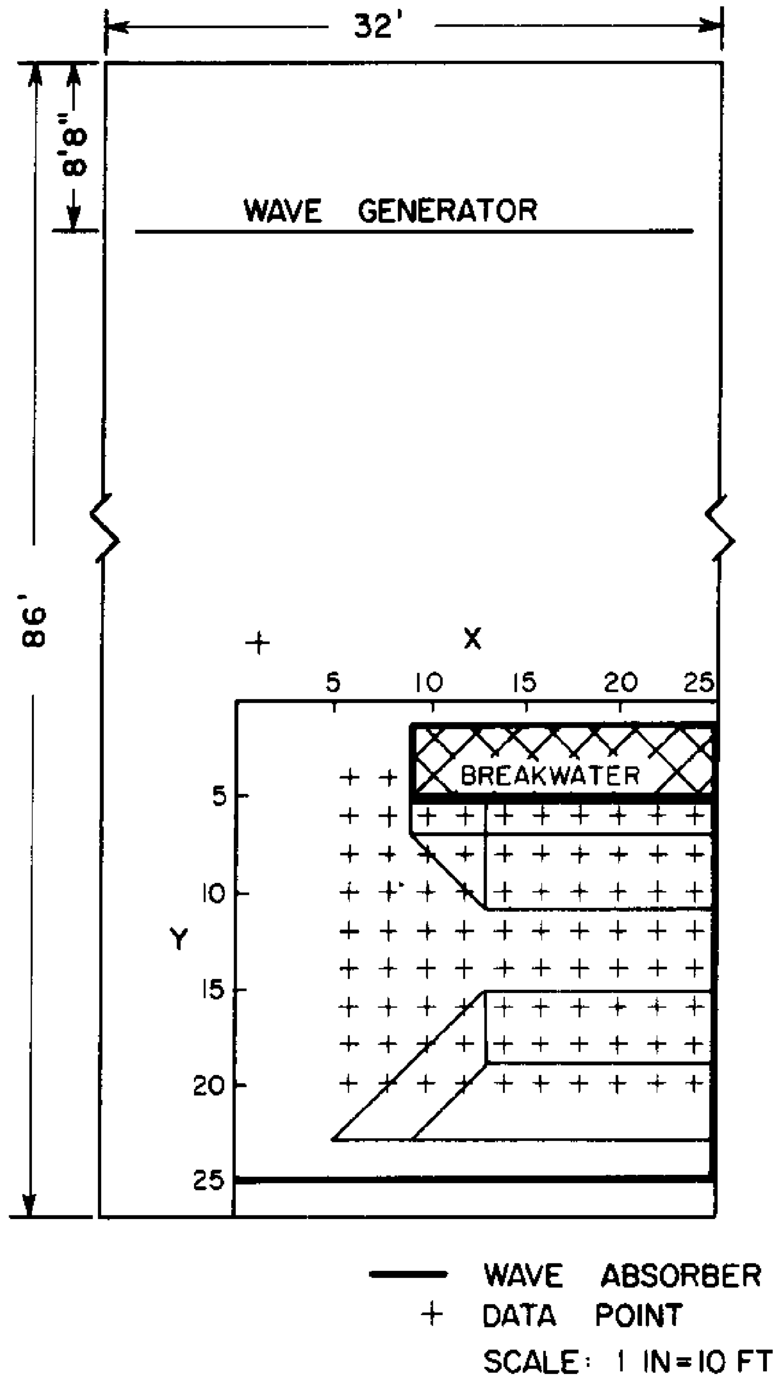

FIG. 4 WAVE TANK PLAN

of the breakwater was constructed by placing horsehair and a porous metal mesh between layers of expanded aluminum reinforcing mesh. This absorber was supported at a 30 degree angle from the horizontal and gave 22% reflection of the wave used in the experiment. This reflection coefficient was determined by measuring the wave envelope in front of the absorber and applying the formula

$$\frac{H_r}{H_i} = \frac{H_{max} - H_{min}}{H_{max} + H_{min}} \qquad (19)$$

where H_r = height of reflected wave, H_i = height of incident wave, H_{max} = maximum height of envelope, and H_{min} = minimum height of envelope.

The bottom of the wave tank is of finished concrete, and the desired irregularities in the bottom were fabricated from plywood and aluminum sheeting. The breakwater was made of concrete cinder blocks weighted on top to prevent overturning by the wave forces.

Wave heights were measured by a battery of wave probes operating on a capacitance bridge principle, and gave water surface location to accuracy of plus or minus .005 feet. Six of these probes were used in the tests and the results were recorded electronically on standard recording paper. (Fig. 6)

The shape of the irregular tank bottom is shown in Figures 5 and 7. This particular bottom shape was chosen to give a sufficiently irregular topography so that the wave refraction would distinctly appear, and the relative depths were likewise chosen to afford distinct wave response to the changes in depth

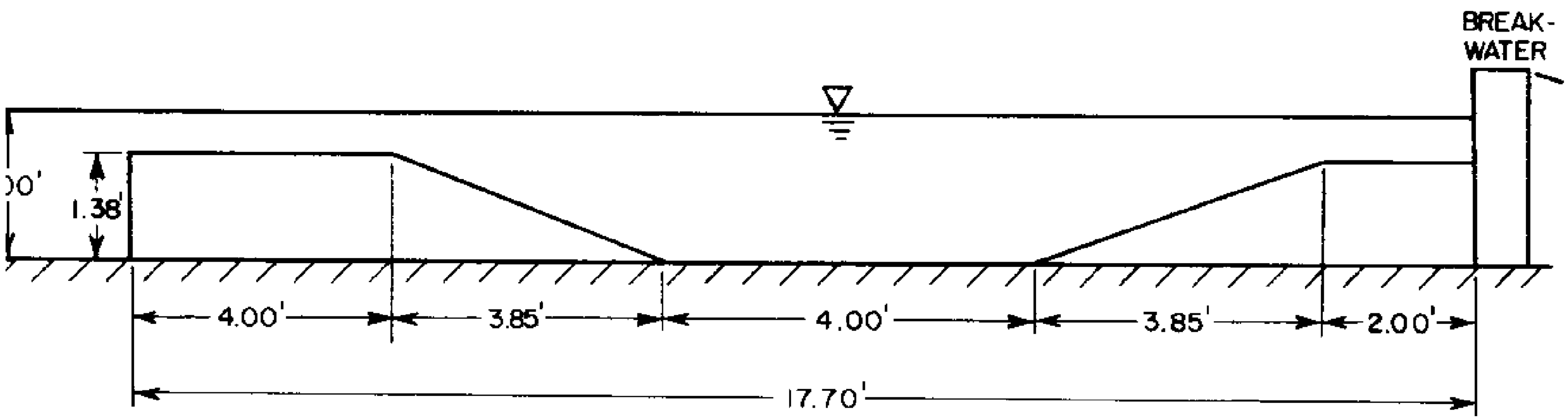

FIG. 5 MODEL HARBOR ELEVATION VIEW

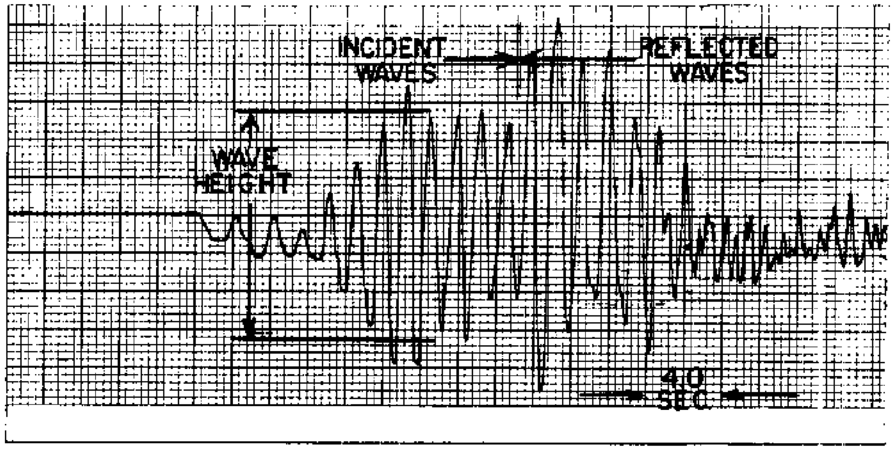

FIG. 6 TYPICAL WAVE HEIGHT DATA

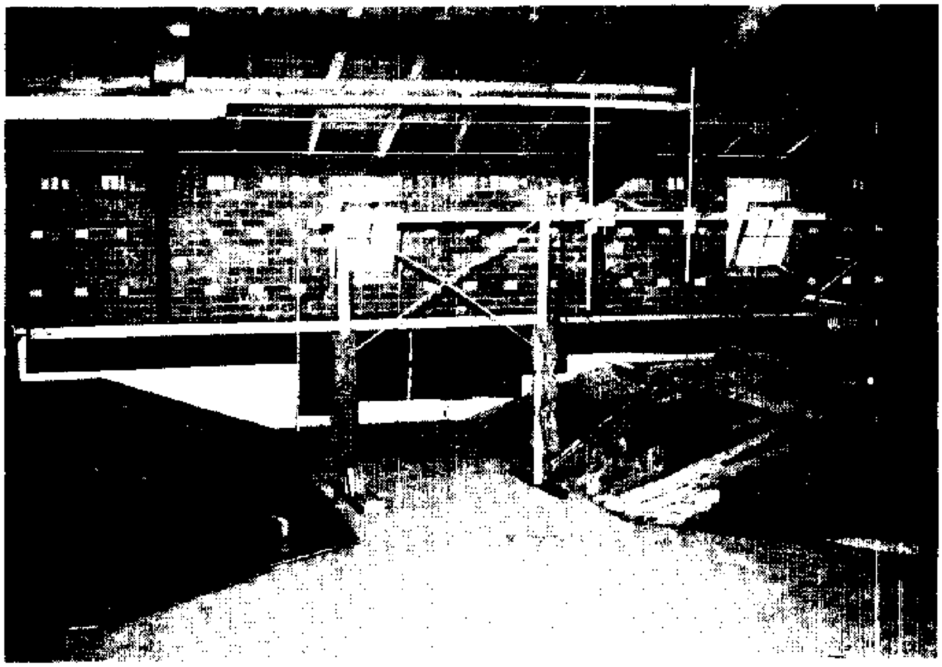

FIG. 7 EXPERIMENTAL BREAKWATER AND BOTTOM

Test Procedures

Tests were conducted in the wave tank to determine the change in the height and direction of the waves due to the effects of the breakwater and the irregular bottom. The wave heights were measured behind the breakwater on a grid with a two foot interval, and the height of the incident wave was measured simultaneously at a point eight feet from the end of the breakwater and eight feet in front of it. (See Fig. 4). Generally data were taken at six points simultaneously: the incident wave and five data points behind the breakwater. At times however it was not possible to use all of the data point gages which were suspended in the water from a moveable probe rack visible in Figure 7.

Due to the reflections from the end and sides of the tank, waves could not be run continuously in the tank to permit the collection of continuous data. Instead, a series of seven waves was propagated into the area of interest and height data was taken continuously until the water began to quiet again. The only data considered however, were the data from the fifth, sixth, and seventh waves. From Figure 6, it can be readily determined where the reflected waves began to affect the recorded wave heights. After each series of waves, the water was allowed to become calm before any further data were taken.

Laboratory Results

incident wave height are presented in Table 1. The incident wave height was found to remain constant at 0.49 feet throughout the testing. A sample of the recorded wave height data is shown in Figure 6, and the wave heights as they were taken from the data, as well as the reflected waves, are demonstrated in this data sample.

Table 1. Experimental Wave Height Coefficients, $\frac{H}{H_I}$ (H_I = 0.49 ft)

Y/X	6	8	10	12	14	16	18	20	22	24
4	1.06	1.08								
6	1.04	.950	.438	.173	.180	.140	.107	.132	.132	.122
8	1.04	.918	.414	.214	.184	.139	.116	.071	.061	.063
10	.979	.700	.447	.306	.200	.144	.102	.087	.078	.037
12	.924	.833	.432	.245	.151	.132	.102	.057	.057	.031
14	.898	.590	.398	.245	.176	.106	.091	.106	.077	.049
16	.939	.796	.388	.261	.135	.102	.063	.063	.041	.035
18	.896	.705	.380	.232	.170	.103	.089	.072	.045	.037
20	.806	.500	.355	.255	.214	.098	.061	.061	.045	.039

Table 2. REDSEA Wave Height Coefficients, $\frac{H}{H_I}$

Y/X	6	8	10	12	14	16	18	20	22	24
4	1.054	1.116								
6	1.144	.884	.359	.230	.268	.198	.096	.120	.104	.174
8	1.06	.744	.402	.235	.194	.135	.124	.060	.049	.054
10	.964	.693	.374	.236	.164	.123	.103	.067	.060	.033
12	.902	.658	.367	.229	.149	.111	.091	.072	.061	.039
14	.851	.641	.360	.234	.155	.111	.084	.072	.060	.043
16	.824	.628	.397	.229	.142	.103	.080	.067	.054	.043
18	.793	.616	.399	.218	.150	.104	.076	.054	.048	.043
20	.772	.609	.402	.206	.178	.097	.060	.056	.043	.033

CHAPTER V

ANALYSIS

Comparison of Wave Height Data to REDSEA Prediction

Wave heights were measured at eighty two data points in the wave tank, and the corresponding wave height coefficients are tabulated in Table 1. The predicted wave height coefficients for the same eighty two points from a REDSEA printout are shown in Table 2, and the values for each of the points is compared in Figure 9. Since REDSEA values of the wave height coefficient correspond to points on the trace of an orthogonal and do not fall directly on the data points, the REDSEA values for the wave height coefficients given in Table 2 and Figure 9 are the result of a two way linear interpolation between the four closest REDSEA orthogonal points.

It should also be noted that the incident wave in the experiment is not truly a deep water wave for it has a d/L_o ratio of 0.238, which gives a shoaling coefficient as it approaches the breakwater of 0.93, as may be determined either from the REDSEA printout in Appendix II or the tabulated values of H/H_o' in Reference 17. Since the wave height coefficient represents the ratio of the attenuated wave height to the deep water wave height, the ratio of the experimental attenuated wave height to the experimental incident wave height is predicted by dividing the REDSEA wave height coefficient at any point by the shoaling coefficient of the incident wave. Also the predicted

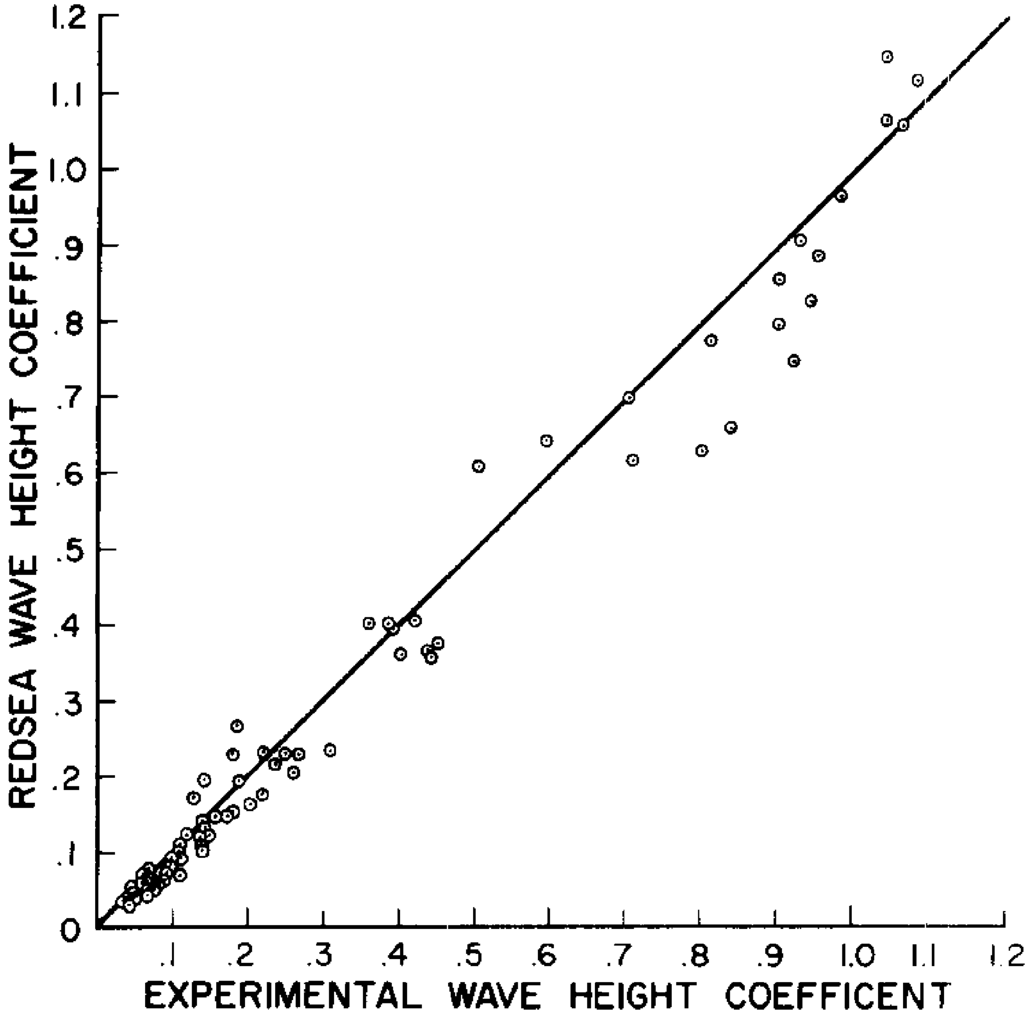

FIG. 9 COMPARISON OF EXPERIMENTAL DATA WITH REDSEA PREDICTION

values in Table 2 were determined from a substantially more detailed REDSEA coverage than the one reproduced in Appendix II (although both represent a prediction for the experimental conditions), and any slight discrepancies between the values in Table 2 and those in Appendix II may be attributed to this. The more detailed coverage was obtained by decreasing the DELT specified (see Appendix II) and by decreasing the radial orthogonal angle increment from fifteen to five degrees. This more detailed coverage is not included due to its much greater length.

The difference between the predicted wave height coefficients and the actual values is depicted graphically in Figure 9. The average error between the two values is 13.0% and the extreme error was 33%.

Sources of Error

It should be pointed out that some of this error is undoubtedly due to the difficulty in determining the true height of the attenuated wave. Although it was noted previously that the location of the water surface at any particular point could be determined to an accuracy of within .005 ft, it was not possible to determine the attenuated wave height nearly so accurately due to the reflection of waves within the experimental tank. Although the fifth, sixth, and seventh waves of a series were used to determine wave height, these waves often varied from an average height for the three by as much as 25% individually. It is estimated that the wave heights used to compile

Table 1 are limited in accuracy to within 15% due to this interference by reflected waves.

Several other possible sources of error existed within the experimental arrangements, although they probably contributed considerably less error than the reflected waves. One additional possibility was the nature of the bottom irregularities. As noted they were constructed of plywood (3/4 inch) and aluminum (1/8 inch) sheets. Although the irregularities were braced at several locations, it was noted that some of the larger pieces would flex by as much as 1/2 inch as waves passed over them, and this may have contributed some errors. Additionally, it was noted that as waves passed through the breakwater lee zone, some water passed between the construction joints in the irregular bottom structures, and this likewise may have altered the wave height somewhat.

REDSEA Prediction for Mobarek Wave Tank

As an additional check on the validity of its predictions, the REDSEA program was used to predict wave heights in the Mobarek tank and the results of this prediction were compared to the data given by Mobarek for a laterally sloping bed and a wave period of 0.68 seconds. The experimental and predicted values are presented graphically in Figure 10. Inspection shows that at higher wave height coefficients, the correlation between the two values is similar to that of the present study, with an average difference of approximately 10%. In the regions of lower wave height coefficients, however, the

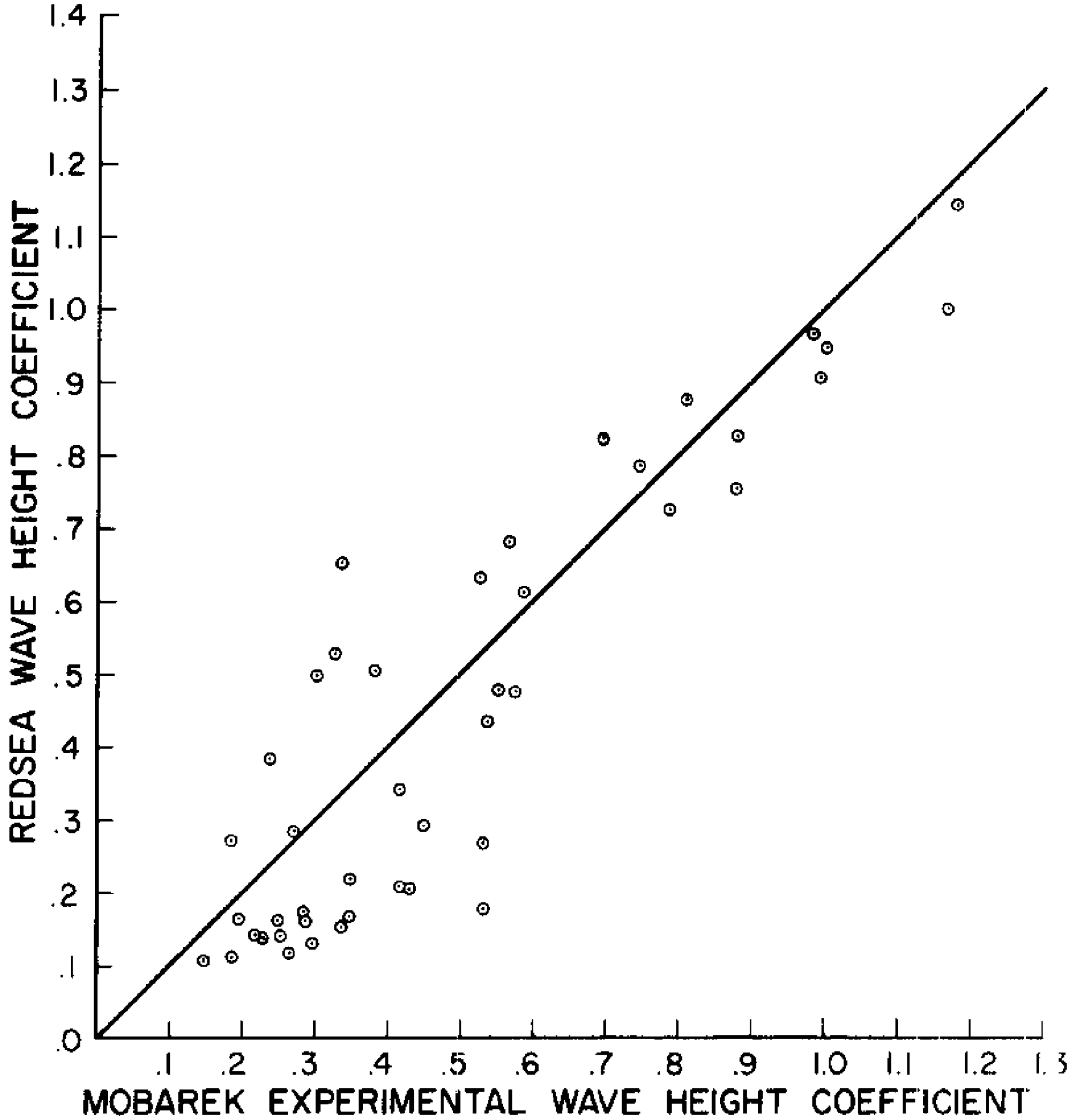

FIG. 10 COMPARISON OF MOBAREK DATA WITH REDSEA PREDICTION

correlation is not as good and the predicted values are substantially smaller than the experimental values.

CHAPTER VI

CONCLUSIONS

REDSEA Capabilities

REDSEA is capable of predicting the wave height and direction under the combined influence of refraction and diffraction by a semi-infinite breakwater. The wave heights obtained from a REDSEA prediction have been demonstrated to be accurate to within 13% of actual values obtained in laboratory investigation, and although the wave direction prediction has not been carefully analyzed, it does coincide generally with the actual pattern observed during tests. REDSEA predictions are extremely fast by comparison with methods used in the past. For instance the time required to execute the program presented in Appendix II on the IBM 360-65 computer system was roughly 10 seconds. The program is very flexible within its intended framework, and may be used to give rapid estimates of the results of variation of breakwater location and design It may also be used to study the results a variety of wave conditions on existing or proposed structures. The scope of study is completely flexible, as REDSEA is equally well adapted to model studies or to prototype conditions.

REDSEA Limitations

The REDSEA program should not be used without a thorough should be recognized that it is intended to apply only to semi-infinite breakwaters or breakwater gaps of five wave lengths or more. There is assumed to be no wave generation within the zone of study, and likewise the assumption is made that there will be no water currents effecting the waves. These assumptions may be invalid under actual conditions.

Another factor that tends to reduce the size of the waves as they might enter a harbor is friction with the bottom,[5] and this is not taken into account by the program. Abrupt depth changes, breaking waves, percolation, reflection from shores, and many other factors may likewise influence the wave height and pattern, yet were not considered as REDSEA was written.

Possible Extensions and Improvements

Enumberable possibilities exist for the extension and improvement of the work done in connection with this study. The most worthwhile extension would probably be the comparison of REDSEA predictions with additional data that might be taken under a variety of conditions. In wave tank experiments there should be a more suitable provision for wave absorption to permit taking continuous data. This would remove much of the possibility for human error in determining the true wave height at any particular location. The comparison of a REDSEA prediction with data taken under field conditions would contribute greatly to the validity that might be attached to a REDSEA prediction.

Subroutine DIFFR offers much area for investigation, for the technique used in handling the diffraction of the reflected wave seems theoretically correct, yet it has never been handled in this fashion before, nor has its validity been tested in the laboratory.

Summary

In summary, it may be stated that the REDSEA program offers a fast and accurate method of predicting wave heights and patterns as they are influenced by simultaneous refraction and diffraction. The versatility of the program extends from small wave tanks to large harbors, and the accuracy of its wave height coefficient predictions has been confirmed in the laboratory. The REDSEA program opens the door to efficiency in breakwater design and location by providing the engineer with a means of determining results in a matter of seconds, rather than months. It may prove to be a valuable supplement to the physical model, although it lacks the flexibility to replace them. The REDSEA program is not intended to replace the experience and sound judgment of the Coastal Engineer, but rather to assist him in exercising his responsibilities to society and to the coastal environment.

REFERENCES CITED

1. Bateman, H., Partial Differential Equations of Mathematical Physics, Dover Publications, New York, 1944.

2. Coastal Engineering Reasearch Center, U. S. Army Corps of Engineers, Shore Protection, Planning and Design, Technical Report Number 4, Third Edition, 1966.

3. Dunham, J.W., "Refraction and Diffraction Diagrams," Proceedings of the First Conference on Coastal Engineering, Long Beach, 1950, pp. 33-49

4. Fan, S., J.E. Cumming, and R.L. Wiegel, "Computer Solution of Wave Diffraction by Semi-Infinite Breakwater," HEL 1-8, University of California, Berkeley, 1967.

5. Ippen, A.T., (ed) Estuary and Coastline Hydrodynamics, McGraw-Hill Company, Inc., 1966.

6. Janke, E. and F. Emde, Tables of Functions with Formulae and Curves, Dover Publications, New York, 1943.

7. Johnson, J.W., "Generalized Wave Diffraction Diagrams," Proceedings of the Second Conference on Coastal Engineering, Houston, 1951, pp. 6-23.

8. Kreyszig, E., Advanced Engineering Mathematics, Wiley and Sons, Inc., New York, 1962.

9. McCracken, D.D., A Guide of Fortran IV Programming, Wiley and Sons, Inc., 1965.

10. Mobarek, I.E., and R.L. Wiegel, "Diffraction of Wind Generated Water Waves," Proceedings of the Tenth Conference on Coastal Engineering, Tokyo, 1966.

11. Mobarek, I.E., "Effect of Bottom Slope of Wave Diffraction," I.E.R. Ser 89, Issue 8, University of California, Berkeley, 1962.

12. Orr, T.E., and J.B. Herbich, "Numerical Calculation of Wave Diffraction by Digital Computer," Sea Grant Publication Number 209, Texas A&M University, 1969.

13. International Business Machines, Inc., "Programmer's Manual, IBM System 360, Scientific Subroutine Package (360A-CM-03X), Version III", White Plains, N.Y., 1968.

14. Putnam, J.A. and R.S. Arthur, "Diffraction of Water Waves by Breakwater," Transactions of the American Geophysical Union, 29 (4), part 1, 1948.

15. Silvester, R. and T.K. Lim, "Application of Wave Diffraction Data," Proceedings of the Eleventh Conference on Coastal Engineering, London, 1968.

16. Wiegel, R.L., "Diffraction of Waves by Simi-Infinite Breakwater," Journal of the Hydraulics Division, ASCE, January 1962, pp. 27-44.

17. Wiegel, R.L., Oceanographical Engineering, Prentice-Hall, Inc., 1964.

APPENDIX I

NOTATION

a	wave amplitude
b	perpendicular distance between orthogonals
C	wave celerity
C_d	coefficient of diffraction
C_r	coefficient of refraction
C_s	coefficient of shoaling
E	energy
g	acceleration of gravity
k	wave number = $2\pi/L$
H	wave height
i	$\sqrt{-1}$
L	wave length
r	polar coordinate radius vector to a point of interest
t	time
T	wave period
η	distance from still water
γ	specific weight of water

subscript "o" refers to deep water conditions

superscript ' refers to conditions unaffected by refraction

APPENDIX II

REDSEA PROGRAM

```
$JOB X111T7,TIME=002,PAGES=040        WORTHINGTON, H.W.                1-J  8 2
C                                                                     REDS A
C                                                                     REDS A
C    REDSEA PROGRAM                                                   REDS A
C                                                                     REDS A
C                                                                     REDS A
C    THIS PROGRAM WILL EVALUATE THE EFFECTS OF A SEMI-INFINITE BREAK- REDS A
C    WATER AND AN IRREGULAR BOTTOM TOPOGRAPHY ACTING SIMULTANEOUSLY TO REDS A
C    CHANGE THE HEIGHT AND DIRECTION OF WATER WAVES                   REDS A
C                                                                     REDS A
C    NECESSARY INPUT DATA IS                                          REDS A
C    CARD 1                                                           REDS A
C      M-NUMBER OF POINTS IN GRID HORIZONTALLY (COL 1-5, I FORMAT)    REDS A
C      N-NUMBER OF POINTS IN GRID VERTICALLY (COL 6-10, I FORMAT)     REDS A
C      NOP- NUMBER OF PROBLEMS TO BE SOLVED (COL 11-15, I FORMAT)     REDS A
C      SP-GRID LINE SPACING IN FEET (COL 16-25)                       REDS A
C    WATER DEPTH CARDS (M X N CARDS REQUIRED)                         REDS A
C      DEPTH IN FEET  (COL 1-10)                                      REDS A
C    PROBLEM DATA CARDS (NOP CARDS REQUIRED)                          REDS A
C      ALPH(2)-WAVE ANGLE W/ HORIZ IN DEGREES (COL 1-5)               REDS A
C      TH-WAVE PERIOD IN SEC (COL 6-10)                               REDS A
C      DELT-ORTHGNL POINT TIME INCREMENT IN SEC (COL 11-15)           REDS A
C      X(1)-INITIAL ORTHGNL ORIGIN HORIZ GRID COORD (COL 16-20)       REDS A
C      Y(1)-INITIAL ORTHGNL ORIGIN VERT GRID COORD (COL 21-25)        REDS A
C      QM-ORTHGNL ORIGIN LIMIT GRID COORD (COL 26-30)                 REDS A
C      UK-DIST BETWEEN ORTHGNLS AT ORIGIN IN GRID SPACINGS (COL 31-35) REDS A
C      BWTX-BKWTR TIP HORIZ GRID COORD (COL 36-40)                    REDS A
C      BWTY-BKWTR TIP VERT GRID COORD (COL 41-45)                     REDS A
C      BWBX-BKWTR BUTT HORIZ GRID COORD (COL 46-50)                   REDS A
C      BWBY-BKWTR BUTT VERT GRID COORD (COL 51-55)                    REDS A
C      CRFL-REFLECTION COEF FROM BKWTR (COL 56-60)                    REDS A
C                                                                     REDS A
C    ALL FORMATS ARE 'F' FORMATS UNLESS OTHERWISE INDICATED           REDS A
C                                                                     REDS A
C                                                                     REDS A
C                                                                     REDS A
C    REDSEA MAIN PROGRAM                                              REDS A
C                                                                     REDS A
C    SPECIFICATION STATEMENTS                                         REDS A
       DIMENSION D(25,25), C(25,25), CX(25,25), CY(25,25),C2X(25,25), REDS A
      1C2Y(25,25), C2XY(25,25)                                        REDS A
       DIMENSION ALPH(100),X(100),Y(100),IX(100),IY(100),F(100),E(100), REDS A
      1CXL(100),CYL(100),C2XL(100),C2YL(100),C2XYL(100),GAMA(100),    REDS A
      2PP(100),Q(100),BETA(100),T(100),V(100),W(100)                  REDS A
       INTEGER RSW, JT, NP, IR                                        REDS A
       COMMON PI                                                      REDS A
       REAL LANG                                                      REDS A
C    READ DATA AND CONDITIONS                                         REDS A
       READ(5,17) M,N,NOP,SP                                          REDS A
    17 FORMAT (3I5,F10.3)                                             REDS A
       READ(5,10) ((D(I,J),I=1,M),J=1,N)                              REDS A
    10 FORMAT (F10.3)                                                 REDS A
    44 READ (5,30) ALPH(2),TH,DELT,X(1),Y(1),QM,UK,BWTX,BWTY,BWBX,BWBY,CR REDS A
      1FL                                                             REDS A
    30 FORMAT (12F5.3)                                                REDS A
C    DEFINE VARIABLES                                                 REDS A
       IGO=1                                                          REDS A
       G=32.17398                                                     REDS A
       PI=3.141592654                                                 REDS A
       RSW=0                                                          REDS A
```

```
      A=(G*TH)/(6.28*SP)
      B=(6.28/TH)
C  PRINT DATA, CONDITIONS, AND HEADINGS
      WRITE (6,38) M,N,NOP,SP
   38 FORMAT (1H1,2X,'WATER DEPTH DATA',///,3X,'NUMBER OF HORIZONTAL GRI
     1D LINES', I6,//,3X,'NUMBER OF VERTICAL GRID LINES ',2X,I5,//3X, 'N
     2UMBER OF PROBLEMS ',13X,I5,//,3X, 'GRID INTERVAL',19X,F5.1,1X,'FT'
     3,////,57X,'D E P T H   S O U N D I N G S')
      WRITE (6,29) ((D(I,J),I=1,M),J=1,N)
   29 FORMAT(1H ,//,3X,25F5.2)
      WRITE (6,33) IGO,ALPH(2),TH,DELT,X(1),Y(1),QM,UK,BWTX,BWTY,BWBX,BW
     1BY,CRFL
   33 FORMAT (1H1,2X,'PROBLEM DATA',///,2X,'PROBLEM NUMBER',16X,I5,//,2X
     1,'ANGLE OF INCIDENCE'12X,F7.2,1X,'DEGREES',//,2X,'WAVE PERIOD',
     219X,F7.2,1X,'SECONDS',// ,2X,'TIME INCREMENT',16X,F7.2,1X,'SECONDS
     3'//,2X,'INITIAL ORTHOGONAL ORIGIN' 5X,2F7.1,1X,'(HORIZ,VERT)',
     4                                                 //, 2X, 'MAX HORIZ
     5ORTHOGONAL ORIGIN' , 3X, F7.1, //, 2X, 'ORTHOGONAL ORIGIN INTERVAL
     6', 4X, F7.1, //, 2X, 'BREAKWATER  TIP', 15X, 2F7.1,1X, '(HORIZ, VE
     7RT)' //, 2X, 'BREAKWATER BUTT', 15X, 2F7.1,1X,'(HORIZ,VERT)',
     8//,2X,'COEFFICIENT OF REFLECTION',/,4X, 'FROM BREAKWATER',13X,F7.2
     9)
C  CALCULATE BREAKWATER ANGLE W/ HORIZ GRID
      ALPH (2)=(PI*ALPH(2))/180.0
      BWDX=BWBX-BWTX
      BWDY=BWTY-BWBY
      BWANG=ATAN2(BWDY,BWDX)
C  CALCULATE WAVE ANGLE FOR DIFFRACTION COORD SYSTEM
      WVANG=ALPH(2)+BWANG
      IR=0
C  CALCULATE CELERITY
      I=1
   15 J=1
      PO=A
   47 IF(IGO.EQ. 1) GO TO 14
C  RECORD DEPTH IN GRID SPACING UNITS
      D(I,J)=D(I,J)*SP
   14 IF (D(I,J)-0.03*SP) 11,11,922
  922 D(I,J)=D(I,J)/SP
   13 P1=A*TANH((B*D(I,J))/PO)
      IF(ABS(P1-PO)-(0.001*PO).LE.0.0) GO TO 12
      PO=P1
       GO TO 13
   12 C(I,J)=P1
      PO=P1
      GO TO 34
   11 C(I,J)=0.0
      D(I,J)=D(I,J)/SP
   34 J=J+1
      IF ((N-J).GE.0) GO TO 47
      I=I+1
      IF ((M-I).GE.0) GO TO 15
C  CALCUALTE CELERITY DERIVITIVES
      I=2
   19 J=2
   18 CX(I,J)=(C(I+1,J)-C(I-1,J))/2.0
      CY(I,J)=(C(I,J+1)-C(I,J-1))/2.0
      C2X(I,J)=(C(I+1,J)-2*C(I,J)+C(I-1,J))
      C2Y(I,J)=(C(I,J+1)-2*C(I,J)+C(I,J-1))
      C2XY(I,J)=(C(I+1,J+1)-C(I-1,J+1)-C(I+1,J-1)+C(I-1,J-1))/4.0
```

```
          J=J+1                                                              REDSEA
          IF((N-J).GT.0) GO TO 18                                            REDSEA
          I=I+1                                                              REDSEA
          IF ((M-I).GT.0) GO TO 19                                           REDSEA
C   TRACE OF ORTHOGONALS                                                     REDSEA
          WRITE(6,63)                                                        REDSEA
       63 FORMAT(1H ,///,4X,'ORTHGNL',3X,'POINT',6X,'TIME',2X,'COORDINATES'  REDSEA
         1, 2X, ' DEPTH ',1X, 'REFRACTION',1X,'SHOALING',1X,'DIFFRACTION', 2 REDSEA
         2X,'HEIGHT',4X, 'WAVE', /, 4X, 'NUMBER', 4X, 'NUMBER', 5X, '(SEC)', REDSEA
         34X,'X', 4X, 'Y', 4X, ' (FT) ' , 5X, 'COEF', 6X, 'COEF', 6X, 'COEF' REDSEA
         4, 6X, ' COEF ', 2X, 'DIRECTION',/,6X,'1')                          REDSEA
          X(2)=X(1)                                                          REDSEA
          Y(2)=Y(1)                                                          REDSEA
          K=1                                                                REDSEA
C   INITIALIZE HEIGHT AND ANGLE   BKWTR TIP FOR DIFFRACTION CALCULATIONS     REDSEA
          TWVANG = WVANG                                                     REDSEA
          THTIP=0.0                                                          REDSEA
          PHTIP=1.0                                                          REDSEA
       28 L=2                                                                REDSEA
          NC=1                                                               REDSEA
          T(2)=0.0                                                           REDSEA
          WRITE (6,909) X(2),Y(2)                                            REDSEA
      909 FORMAT(1H ,11X,5H     1,2X,10H       0.00,2X,2F5.1,2X,'ORTHOGONAL  REDSEA
         1ORIGIN')                                                           REDSEA
          JT=0                                                               REDSEA
          IR=0                                                               REDSEA
C   RECORD THE HEIGHT OF THE LAST ORTHOGONAL TO PASS BKWTR                   REDSEA
          IF(THTIP.NE.0.0) PHTIP=THTIP                                       REDSEA
          THTIP=0.0                                                          REDSEA
          BETA(1)=1.0                                                        REDSEA
          BETA(2)=1.0                                                        REDSEA
C   INTERPOLATE F(L),E(L) AND DERIVITIVES                                    REDSEA
       25 IX(L)=X(L)                                                         REDSEA
          IY(L)=Y(L)                                                         REDSEA
          G0=X(L)-IX(L)                                                      REDSEA
          G5=Y(L)-IY(L)                                                      REDSEA
          G1=G0*G5                                                           REDSEA
          G2=G1-G0                                                           REDSEA
          G3=G1-G5                                                           REDSEA
          G4=G2-G5+1                                                         REDSEA
          I=IX(L)                                                            REDSEA
C   TERMINATE ORTHGNL REACHING EDGE OF GRID                                  REDSEA
          IF(I.GE.M-1.OR.I.LT.2) GO TO 21                                    REDSEA
          J=IY(L)                                                            REDSEA
          IF(J.GE.N-2.OR.J.LT.2) GO TO 21                                    REDSEA
          F(L)=G4*D(I,J)-G3*D(I,J+1)+G1*D(I+1,J+1)-G2*D(I+1,J)               REDSEA
C   TERMINATE ORTHGNL REACHING SHORE                                         REDSEA
          IF(F(L)-.01*A.LE.0.0) GO TO 21                                     REDSEA
          E(L)=G4*C(I,J)-G3*C(I,J+1)+G1*C(I+1,J+1)-G2*C(I+1,J)               REDSEA
          CXL(L)=G4*CX(I,J)-G3*CX(I,J+1)+G1*CX(I+1,J+1)-G2*CX(I+1,J)         REDSEA
          CYL(L)=G4*CY(I,J)-G3*CY(I,J+1)+G1*CY(I+1,J+1)-G2*CY(I+1,J)         REDSEA
          C2XL(L)=G4*C2X(I,J)-G3*C2X(I,J+1)+G1*C2X(I+1,J+1)-G2*C2X(I+1,J)    REDSEA
          C2YL(L)=G4*C2Y(I,J)-G3*C2Y(I,J+1)+G1*C2Y(I+1,J+1)-G2*C2Y(I+1,J)    REDSEA
          C2XYL(L)=G4*C2XY(I,J)-G3*C2XY(I,J+1)+G1*C2XY(I+1,J+1)-             REDSEA
         1G2*C2XY(I+1,J)                                                     REDSEA
          GAMA(L)=(CXL(L)*SIN(ALPH(L)))-(CYL(L)*COS(ALPH(L)))                REDSEA
       27 IF(JT.EQ.1) GO TO 22                                               REDSEA
          IF(JT.GT.1) GO TO 23                                               REDSEA
          DEL=GAMA(L)                                                        REDSEA
          TAU=E(L)                                                           REDSEA
```

```
      GO TO 24                                                          REDS A
   22 DEL=(GAMA(L-1)+GAMA(L))/2.0                                       REDS A
      TAU=(E(L-1)+E(L))/2.0                                             REDS A
      L=L-1                                                             REDS A
   24 DALPH=DEL*DELT                                                    REDS A
      GOOS=ALPH(L)+(DALPH/2.0)                                          REDS A
      ALPH(L+1)=ALPH(L)+DALPH                                           REDS A
C  DETERMINE COORD OF NEXT POINT ON ORTHGNL                             REDS A
      X(L+1)=X(L)+(TAU*DELT*COS(GOOS))                                  REDS A
      Y(L+1)=Y(L)+(TAU*DELT*SIN(GOOS))                                  REDS A
      L=L+1                                                             REDS A
      JT=JT+1                                                           REDS A
      GO TO 25                                                          REDS A
   23 DYBB=Y(L)-BWBY                                                    REDS A
      DXBB=BWBX-X(L)                                                    REDS A
      LANG = ATAN2(DYBB, DXBB)                                          REDS A
C  TERMINATE ORTHGNL INTERCEPTING BRKWTR                                REDS A
      IF(X(L)-BWTX) 905,905,900                                         REDS A
  900 IF(LANG.GE.BWANG.AND.RSW.EQ.0) GO TO 21                           REDS A
      IF(LANG.LT.BWANG.AND.RSW.GT.0) GO TO 21                           REDS A
  905 IF(RSW.GT.0) GO TO 921                                            REDS A
      IF(LANG.GE.BWANG.OR.IR.EQ.1) IR=IR+1                              REDS A
C  RECORD ANGLE OF FIRST POINT ON PRIMARY ORTHGNL PAST BKWTR LINE       REDS A
      IF(IR.EQ.1) TWVANG=ALPH(L) + BWANG                                REDS A
  921 T(L)=T(L-1)+DELT                                                  REDS A
C  CALCULATE COEFFICIENTS OF REFRACTION AND SHOALING                    REDS A
      L=L-1                                                             REDS A
      PP(L)=-CXL(L)*COS(ALPH(L))+CYL(L)*SIN(ALPH(L))                    REDS A
      Q(L)=E(L)*((C2XL(L)*SIN(ALPH(L)))**2  )-2.0*C2XYL(L)*SIN(ALPH(L))*REDS A
     1COS(ALPH(L))+C2YL(L)*(COS(ALPH(L))*COS(ALPH(L))))                 REDS A
      BETA(L+1)=((PP(L)*DELT-2.0)*BETA(L-1)+(4.0-2.0*Q(L)*(DELT**2.0))  REDS A
     1*BETA(L))/(PP(L)*DELT+2.0)                                        REDS A
      L=L+1                                                             REDS A
      BAFFLE=(B*F(L))/E(L)                                              REDS A
      RACK=EXP(BAFFLE)                                                  REDS A
      RACKX=1.0/RACK                                                    REDS A
      COSHX=(RACK+RACKX)/2.0                                            REDS A
      SINHX=(RACK-RACKX)/2.0                                            REDS A
C  CALCULATE SHOALING COEFFICIENT                                       REDS A
      W(L)=(COSHX)/(SQRT(SINHX*COSHX+BAFFLE))                           REDS A
C  CALCULATE REFRACTION COEFFICIENT                                     REDS A
      CR=1.0/SQRT(ABS(BETA(L)))                                         REDS A
C  RECORD REFRACTION COEFFICIENT IF WAVE PASSES BRKWTR                  REDS A
      IF(IR.EQ.1.AND.RSW.EQ.0) THTIP=CR                                 REDS A
C  CONVERT ORTHGNL ANGLE TO DEGREES FOR PRINTOUT                        REDS A
      ALPHLD=ALPH(L)*180.0/PI                                           REDS A
C  COMPUTE WAVE LENGTH AND X-Y COORDINATES FOR DIFFRACTION COORD SYSTEM REDS A
      WLX=E(L)*TH                                                       REDS A
      XD=(X(L)-BWTX)*COS( BWANG)-(Y(L)-BWTY)*SIN( BWANG)                REDS A
      YD=(X(L)-BWTX)*SIN( BWANG)+(Y(L)-BWTY)*COS( BWANG)                REDS A
      CALL DIFFR (WLX,XD,YD,WVANG,CRFL,RG,CD)                           REDS A
C  RECOMPUTE ACTUAL DEPTH FOR PRINTOUT                                  REDS A
      DEP= F(L)*SP                                                      REDS A
      NC=NC+1                                                           REDS A
C  WAVE HT OF RADIAL ORTHGNLS                                           REDS A
      IF(RSW.EQ.0) GO TO 950                                            REDS A
      V(L)=W(L)*CR*CD*PHTIP                                             REDS A
      GO TO 960                                                         REDS A
C  WAVE HT OF PRIMARY ORTHGNLS                                          REDS A
  950 V(L)=W(L)*CR*CD                                                   REDS A
```

```
      960 WRITE (6,26) NC,T(L),X(L),Y(L),DEP,CR,W(L),CD,V(L),ALPHLD        REDS A
       26 FORMAT(1H ,11X, I5,2X,F10.2,2X,2F5.1,F8.2,5F10.2)                 REDS A
          JT=0                                                              REDS A
          GO TO 27                                                          REDS A
       21 K=K+1                                                             REDS A
          WRITE (6,37) K                                                    REDS A
       37 FORMAT(1H ,/,4X,I3)                                               REDS A
C   MOVE TO NEXT ORTHGNL ORIGIN                                             REDS A
          X(2)=X(2) + ABS(UK/SIN(ALPH(2)))                                  REDS A
          IF(QM-X(2).GE.0.0) GO TO 28                                       REDS A
C   BEGIN RADIAL ORTHGNLS                                                   REDS A
          IF(RSW.EQ.0) WVANG=TWVANG                                         REDS A
          RSW=RSW+1                                                         REDS A
C   ESTABLISH ORTHGNL DIRECTION FROM BRKWTR TIP                             REDS A
          ALPH(2)=(15.0*PI/180.0)*RSW - BWANG                               REDS A
C   TERMINATE PROB IF ORTHGNL LEAVES LEE                                    REDS A
          IF(ALPH(2).GT.WVANG) GO TO 930                                    REDS A
C   ESTABLISH RADIAL ORTHGNL ORIGIN AT BKWTR TIP                            REDS A
          X(2)=BWTX                                                         REDS A
          Y(2)=BWTY                                                         REDS A
C   LIMIT RADIAL ORTHGNLS TO ONE AT EACH ANGLE                              REDS A
          QM=BWTX + 1.0                                                     REDS A
          UK=2.0                                                            REDS A
          IF(RSW.GT.1) GO TO 940                                            REDS A
C   CONVERT TO DEGREES FOR PRINTOUT                                         REDS A
          WVANGD=WVANG*180.0/PI                                             REDS A
          WRITE(6,920) PHTIP,WVANGD                                         REDS A
      920 FORMAT(1H ,//,2X,'ORTHOGONALS IN LEE OF BREAKWATER',/, 15X,       REDS A
         1'WAVE HT PASSING BREAKWATER TIP TAKEN AS', F14.2,2X, 'X  DEEP WATE REDS A
         2R HEIGHT', /, 15X, 'WAVE ANGLE (THETAO FOR DIFFRACTION) TAKEN AS', REDS A
         3F8.1,2X,'DEGREES', //)                                            REDS A
      940 GO TO 28                                                          REDS A
C   TERMINATE COMPUTER RUN IF THIS IS LAST PROBLEM                          REDS A
      930 IF(NOP-IGO.EQ.0) GO TO 46                                         REDS A
          IGO=IGO+1                                                         REDS A
          GO TO 44                                                          REDS A
       46 STOP                                                              REDS A
          END                                                               REDS A
C   EVALUATE COEFFICIENT OF DIFFRACTION                                     REDS A

          SUBROUTINE DIFFR (WLX,X,Y,ANG,CRFL,RG,CD)                         REDS A
          COMMON PI                                                         REDS A
          REAL K                                                            REDS A
          DATA RGQ/4H  Q /, RGR/4H  R /, RGS/4H  S /                        REDS A
          THETAO=ANG                                                        REDS A
C   ASSIGN CD AND THETA AT BKWTR TIP                                        REDS A
          IF (X.NE.0.0.OR.Y.NE.0.0) GO TO 200                               REDS A
          CD=1.0                                                            REDS A
          THETA=0.0                                                         REDS A
          RG=RGQ                                                            REDS A
          RETURN                                                            REDS A
C   EVALUATE PARAMETERS FOR DIFFRACTION CALCULATIONS                        REDS A
      200 K=2.0*PI/WLX                                                      REDS A
          THETA=ATAN2(Y,X)                                                  REDS A
          R=SQRT(X**2 + Y**2)                                               REDS A
          SIGMA=2.0*SQRT(K*R/PI)*SIN(0.5*(THETA-THETAO))                    REDS A
          SIGPRM=-2.0*SQRT(K*R/PI)*SIN(0.5*(THETA + THETAO))                REDS A
          U=PI*SIGMA**2/2.0                                                 REDS A
          CALL CS(C,S,U)                                                    REDS A
          U1=0.5*(1.0-C-S)                                                  REDS A
```

```
      W1=0.5*(S-C)                                                      REDS A
      U=PI*SIGPRM**2/2.0                                                REDS A
      CALL CS(C,S,U)                                                    REDS A
      U2=0.5*(1.0-C-S)                                                  REDS A
      W2=0.5*(S-C)                                                      REDS A
      ALPHA=K*R*COS(THETA-THETAO)                                       REDS A
      BETA=K*R*COS(THETA+THETAO)                                        REDS A
      A = U1*COS(ALPHA) + W1*SIN(ALPHA) + (U2*COS(BETA) + W2*SIN(BETA)) REDS A
     1*CRFL                                                             REDS A
      B = -U1*SIN(ALPHA) + W1*COS(ALPHA) - (U2*SIN(BETA) + W2*COS(BETA) REDS A
     1)*CRFL                                                            REDS A
      D = COS(ALPHA) - U1*COS(ALPHA) - W1*SIN(ALPHA) +(U2*COS(BETA) +   REDS A
     1W2*SIN(BETA))*CRFL                                                REDS A
      E = -SIN(ALPHA) - W1*COS(ALPHA) + U1*SIN(ALPHA) + (W2*COS(BETA) - REDS A
     1U2*SIN(BETA)) *CRFL                                               REDS A
      G = COS(ALPHA) - U1*COS(ALPHA) - W1*SIN(ALPHA) +(COS(BETA) - U2*C REDS A
     1OS(BETA) - W2*SIN(BETA))*CRFL                                     REDS A
      H = -SIN(ALPHA) -W1*COS(ALPHA) + U1*SIN(ALPHA) + (-SIN(BETA)      REDS A
     1- W2*SIN(BETA) + U2*SIN(BETA))*CRFL                               REDS A
C  DETERMINE REGION R,S, OR Q                                           REDS A
      IF(X.LE.R*COS(THETAO)) GO TO 210                                  REDS A
      IF(Y.LT.0.0.AND.X.GT.R*COS(THETAO)) GO TO 220                     REDS A
      IF(Y.GE.0.0.AND.X.GT.R*COS(THETAO)) GO TO 230                     REDS A
  210 CD     =SQRT(D**2+E**2)                                           REDS A
      RG=RGQ                                                            REDS A
      GO TO 250                                                         REDS A
  220 CD     =SQRT(G**2+H**2)                                           REDS A
      RG=RGR                                                            REDS A
      GO TO 250                                                         REDS A
  230 CD     =SQRT(A**2+B**2)                                           REDS A
      RG=RGS                                                            REDS A
  250 RETURN                                                            REDS A
      END                                                               REDS A
C                                                                       REDS A
C  EVALUATE FRESNEL INTEGRAL                                            REDS A

      SUBROUTINE CS(C,S,X)                                              REDS A
      Z=ABS(X)                                                          REDS A
      IF(Z-4.)1,1,2                                                     REDS A
    1 C=SQRT(Z)                                                         REDS A
      S=Z*C                                                             REDS A
      Z=(4.-Z)*(4.+Z)                                                   REDS A
      C=C*((((((5.100785E-11*Z+5.244297E-9)*Z+5.451182E-7)*Z            REDS A
     1+3.273308E-5)*Z+1.020418E-3)*Z+1.102544E-2)*Z+1.840965E-1)        REDS A
      S=S*(((((6.677681E-10*Z+5.883158E-8)*Z+5.051141E-6)*Z             REDS A
     1+2.441816E-4)*Z+6.121320E-3)*Z+8.026490E-2)                       REDS A
      RETURN                                                            REDS A
    2 D=COS(Z)                                                          REDS A
      S=SIN(Z)                                                          REDS A
      Z=4./Z                                                            REDS A
      A=(((((((8.768258E-4*Z-4.169289E-3)*Z+7.970943E-3)*Z-6.792801E-3) REDS A
     1*Z-3.095341E-4)*Z+5.972151E-3)*Z-1.606428E-5)*Z-2.493322E-2)*Z    REDS A
     2-4.444091E-9                                                      REDS A
      B=((((((-6.633926E-4*Z+3.401409E-3)*Z-7.271690E-3)*Z+7.428246E-3) REDS A
     1*Z-4.027145E-4)*Z-9.314910E-3)*Z-1.207998E-6)*Z+1.994711E-1       REDS A
      Z=SQRT(Z)                                                         REDS A
      C=0.5+Z*(D*A+S*B)                                                 REDS A
      S=0.5+Z*(S*A-D*B)                                                 REDS A
      RETURN                                                            REDS A
      END                                                               REDS A
```

NUMBER OF HORIZONTAL GRID LINES 25

NUMBER OF VERTICAL GRID LINES 25

NUMBER OF PROBLEMS 1

GRID INTERVAL 1.0 FT

DEPTH SOUNDINGS

2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.80	1.40	1.00	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.80	1.40	1.00	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.80	1.40	1.00	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.80	1.40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.80	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

PROBLEM DATA

PROBLEM NUMBER	1
ANGLE OF INCIDENCE	90.00 DEGREES
WAVE PERIOD	1.28 SECONDS
TIME INCREMENT	0.25 SECONDS
INITIAL ORTHOGONAL ORIGIN	6.0 2.0 (HORIZ,VERT)
MAX HORIZ ORTHOGONAL ORIGIN	10.1
ORTHOGONAL ORIGIN INTERVAL	1.0
BREAKWATER TIP	9.3 5.0 (HORIZ, VERT)
BREAKWATER BUTT	25.0 5.0 (HORIZ,VERT)
COEFFICIENT OF REFLECTION FROM BREAKWATER	0.22

ORTHGNL NUMBER	POINT NUMBER	TIME (SEC)	COORDINATES X	Y	DEPTH (FT)	REFRACTION COEF	SHOALING COEF	DIFFRACTION COEF	HEIGHT COEF	WAVE DIRECTION
1										
	1	0.00	6.0	2.0	ORTHOGONAL	ORIGIN				
	2	0.25	6.0	3.5	2.00	1.00	0.93	0.99	0.92	90.00
	3	0.50	6.0	5.0	2.00	1.00	0.93	1.13	1.05	90.00
	4	0.75	6.0	6.5	2.00	1.00	0.93	1.12	1.04	90.00
	5	1.00	6.0	8.1	2.00	1.00	0.93	1.04	0.97	90.00
	6	1.25	6.0	9.6	2.00	1.00	0.93	0.97	0.90	90.00
	7	1.50	6.0	11.1	2.00	1.00	0.93	0.92	0.85	90.00
	8	1.75	6.0	12.6	2.00	1.00	0.93	0.88	0.81	90.00
	9	2.00	6.0	14.1	2.00	1.00	0.93	0.84	0.78	90.00
	10	2.25	6.0	15.6	2.00	1.00	0.93	0.82	0.76	90.00
	11	2.50	6.0	17.2	2.00	1.00	0.93	0.80	0.74	90.00
	12	2.75	6.0	18.7	2.00	1.00	0.93	0.78	0.72	90.00
	13	3.00	6.0	20.2	2.00	1.00	0.93	0.76	0.71	90.00
	14	3.25	6.0	21.7	2.00	1.00	0.93	0.75	0.70	89.47
2										
	1	0.00	7.0	2.0	ORTHOGONAL	ORIGIN				
	2	0.25	7.0	3.5	2.00	1.00	0.93	1.05	0.98	90.00
	3	0.50	7.0	5.0	2.00	1.00	0.93	1.12	1.04	90.00
	4	0.75	7.0	6.5	2.00	1.00	0.93	1.01	0.93	90.00
	5	1.00	7.0	8.1	2.00	1.00	0.93	0.90	0.84	90.00
	6	1.25	7.0	9.6	2.00	1.00	0.93	0.84	0.78	90.00
	7	1.50	7.0	11.1	2.00	1.00	0.93	0.79	0.73	90.00
	8	1.75	7.0	12.6	2.00	1.00	0.93	0.76	0.71	90.00
	9	2.00	7.0	14.1	2.00	1.00	0.93	0.74	0.68	90.00
	10	2.25	7.0	15.6	2.00	1.00	0.93	0.72	0.67	90.00
	11	2.50	7.0	17.2	2.00	1.00	0.93	0.70	0.65	90.00
	12	2.75	7.0	18.7	2.00	1.00	0.93	0.69	0.64	90.00
	13	3.00	7.0	20.2	2.00	1.00	0.93	0.68	0.63	89.86
	14	3.25	7.0	21.7	1.79	0.99	0.92	0.67	0.61	88.03
3										
	1	0.00	8.0	2.0	ORTHOGONAL	ORIGIN				
	2	0.25	8.0	3.5	2.00	1.00	0.93	1.09	1.01	90.00
	3	0.50	8.0	5.0	2.00	1.00	0.93	1.02	0.94	90.00
	4	0.75	8.0	6.5	2.00	1.00	0.93	0.82	0.76	90.00
	5	1.00	8.0	8.1	2.00	1.00	0.93	0.73	0.68	90.00
	6	1.25	8.0	9.6	2.00	1.00	0.93	0.69	0.64	90.00
	7	1.50	8.0	11.1	2.00	1.00	0.93	0.66	0.62	90.00
	8	1.75	8.0	12.6	2.00	1.00	0.93	0.65	0.60	90.00
	9	2.00	8.0	14.1	2.00	1.00	0.93	0.63	0.59	90.00
	10	2.25	8.0	15.6	2.00	1.00	0.93	0.62	0.58	90.00
	11	2.50	8.0	17.2	2.00	1.00	0.93	0.61	0.57	90.00
	12	2.75	8.0	18.7	2.00	1.00	0.93	0.61	0.56	90.00
	13	3.00	8.0	20.2	1.94	1.00	0.93	0.60	0.56	89.30
	14	3.25	8.1	21.6	1.45	0.96	0.91	0.59	0.52	85.23
4										
	1	0.00	9.0	2.0	ORTHOGONAL	ORIGIN				
	2	0.25	9.0	3.5	2.00	1.00	0.93	1.09	1.01	90.00
	3	0.50	9.0	5.0	2.00	1.00	0.93	0.78	0.73	89.51
	4	0.75	9.0	6.5	1.99	0.98	0.93	0.59	0.54	88.48
	5	1.00	9.1	8.1	2.00	0.93	0.93	0.56	0.48	87.89
	6	1.25	9.1	9.6	2.00	0.89	0.93	0.54	0.44	87.85
	7	1.50	9.2	11.1	2.00	0.85	0.93	0.53	0.42	87.85
	8	1.75	9.3	12.6	2.00	0.82	0.93	0.52	0.39	87.85
	9	2.00	9.3	14.1	2.00	0.79	0.93	0.51	0.38	87.85
5										
	1	0.00	10.0	2.0	ORTHOGONAL	ORIGIN				

6

ORTHOGONALS IN LEE OF BREAKWATER
WAVE HT PASSING BREAKWATER TIP TAKEN AS 1.00 X DEEP WATER HEIGHT
WAVE ANGLE (THETAO FOR DIFFRACTION) TAKEN AS 89.5 DEGREES

1	0.00	9.3	5.0	ORTHOGONAL	ORIGIN				
2	0.25	10.7	5.4	1.51	1.01	0.91	0.22	0.20	15.04
3	0.50	12.0	5.7	1.00	1.08	0.92	0.21	0.21	14.90
4	0.75	13.1	6.0	0.62	1.21	0.96	0.18	0.21	13.98
5	1.00	14.1	6.2	0.62	1.40	0.96	0.15	0.21	12.62
6	1.25	15.1	6.4	0.62	1.79	0.96	0.14	0.24	10.59
7	1.50	16.1	6.6	0.62	3.33	0.96	0.13	0.41	7.44
8	1.75	17.2	6.7	0.62	2.66	0.96	0.12	0.32	3.49
9	2.00	18.2	6.7	0.62	1.69	0.96	0.10	0.17	-0.83
10	2.25	19.2	6.7	0.62	1.41	0.96	0.11	0.15	-5.06
11	2.50	20.2	6.6	0.62	1.31	0.96	0.10	0.13	-8.72
12	2.75	21.3	6.4	0.62	1.29	0.96	0.10	0.12	-11.45
13	3.00	22.3	6.2	0.62	1.33	0.96	0.09	0.11	-12.99
14	3.25	23.3	5.9	0.62	1.39	0.96	0.08	0.11	-12.86

7

1	0.00	9.3	5.0	ORTHOGONAL	ORIGIN				
2	0.25	10.6	5.7	1.56	1.01	0.92	0.27	0.25	28.57
3	0.50	11.8	6.3	1.08	1.03	0.92	0.24	0.23	24.70
4	0.75	12.9	6.7	0.67	1.06	0.95	0.18	0.16	18.87
5	1.00	13.9	7.0	0.63	1.19	0.96	0.17	0.20	12.69
6	1.25	14.9	7.2	0.70	1.58	0.95	0.13	0.20	6.24
7	1.50	16.0	7.3	0.72	5.79	0.95	0.12	0.66	-0.64
8	1.75	17.1	7.2	0.69	1.70	0.95	0.13	0.21	-7.46
9	2.00	18.1	7.0	0.62	1.22	0.96	0.10	0.11	-13.66
10	2.25	19.1	6.7	0.62	1.08	0.96	0.11	0.11	-18.53
11	2.50	20.1	6.3	0.62	1.03	0.96	0.10	0.10	-21.49
12	2.75	21.0	6.0	0.62	1.02	0.96	0.10	0.09	-22.18
13	3.00	22.0	5.6	0.62	1.02	0.96	0.09	0.09	-19.26
14	3.25	23.0	5.3	0.62	1.12	0.96	0.06	0.06	-11.96
15	3.50	24.0	5.2	0.62	1.61	0.96	0.08	0.12	-1.75

8

1	0.00	9.3	5.0	ORTHOGONAL	ORIGIN				
2	0.25	10.4	6.0	1.64	1.00	0.92	0.33	0.30	42.69
3	0.50	11.5	6.9	1.22	0.98	0.91	0.28	0.25	37.02
4	0.75	12.5	7.6	1.03	0.98	0.92	0.20	0.18	28.56
5	1.00	13.7	8.1	1.04	0.99	0.92	0.19	0.18	19.21
6	1.25	14.9	8.4	1.15	0.96	0.91	0.17	0.15	10.41
7	1.50	16.2	8.6	1.20	0.90	0.91	0.12	0.10	2.40
8	1.75	17.5	8.5	1.19	0.82	0.91	0.14	0.10	-5.46
9	2.00	18.8	8.3	1.11	0.73	0.92	0.11	0.07	-13.53
10	2.25	20.0	7.9	0.98	0.65	0.92	0.10	0.06	-22.26
11	2.50	21.0	7.4	0.78	0.57	0.94	0.09	0.05	-29.88
12	2.75	21.9	6.8	0.62	0.52	0.96	0.10	0.05	-35.15
13	3.00	22.8	6.2	0.62	0.52	0.96	0.08	0.04	-37.76
14	3.25	23.6	5.6	0.62	0.52	0.96	0.07	0.04	-36.12

9

1	0.00	9.3	5.0	ORTHOGONAL	ORIGIN				
2	0.25	10.1	6.3	1.76	0.99	0.92	0.39	0.35	57.46
3	0.50	10.9	7.5	1.61	0.95	0.92	0.33	0.29	52.99
4	0.75	11.9	8.6	1.66	0.88	0.92	0.26	0.21	46.39
5	1.00	12.9	9.5	1.58	0.78	0.92	0.26	0.18	40.23
6	1.25	14.1	10.4	1.84	0.71	0.92	0.23	0.15	36.37
7	1.50	15.3	11.3	2.00	0.64	0.93	0.20	0.12	34.75
8	1.75	16.5	12.2	2.00	0.58	0.93	0.18	0.10	34.33
9	2.00	17.8	13.0	2.00	0.54	0.93	0.16	0.08	34.33
10	2.25	19.0	13.9	2.00	0.50	0.93	0.16	0.07	34.33
11	2.50	20.3	14.7	2.00	0.47	0.93	0.15	0.07	34.79
12	2.75	21.5	15.6	1.82	0.44	0.92	0.13	0.05	36.54
13	3.00	22.6	16.5	1.52	0.40	0.91	0.13	0.05	39.68
14	3.25	23.6	17.4	1.20	0.37	0.91	0.12	0.04	44.76

10

1	0.00	9.3	5.0	ORTHOGONAL	ORIGIN				
2	0.25	9.7	6.4	1.85	0.98	0.92	0.45	0.41	72.64
3	0.50	10.2	7.9	1.92	0.92	0.93	0.40	0.34	69.72
4	0.75	10.8	9.3	2.00	0.84	0.93	0.35	0.27	66.14
5	1.00	11.3	10.7	2.00	0.76	0.93	0.36	0.25	67.83
6	1.25	11.9	12.1	2.00	0.70	0.93	0.33	0.22	67.78
7	1.50	12.5	13.5	2.00	0.65	0.93	0.30	0.18	67.78
8	1.75	13.0	14.9	2.00	0.61	0.93	0.30	0.17	68.04
9	2.00	13.6	16.3	1.62	0.57	0.92	0.26	0.14	68.62
10	2.25	14.1	17.5	1.16	0.55	0.91	0.27	0.14	70.17
11	2.50	14.4	18.7	0.75	0.53	0.94	0.24	0.12	73.10
12	2.75	14.7	19.7	0.62	0.50	0.96	0.24	0.12	74.37
13	3.00	15.0	20.7	0.62	0.49	0.96	0.22	0.10	74.63

APPENDIX III

REDSEA VARIABLE DESCRIPTIONS

ALPH(L)	angle of wave approach with X axis
ALPHLD	angle of wave approach expressed in degrees
BETA(L)	coefficient of spread between adjacent orthogonals
BWANG	angle of breakwater with X axis
BWDX	length of breakwater projected on X axis
BWDY	length of breakwater projected on Y axis
C(I,J)	wave celerity at grid point I,J
CR	coefficient of refraction
CX(I,J)	derivative of celerity with respect to X at grid point I,J
CY(I,J)	derivative of celerity with respect to Y at grid point I,J
C2X(I,J)	second derivative of celerity with respect to X at grid point I,J
DELT	unit time along an orthogonal
DEP	actual depth in feet
D(I,J)	water depth at grid point I,J
DXBB	X distance between point L and breakwater butt
DYBB	Y distance between point L and breakwater butt
E(L)	interpolated celerity between grid points
F(L)	interpolated depth between grid points
GAMA(L)	derivative of ALPH(L) with respect to time at point X(L), Y(L)
GO-5	interpolation coefficients

I	unit length along X axis
IGO	problem number counter
IR	a position indicator switch, incremented when an orthogonal passes breakwater tip
IX	integer portion of number X(L)
IY	integer portion of number Y(L)
J	unit length along X axis
JT	switch factor within program
K	orthogonal number counter
L	point number along orthogonal
LANG	angle with X axis as initial line and line from breakwater butt to point L as terminal line
M	maximum value of I
N	maximum value of J
NC	point number counter along orthogonal
NOP	number of problems to be executed
PHTIP	permanent storage location for wave height at tip
PI	revised estimate of celerity
PO	preliminary estimate of celerity
QM	maximum value of an orthogonal origin
RSW	radial orthogonal indicator
SP	grid spacing
T(L)	elapsed time from orthogonal origin to point L
TH	wave period
THTIP	temporary storage location for wave height at tip
TWVANG	temporary storage location for wave angle at tip

UK	unit perpendicular grid spacing between orthogonal origins
V(L)	wave height coefficient at point L
X(1), Y(1)	origin coordinates of initial orthogonal
XD, YD	coordinates of point L transposed to diffraction coefficient coordinate system
W(L)	shoaling coefficient at point L
WLX	wave length used in diffraction coefficient computation
WVANG	wave angle with breakwater
WVANGD	wave angle with breakwater in degrees