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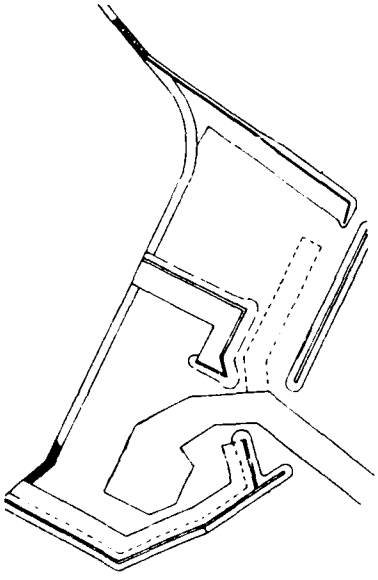

MISCELLANEOUS PAPER CERC-90-8

WAVE RESPONSE OF PROPOSED IMPROVEMENTS TO THE SHALLOW-DRAFT HARBOR AT KAWAIHAE, HAWAII

by

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Coastal Engineering Research Center

DEPARTMENT OF THE ARMY
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November 1990

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for US Army Engineer Division, Pacific Ocean
Honolulu, Hawaii 96858-5400

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): Miscellaneous Paper CERC-90-8	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: USAEWES, Coastal Engineering Research Center; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code): 3909 Halls Ferry Road, Vicksburg, MS 39180-6199	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: USAED, Pacific Ocean; 8b. OFFICE SYMBOL (If applicable): CEPOD-ED-P	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Intra-Army Order No. E86890028
8c. ADDRESS (City, State, and ZIP Code): Building 230, Honolulu, HI 96858-5400	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

Wave Response of Proposed Improvements to the Shallow-Draft Harbor at Kawaihae, Hawaii

12. PERSONAL AUTHOR(S)

Lillycrop, Linda S.; Bratos, Steven M.; Thompson, Edward F.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final report	FROM Oct 89 TO Mar 90	November 1990	107

16. SUPPLEMENTARY NOTATION

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	Harbor	Numerical modeling
			Hawaii	Wave refraction
			Kawaihae	Wave response

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The US Army Engineer Waterways Experiment Station's Coastal Engineering Research Center was requested by the US Army Engineer Division, Pacific Ocean (POD), to numerically study the wave response of two proposed plans of improvement to the shallow-draft harbor at Kawaihae, Hawaii. The existing harbor consists of an 850-ft-long, 120-ft-wide entrance channel, a 1.2-acre turning basin, and an 850-ft-long breakwater. Plan 1 includes a 640-ft-long, 80-ft-wide main access channel, a 375-ft-long extension to the existing 850-ft-long west breakwater with a 200-ft-long stub on the harbor side, a 425-ft-long access breakwater with a 400-ft-long wave absorber, a 1,025-ft-long east breakwater, and a 650-ft-long offshore breakwater. Plan 2 includes the same improvements as Plan 1 with the exception of the removal of 200 ft of the west breakwater tip. These plans were developed to provide protection to the existing harbor. This report details the study and provides final results to POD.

(Continued)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION	
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

19. ABSTRACT (Contined)

Significant wave heights, periods, and directions taken from the Wave Information Studies' hindcast data base were combined with nondirectional wave measurements from the Coastal Field Data Collection Program buoy at Barbers Point, Oahu. The resulting climatological data were input into the Regional Coastal Processes Wave finite differences model and transformed to the Kawaihae Harbor vicinity.

The transformed wave conditions were then input to the Harbor Wave Response finite element model to determine the wave climate inside the harbor. The harbor plans were tested with waves ranging in period from 7 to 20 sec and with westerly approach directions ranging from 202.5 deg (from SSW) to 337.5 deg (from NNW). A 5.5-ft above mean lower low water storm surge was used.

The results of this study found that Plan 1 met the requirements to adequately protect the harbor from the incident wave climate. It was determined that this plan will keep the wave height in the harbor berthing areas at 1 ft or lower and in the harbor channels and turning basin at 2 ft or lower approximately 90 percent of the time per year.

PREFACE

This study was authorized by the US Army Engineer Division, Pacific Ocean (POD), and was conducted during the period October 1989 through March 1990 by the personnel of the Coastal Oceanography Branch (COB), Research Division (RD), Coastal Engineering Research Center (CERC), of the US Army Engineer Waterways Experiment Station (WES). Mr. John H. Lockhart, Jr., Headquarters, US Army Corps of Engineers (HQUSACE), provided project oversight on behalf of HQUSACE. Messrs. Stanley Boc, POD, and Lockhart also visited CERC to oversee progress of the study.

This report was prepared by Ms. Linda S. Lillycrop, Hydraulic Engineer, COB; Mr. Steven M. Bratos, Hydraulic Engineer, COB; and Dr. Edward F. Thompson, Research Hydraulic Engineer, RD. Ms. Panola Rivers, Civil Engineering Technician, COB, assisted in preparing various files and tables for this study. Ms. Lillycrop, Mr. Bratos, and Ms. Rivers were under the direct supervision of Dr. Martin C. Miller, Chief, COB, and Mr. H. Lee Butler, Chief, RD, and under the general supervision of Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC, and Dr. James R. Houston, Chief, CERC.

The assistance of Mr. Paul D. Farrar, Research Oceanographer, COB, is deeply appreciated. Dr. H. S. Chen, Marine Products Branch, Development Division, National Meteorological Center, National Oceanic and Atmospheric Administration, provided valuable suggestions for implementing the harbor model used in this study. Ms. Lori Copland, US Army Engineer District, Sacramento, and Mr. Steve Hatton, Information Technology Laboratory, WES, developed the initial finite element grid for the harbor model.

Commander and Director of WES during publication of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)

UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radian
feet	0.3048	meters
nautical mile	1.852	kilometers
nautical mile/hour	1.852	kilometers/hour

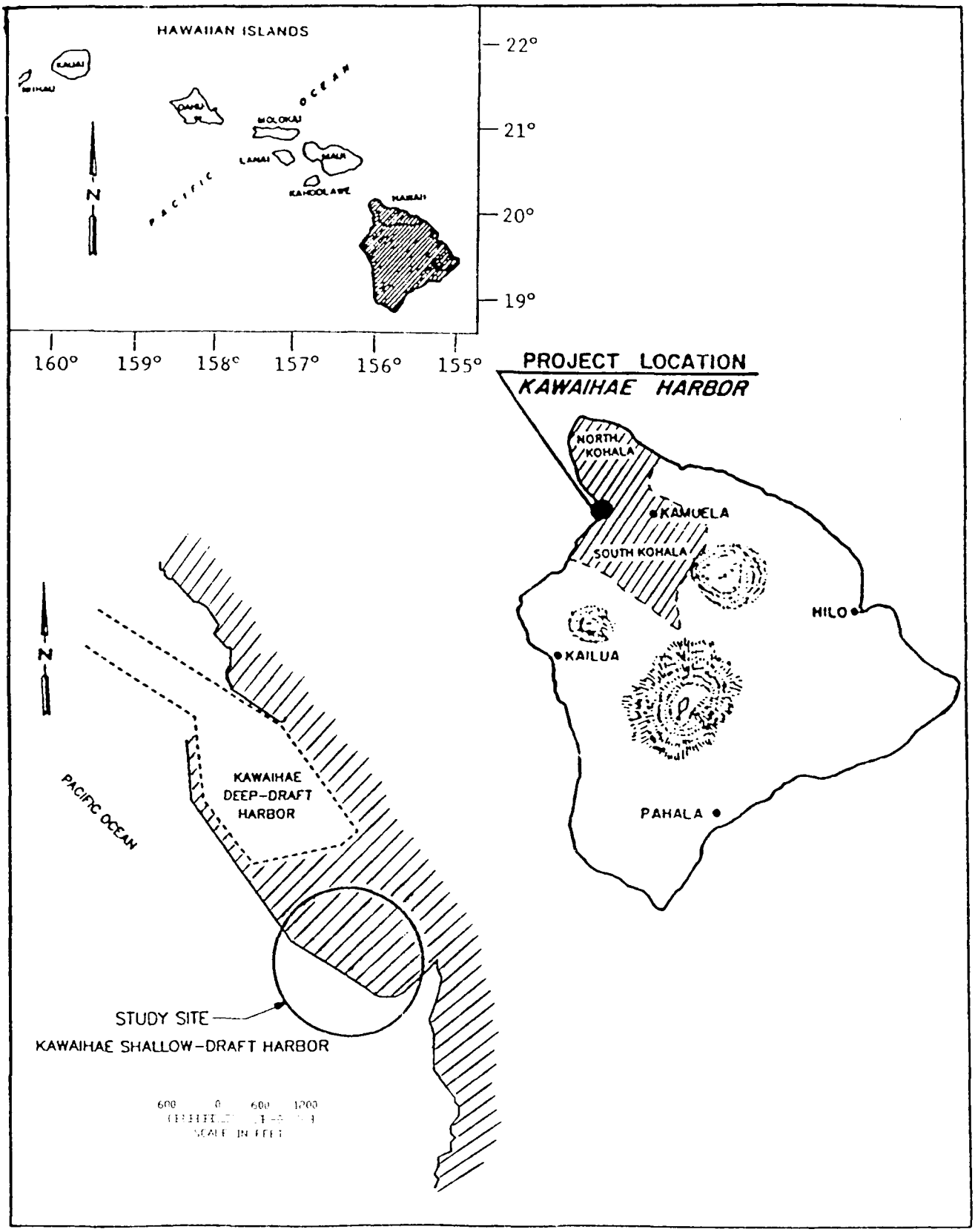

Figure 1. Study Location

WAVE RESPONSE OF PROPOSED IMPROVEMENTS TO THE SHALLOW-DRAFT HARBOR AT KAWAIHAE, HAWAII

PART I: INTRODUCTION

Background

1. At the request of the US Army Engineer Division, Pacific Ocean (POD), a numerical model study of wave response of the proposed improvements to Kawaihae shallow-draft harbor was conducted by the U.S. Army Engineer Waterways Experiment Station's (USAEWES) Coastal Engineering Research Center (CERC). The study was conducted to determine if proposed improvements (Plan 1) would provide the shallow-draft harbor with adequate protection from the incident wave climate. The shallow-draft harbor is part of a harbor complex plan consisting of an existing deep-draft harbor and proposed ferry terminal. The shallow-draft harbor includes an entrance channel, turning basin, and breakwater to provide limited shelter for small craft until harbor improvements are completed. Following the evaluation of Plan 1, a second plan (Plan 2) consisting of a breakwater modification was tested to determine if the cost-saving changes would provide adequate protection.

Study Location

2. The Kawaihae harbor complex is located on the northwest coast of the island of Hawaii, the largest and most southerly island in the Hawaiian Island chain. The shallow-draft harbor site is immediately south of the existing Kawaihae deep-draft harbor. The tributary area for the harbor complex includes the North and South Kohala Judicial Districts (Figure 1).

3. Selection of the harbor site was based on a wide bordering coral

reef which provides natural protection from storm waves approaching the area, excellent navigation conditions, adequate area for development of shoreside facilities, and compatibility with the existing and proposed uses of the harbor complex.

4. During the project formulation phase of the harbor complex design, the shallow-draft harbor site went under extensive investigation by the US Army Engineer Nuclear Cratering Group (USAENCG). The site was a potential test area for the USAENCG research and development project (Project Tugboat), a study to test excavations using a high explosive row charge cratering technique. Due to favorable test conditions such as an extensive coral reef, the remoteness of the area from large developments, and accessibility to the test site from land, the shallow-draft harbor site was selected for the study. The objectives of Project Tugboat were to collect technical data on high explosive cratering techniques and their applicability to harbor excavation work. In addition, the explosive excavations would provide a useful portion of the shallow-draft harbor. Results of the Project Tugboat explosions yielded construction of an 850 ft* long, 120 ft wide, and approximate 12 ft deep entrance channel and a 1.2 acre 12 ft deep turning basin. An 850 ft long breakwater was also constructed under Project Tugboat and was incorporated into the design plan of the shallow-draft harbor. The breakwater and excavated area would provide limited shelter for small craft until the proposed shallow-draft harbor improvements were completed. The General Design Memorandum (GDM) for Kawaihae Harbor for Light-Draft Vessels (US Army Engineer District, Honolulu 1971) contains a record of the research and planning which led to the proposed design improvements, Plan 1 (Figure 2).

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

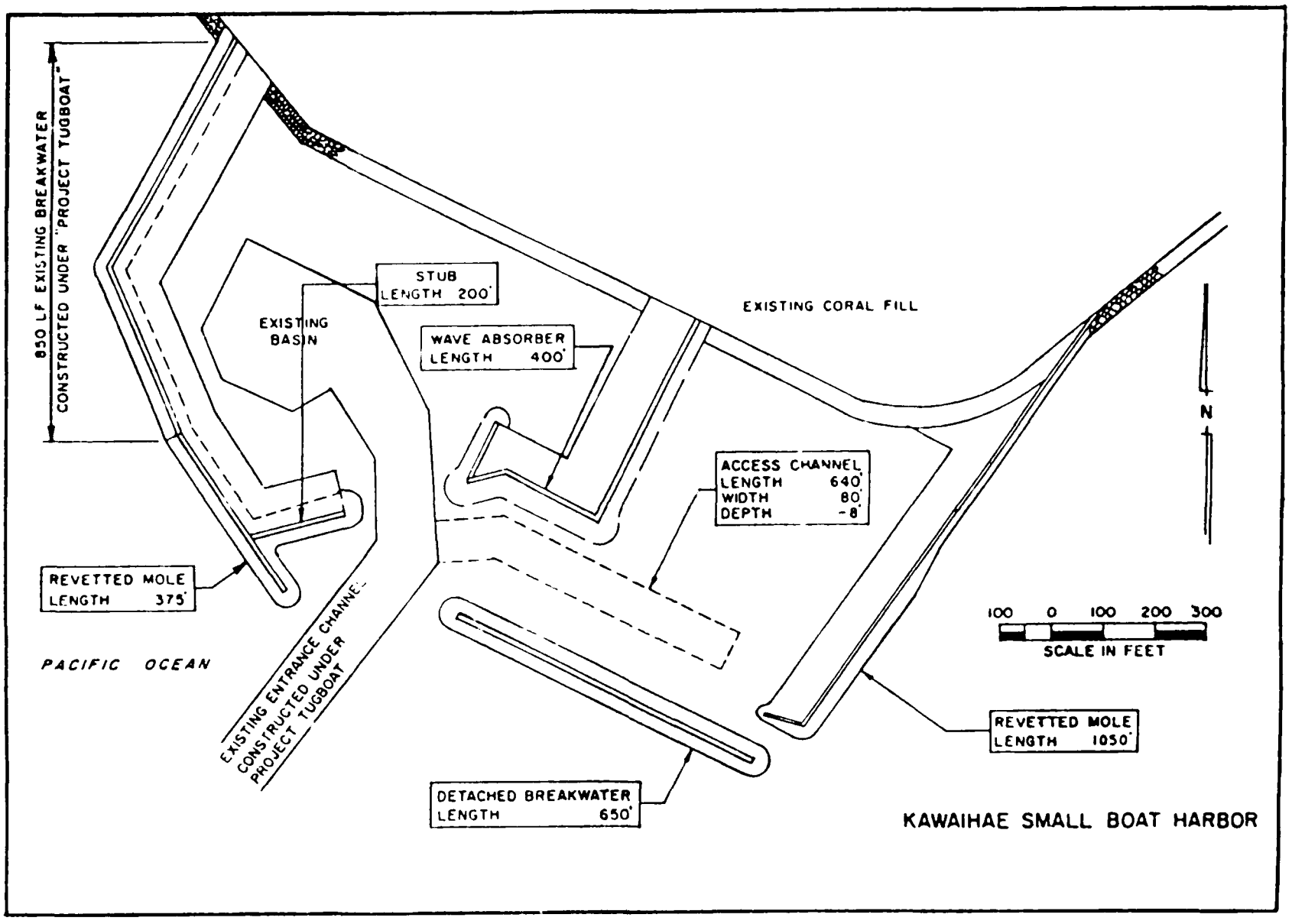

Figure 2. Plan 1

5. Plan 1 will provide berthing facilities for approximately 300 small craft, and includes the following improvements:

a. A 640 ft long, 80 ft wide, 8 ft deep main access channel to provide access from the entrance channel to an approximate 5.8 acre east basin.

b. A 375 ft long revetted mole breakwater extension of the existing 850 ft west breakwater, with a 200 ft long stub mole on the harbor side of the extension.

c. A 400 ft long wave absorber on the seaward end of a 425 ft long access mole.

d. A 1,050 ft long east revetted mole.

e. A 650 ft long, 12 ft wide offshore breakwater located adjacent to the entrance channel.

6. Plan 2 (Figure 3) includes the same improvements as Plan 1 with the exception of a modification to the west revetted mole breakwater extension of the existing breakwater. The breakwater extension will be reduced from 375 ft to 175 ft to reduce construction costs.

7. Study objectives of the Headquarters, US Army Corps of Engineers (HQUSACE) and POD were to verify that the proposed harbor design improvements meet the criteria that the wave heights not exceed 1 ft in the berthing areas and 2 ft in the entrance channel and turning basin more than approximately 10 percent of the time. To accomplish this objective, Plan 1 was tested using the HARBD numerical harbor response model (Chen and Houston 1987) developed at CERC. Modifications to Plan 1 would then be considered and tested if (a) Plan 1 did not meet the HQUSACE criteria or (b) Plan 1 could then be modified to lower construction costs.

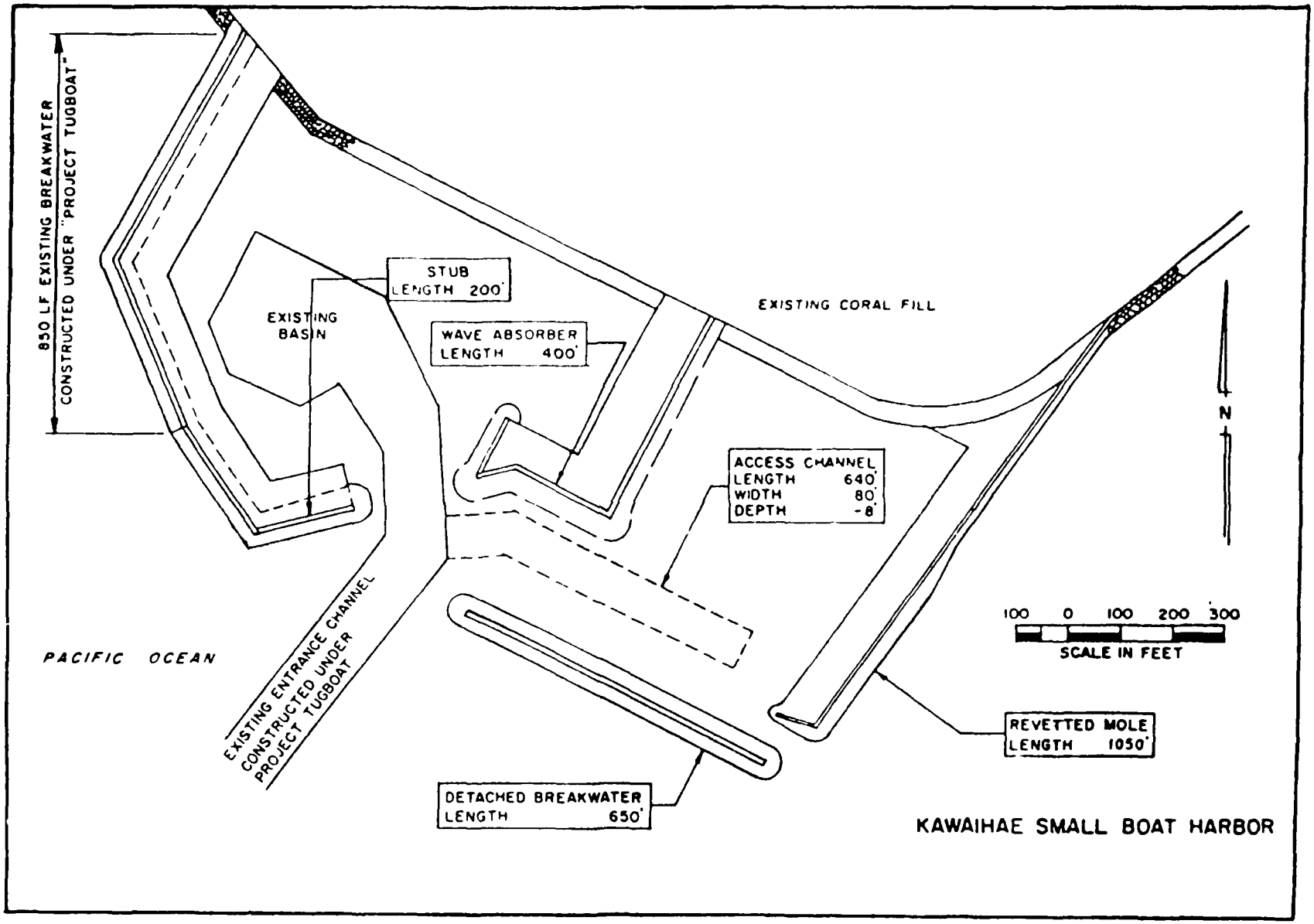

Figure 3. Plan 2

Modeling Approach

8. Both numerical and physical modeling alternatives were considered for this study. Physical modeling would have the advantages of providing more complete, reliable results for this particular study and would allow more comprehensive optimization of the project design. However, the physical model probably would cost significantly more and take longer to complete than the numerical model. The assumptions inherent in the numerical modeling approach are as follows:

- no wave transmission through the breakwater,
- no wave overtopping of structures,
- structure crest elevations will not be tested or optimized,
- wave current interaction in the channel through the reef will not be evaluated,
- wave breaking effects in the entrance channel will not be considered,
- diffraction around the structure ends will be represented by diffraction around a blunt vertical wall with specified reflection coefficient.

Within the limits of the assumptions, the numerical modeling approach can be expected to give a reasonable assessment of the proposed plan. The numerical modeling approach was selected because POD's allowable time, study funds, and design modification alternatives for this particular project were extremely limited. The procedure of this study is described in the following paragraphs.

9. The deepwater wave conditions for the northwest side of the island of Hawaii were established from available sources such as the Wave Information Study (WIS) deepwater hindcasts for the Pacific Coast (Corson, et al 1986), the National Oceanic and Atmospheric Administration's National Data Buoy Center (NDBC) measurements (Gilhousen, et al 1986), the Coastal Field Data Collection Program (CFDCP) (US Army Corps of Engineers (USACE) 1987), and the Summary of Synoptic Meteorological Observations (SSMO) (US Naval Weather Service Command 1976). The percent occurrences of the deepwater conditions

were calculated to later determine the percent occurrence of the wave heights inside the harbor. The method to establish the deepwater conditions is presented in PART II of this report: Deepwater Wave Conditions.

10. The offshore waves were input to the Regional Coastal Processes WAVE Propagation Model, RCPWAVE, (Ebersole, Cialone, and Prater 1986). The model was used to transform and refract the offshore waves to the Kawaihae vicinity. The RCPWAVE Model is presented in PART III of this report: Wave Transformation Modeling.

11. The resulting wave conditions of RCPWAVE were then used as input to HARBD to determine the wave response inside the harbor. The resulting wave heights in the harbor channels, turning basin, and berthing areas were determined and the percent occurrence of those conditions were calculated using the results of both the RCPWAVE and HARBD models. The HARBD Model and the details and results of the procedures are presented in PART IV of this report: Wave Response Modeling.

PART II: DEEPWATER WAVE CONDITIONS

Data Sources

12. The coastline in the vicinity of Kawaihae shallow-draft harbor is exposed to waves coming from westerly directions ranging from about north-northwest to south-southwest. Several relevant sources of wave information are available though none are ideally suited for use at Kawaihae.

13. The Wave Information Studies (WIS) deepwater hindcasts for the Pacific coast include seven stations around the Hawaiian Islands (Corson, et al 1986). Two of the stations are on the west side of the island of Hawaii and have exposures somewhat representative of Kawaihae (Figure 4). Station 34 lies about 250 nautical miles (nm) due west of Kawaihae. Station 35 is approximately 150 nm southwest of Kawaihae. The WIS 20-year wave climate is very similar for both stations. The WIS stations show that well over 90 percent of the wave conditions come from a northerly direction, between northwest and northeast.

14. The WIS information has some important limitations relative to the project site. The stations are relatively distant from the site; they are subject to somewhat different exposures than the project site; they represent deep water rather than the very shallow conditions at the site; the WIS hindcasting grid did not extend south of the equator; and, the grid omitted the southwestern part of the north Pacific basin in order to ease computational requirements (Corson, et al 1986). Thus waves from the quadrant between west and south, including some important exposure directions for the project site, may be under represented in the WIS information.

15. Another data source is the deepwater buoys operated by the National Oceanic and Atmospheric Administration's National Data Buoy Center (NDBC).

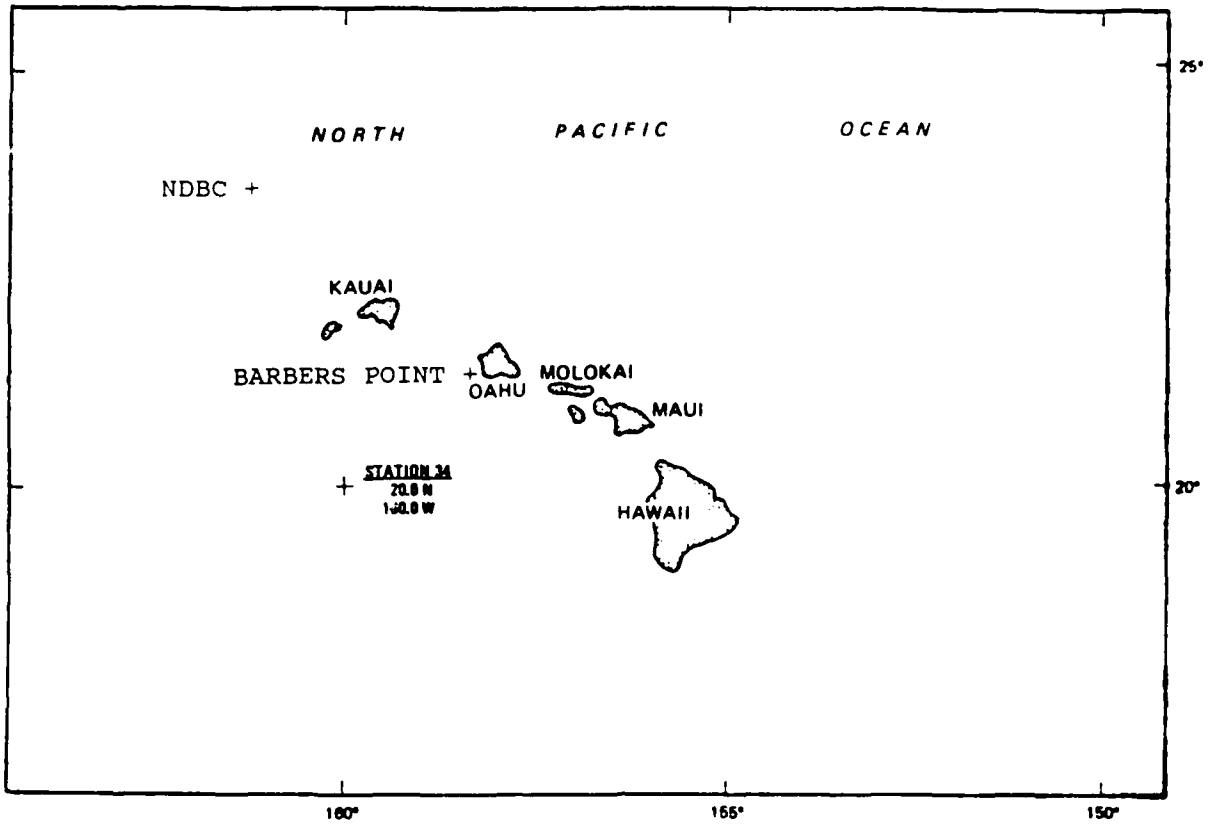

Figure 4. Sources of wave information for the Kawaihae area

Climatological information in the vicinity of the Hawaiian Islands is readily available from only one buoy, Station 51001 (Gilhousen, et al 1986). Measurements include wind speed and direction and wave height and period over the years 1981-84. However, wave direction measurements are not available from this station. The station is not representative of the project site since it is fully exposed to the important north and east approach directions, Figure 4.

16. Nondirectional wave measurements are available from a nearshore buoy at Barbers Point, Oahu, Figure 4. Water depth at the buoy is 600 ft. The buoy, funded through the Monitoring Completed Coastal Projects (MCCP) Program of the US Army Corps of Engineers (USACE 1987), has been in operation since June 1986, a long enough time period to provide general climatological data. Although Barbers Point is on a different island than Kawaihae, the

local coastline orientation and exposure are remarkably similar at the two sites. The main difference is that Barbers Point is more open to the south than Kawaihae.

17. A final data source examined is the Summary of Synoptic Meteorological Observations (US Naval Weather Service Command 1976). These climatological summaries of shipboard wave observations were considered to be of lower quality due to poor comparisons with the other available sources and they were not used.

Deepwater Wave Climate

18. Offshore wave climate at the Kawaihae shallow-draft harbor site was estimated using information from WIS Station 34, NDBC Station 51001, and MCCP Barbers Point buoy. Each of the 3 sources has strengths and limitations relative to the others. The percent occurrence of significant wave height and peak spectral period from WIS (for all directions) and NDBC were compared and the results were very similar. Since the NDBC buoy is exposed to all directions, it appears that major elements of the offshore wave climate are adequately represented in the WIS information despite limitations on the grid coverage. Further validation of the WIS data became available in the final stages of this study. Gilhousen et al (1990) provide a climatological summary for a NDBC buoy located very near the WIS station 34 and results are comparable.

19. The Kawaihae shallow-draft harbor site is exposed to a sector from about 202.5 deg to 337.5 deg azimuth. WIS information within this sector was taken as part of the deepwater climate at Kawaihae. WIS information outside this sector was not used because Kawaihae is sheltered by land from those directions.

20. The WIS percent occurrence for the exposed sector show

significantly higher wave events than at Barbers Point. It appears that Barbers Point summaries represent a general wave climate for a southwest-facing coast and are not distorted by unusual high-energy events. Therefore the joint height-period distribution table from a relatively complete year at Barbers Point (USACE 1987) was used to augment the WIS estimates. The Barbers Point data, weighted to represent the rejected sectors of WIS, was added to the WIS percent occurrence from each direction in the exposed sector. The relative frequency of occurrence of each direction in the exposed sector was maintained throughout the addition of the Barbers Point data. The resulting percent occurrence, given in Appendix A and summarized by direction in Table 1 at the end of the text of this report, is considered as the best possible representation of the deep water wave climate at Kawaihae shallow-draft harbor. The percent occurrence of waves corresponding to Table 1 is shown in Figure 5.

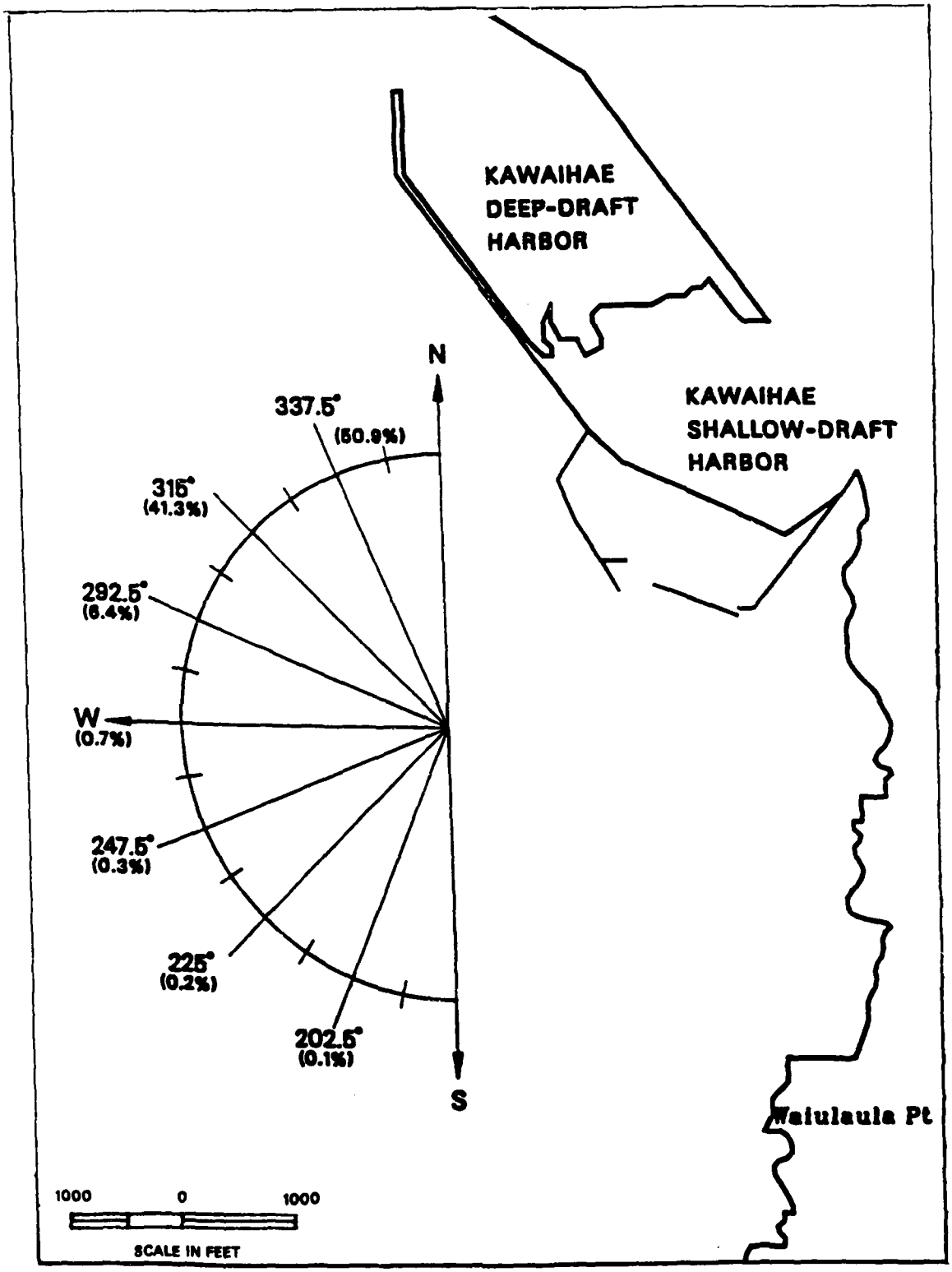

Figure 5. Percent occurrence of deepwater wave conditions by direction

PART III: WAVE TRANSFORMATION MODELING

Wave Transformation Model

21. Once the deepwater wave conditions were established, it was necessary to transform the waves shoreward to the Kawaihae vicinity. This was accomplished using the wave refraction-diffraction numerical model RCPWAVE (Ebersole, Cialone and Prater 1986). RCPWAVE is a finite difference wave propagation model based on the mild slope equation (Berkhoff 1972), which approximates monochromatic, unidirectional wave transformation over smooth bathymetry, including refraction and diffraction. The mild slope equation is given by:

$$\frac{\partial}{\partial x} cc_g \frac{\partial \phi}{\partial x} + \frac{\partial}{\partial y} cc_g \frac{\partial \phi}{\partial y} + \frac{\omega^2 c_g}{c} \phi = 0 \quad (1)$$

where:

x, y = orthogonal horizontal coordinates

c = wave celerity

c_g = group velocity

ω = radian wave frequency

ϕ = complex velocity potential

By neglecting wave reflections the velocity potential function can be expressed as:

$$\phi = ae^{is} \quad (2)$$

where:

$a(x,y)$ = wave amplitude function

e = 2.71828, the base of the natural logarithm

$i = (-1)^{1/2}$

$s(x,y)$ = wave phase function

Substituting the expression for velocity potential into Equation 1 and solving

for the real and imaginary parts separately yields (Berkhoff 1976):

$$\frac{1}{a}\left(\frac{\partial^2 a}{\partial x^2} + \frac{\partial^2 a}{\partial y^2} + \frac{1}{cc_g}\left[\nabla a * \nabla(cc_g)\right]\right) + k^2 - |\nabla s|^2 = 0 \quad (3)$$

$$\nabla * (a^2 cc_g \nabla s) = 0 \quad (4)$$

where:

∇ = $(\partial/\partial x + \partial/\partial y)$, the gradient operator

22. Expressing the irrotationality of the wave phase function gradient in the vector form yields an expression which can be solved for local wave angles once the magnitude of the wave phase function gradient is known. The vector forms can be substituted into Equation 4 to give the following expression for energy:

$$\frac{\partial}{\partial x}\left[\, a^2 cc_g \, |\nabla s| \cos\theta \,\right] + \frac{\partial}{\partial y}\left[\, a^2 cc_g \, |\nabla s| \sin\theta \,\right] = 0 \quad (5)$$

Once the wave phase characteristics ∇s and θ are determined this equation can be solved for the wave amplitude function. Since the wave frequency is constant, the wave height which is proportional to the amplitude function can be determined.

23. Equations 3 and 5, along with the local wave angle expression and the dispersion relation, describe the combined refraction and diffraction process for linear waves with the assumption that the bottom slopes are small, wave reflections are negligible, and energy losses due to bottom friction or wave breaking outside the surf zone can be neglected. For the purpose of determining input wave conditions at the Kawaihae vicinity (outer boundary of the HARBD model) these assumptions are reasonable.

Wave Transformation Simulation

24. RCPWAVE transformation estimates were performed from a depth of approximately 180 ft offshore to 22 ft at the HARBD outer boundary (Kawaihae vicinity). Representative period-direction combinations with a unit wave

height were selected from the modified WIS percent occurrence tables, summarized by direction in Table 1, for input into RCPWAVE. Each deepwater wave input to RCPWAVE was refracted using Snell's law and assuming straight parallel contours up to the seaward boundary of the RCPWAVE grid.

25. The RCPWAVE model uses a rectangular uniformly spaced finite difference grid. The grid used in this study, Figure 6, had 35 cells alongshore (positive y-axis directed south) and 45 cells across-shore (positive x-axis directed offshore or west). Each cell is 200 ft alongshore and 100 ft offshore. The grid spacing is somewhat fine for this application so that transformations over the sometimes complex and rapidly varying bathymetry can be resolved. The grid is situated so that the maximum amount of waves incident on the harbor are accounted for. Since the greatest exposure is to the west and south the majority of the grid extends south of the harbor area.

26. Input requirements for RCPWAVE are deepwater wave height, period and direction. As stated earlier a unit wave height was selected for all RCPWAVE runs to produce a normalized amplification factor based on the ratio of wave height to incident wave height. The amplification factors obtained from the deepwater period-direction combination can be used to calculate the transformed wave height. This greatly reduces the number of RCPWAVE runs required. Wave period-direction combinations selected from the modified WIS data range from 7 to 20 sec and 202 to 337 deg azimuth respectively. The limits in which RCPWAVE remains stable are generally up to 60 deg angle of approach. Upon testing, the model became unstable for waves with periods longer than 7 sec from 337 deg. For waves approaching from 337 deg, there is a 40-50 nm fetch between Kawaihae harbor and the nearest island, Maui. Based on the fetch and average wind speed for the area of 30 knots (NDBC station

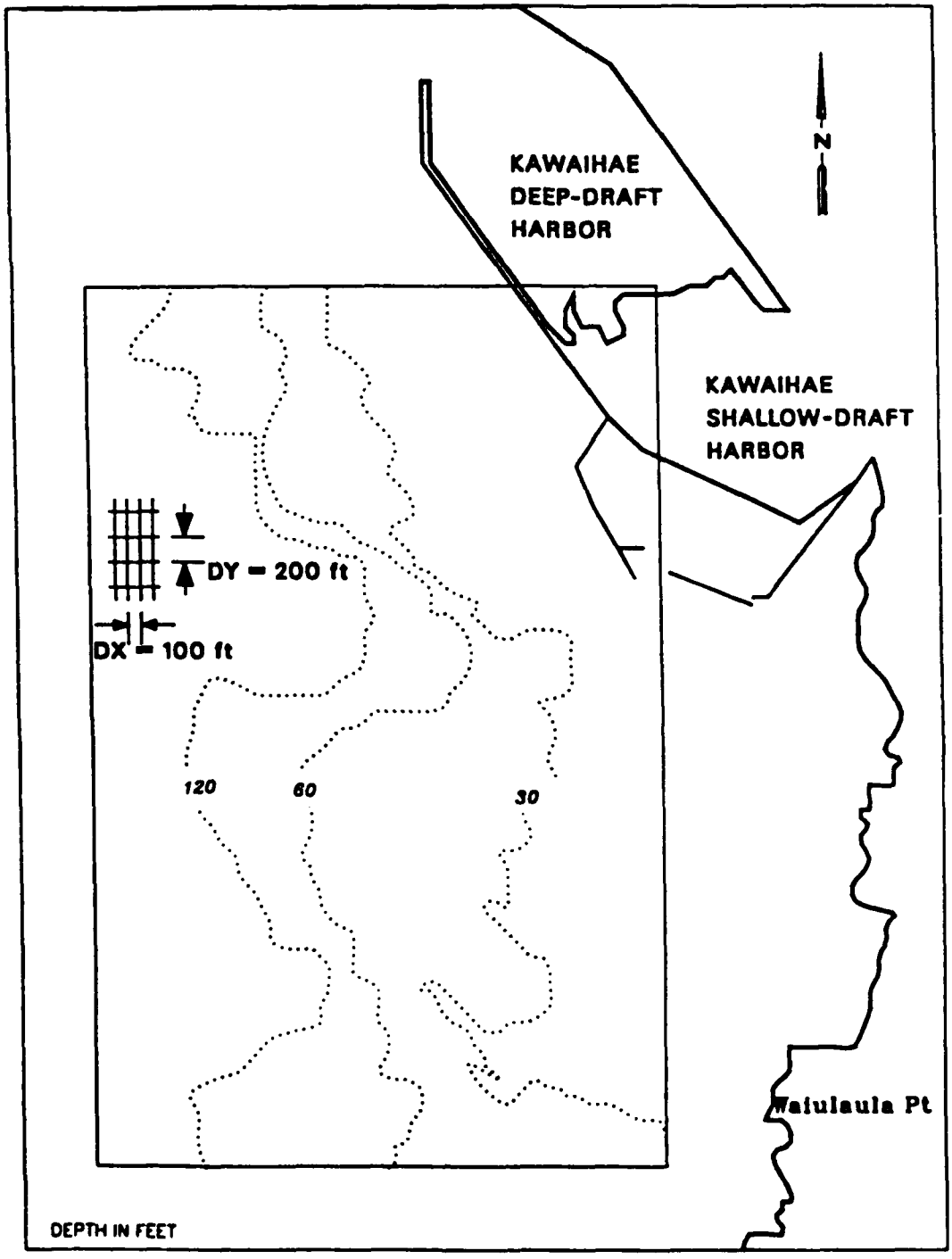

Figure 6. Extent of RCPWAVE finite difference grid

51001) wave periods generated within this fetch are limited to 7 sec and shorter (SPM Fig. 3-24, p 3-50). Assuming that waves from 337 deg generated outside this fetch area are sufficiently attenuated by the sheltering islands north-northwest of the harbor, waves with periods longer than 7 sec from this direction can be neglected.

27. Output from RCPWAVE, for each period-direction combination, consists of resulting local wave angles and amplification factors for each grid cell. For each input wave condition the average local wave angle (ALWA) and average amplification factor of the cells directed toward the harbor which coincided with the HARBD outer boundary were computed. The input deepwater wave periods and directions, and the corresponding transformed ALWA's and average amplification factors are given in Table 2. The table shows that the ALWA's at the HARBD boundary range from 245 to 240 deg for deepwater wave conditions from 247, 270, and 292 deg with the exception of the 7 sec wave in the 292 deg deepwater wave direction. The ALWA in this case is 250 deg. The average amplification factors for these deepwater wave directions also have little variation, ranging from 0.60 to 0.70 with the exception of the 17 and 20 sec waves in the 292 deg deepwater wave direction. ALWA's show more sensitivity to change in wave period for the 225 and 315 deg deepwater wave directions. Deepwater waves approaching from 225 deg and ranging from 7 to 20 sec have transformed ALWA's ranging from 234 to 244 deg, while deepwater waves from 315 deg have ALWA's ranging from 255 to 238 deg. The average amplification factors for 225 and 315 deg deepwater wave directions ranges from 0.70 to 0.80 and 0.55 to 0.70 respectively.

28. Figures 7, 8, and 9 are wave refraction diagrams for the 7, 13, and 20 sec deepwater periods from 225, 247, 292, and 315 deg. Table 2 and the wave refraction diagrams show that with the exception of some of the shorter

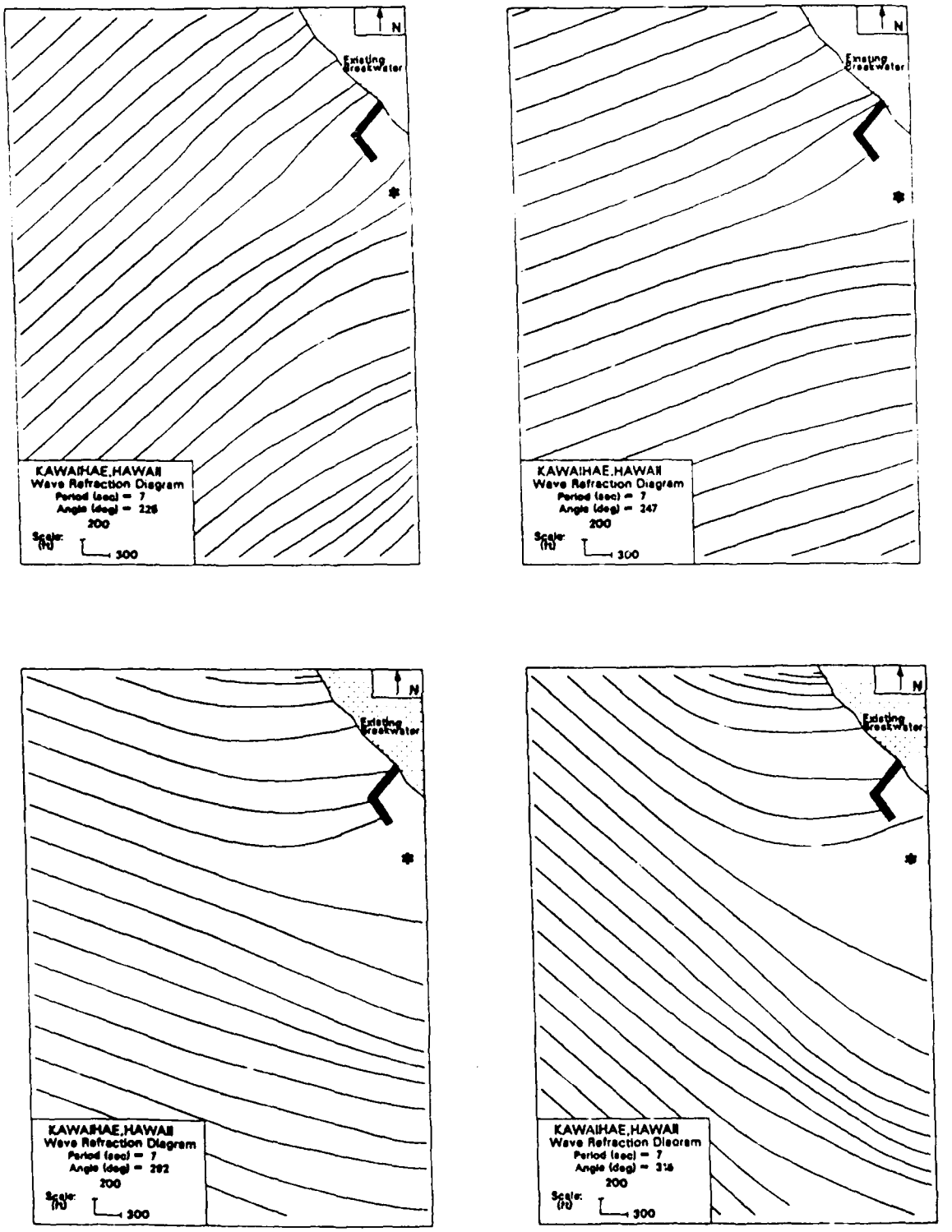

Figure 7. RCPWAVE wave refraction diagrams, 7 sec waves
(* = location of harbor entrance)

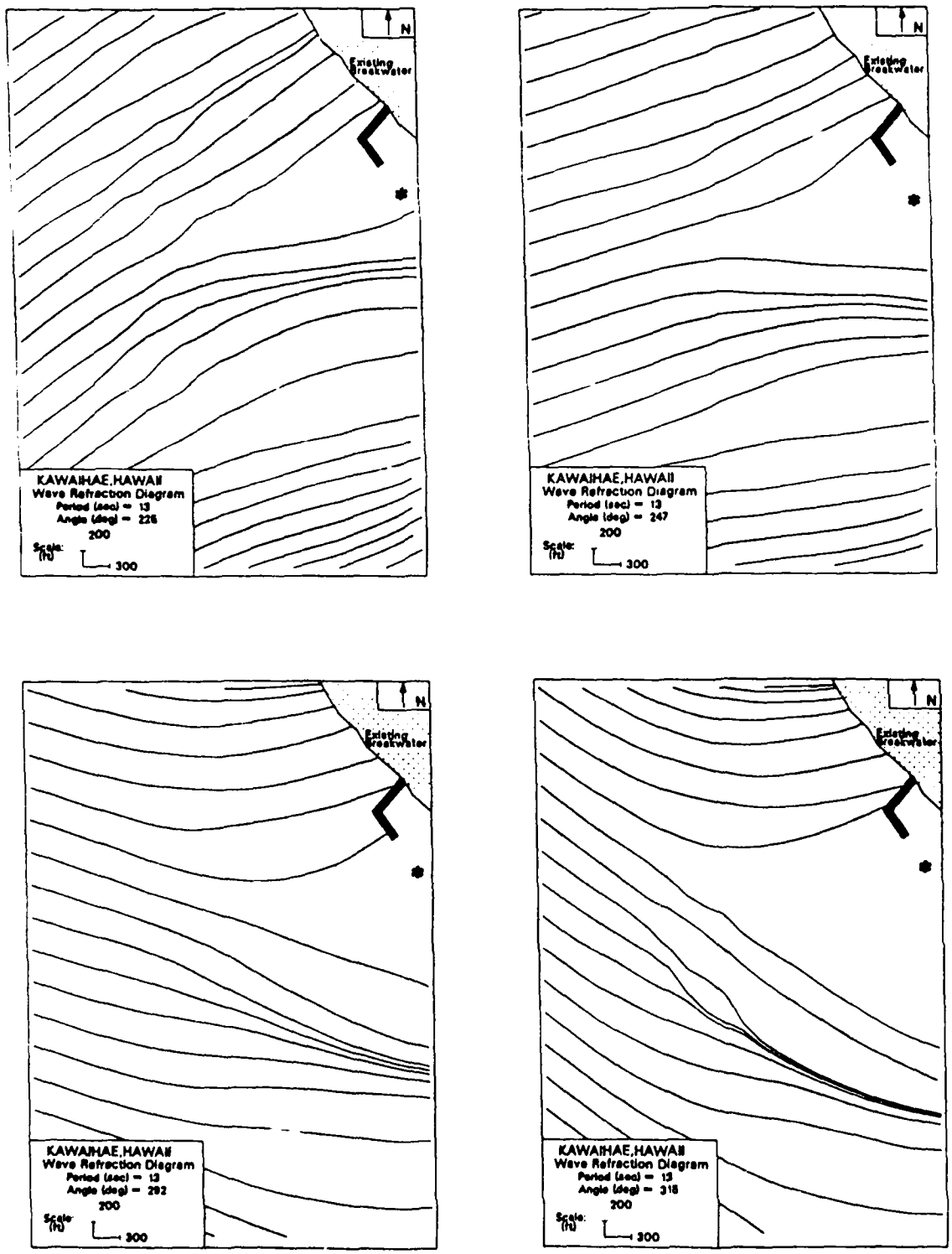

Figure 8. RCPWAVE wave refraction diagrams, 13 sec waves
(* = location of harbor entrance)

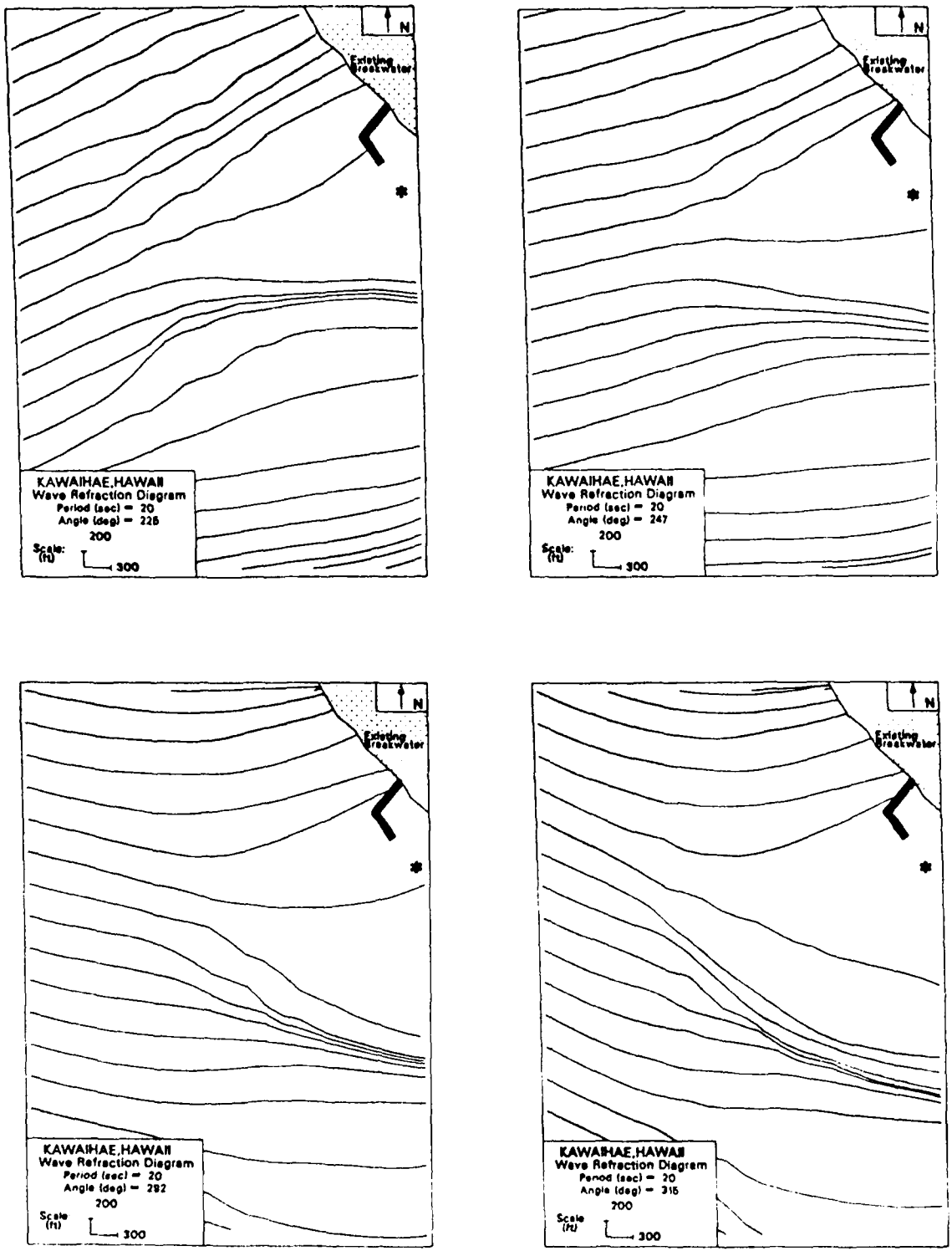

Figure 9. RCPWAVE wave refraction diagrams, 20 sec waves
(* = location of harbor entrance)

wave periods the majority of deepwater waves from different direction bands are refracted to an average angle within 2 or 3 degrees of 240 deg at the HARBD boundary.

29. The wave refraction diagrams also show spreading of energy near the harbor area caused by a canyon like feature in the bathymetry. This spreading of energy results in significantly reduced wave heights at the harbor.

Part IV: HARBOR WAVE RESPONSE MODELING

Harbor Wave Response Model

30. The numerical model HARBD (Chen and Houston 1987) was used to model the harbor wave response at Kawaihae shallow-draft harbor, Hawaii. HARBD is a steady state hybrid finite element model which calculates linear wave oscillations in harbors of arbitrary configuration and variable water depth. The model is advantageous over other numerical harbor models since bottom friction and boundary absorption are included. The bottom friction is assumed to be proportional to flow velocity with a phase difference. The boundary absorption is based on a formulation similar to that in the impedance condition in acoustics and is expressed in terms of wave number ($2\pi/L$ where L is the wavelength) and reflection coefficient of the boundary. The result is that HARBD predicts wave amplitudes which are more realistic than those from previous models (Chen and Houston 1987). HARBD was originally developed for harbor oscillations (long period waves), and the general formulation was adapted for wind waves (short period waves) by Houston (1981).

31. The model has been tested and compared with excellent results for a number of cases for which analytic solutions are known (Chen 1984 and Chen and Houston 1987). It has been applied in the design of Agat Harbor, Guam (Farrar and Chen 1987), studying the effects of entrance channel dredging at Morro Bay Harbor, California (Kaihatu, Lillycrop, and Thompson, 1989), and analyzing harbor resonance at Los Angeles-Long Beach Harbor California (Sargent 1989). The model was used to plan wave protection at Fisherman's Wharf, San Francisco, California (Bottin, Sargent, and Mize, 1985), Green Harbor, Massachusetts (Weishar 1986), Los Angeles-Long Beach Harbor, California (Houston 1976), and to estimate the wave conditions in Indiana Harbor, Indiana

during a study of sediment disposal alternatives (Clausner and Abel 1986). HARBD was compared to laboratory data collected from the physical model study of Barcelona Harbor, Buffalo, New York (Crawford and Chen 1988) with encouraging results.

32. In the HARBD solution formulation, the water domain is divided into near and far regions. The near region is bounded by an artificial semicircular ring outside the harbor and includes the harbor and all marine structures and bathymetry of interest. The far region is an infinite semicircular ring bounded by the near region and extends to infinity in all horizontal directions. The infinite far region is assumed to have straight coastlines, a constant water depth, and no bottom friction. The finite near region, which contains the area of interest, is subdivided into a mesh of triangular shaped finite elements. The length of the sides of each element is determined from the desired grid resolution and design wave parameters. The water depth and bottom friction coefficient are specified for each element, and a reflection coefficient is assigned to each element on the solid boundaries. The model requires a wave period and direction as input. The solution consists of an amplification factor (i.e. the ratio of the wave height to the incident wave height) and a corresponding phase angle for the entire near region. The phase angle is of little importance to the present study.

33. The model solves the following governing equation:

$$\frac{\partial}{\partial x} \lambda cc_g \frac{\partial \phi}{\partial x} + \frac{\partial}{\partial y} \lambda cc_g \frac{\partial \phi}{\partial y} + \frac{\omega^2 c_g}{c} \phi = 0 \qquad (6)$$

where

c = wave phase velocity

c_g = wave group velocity

ϕ = spatial flow potential

ω = radian wave frequency

The complex bottom friction factor λ is assumed proportional to the maximum velocity at the bottom of the flow field and is defined as

$$\lambda = 1/(1+(i\beta a_o/h \sinh kh)e^{i\gamma}) \quad (7)$$

where

β = dimensionless bottom friction coefficient, = 0.05 for all cases

a_o = incident wave amplitude

k = wave number $2\pi/L$, where L = wavelength

e = 2.71828, the base of the natural logarithm

i = $(-1)^{1/2}$

h = water depth

γ = phase difference from flow velocity

An absorbing boundary condition is applied along the solid boundaries inside the harbor and is expressed as

$$\partial\phi/\partial n - \alpha\phi = 0 \quad (8)$$

and

$$\alpha = ik\ (1-K_r/1+K_r) \quad (9)$$

where

n = independent variable in the direction of the unit-normal vector.

K_r = the reflection coefficient of the boundary.

34. A conventional finite element approximation is used in the near region, and an analytical solution with unknown coefficients is used to describe the far region. The conditions in the near and far regions must be matched along the artificial semicircle boundary. This requirement is met by HARBD routines which automatically match the solutions using the stationarity of a functional, to a series of Hankel Functions which give the solution for

the infinite region (Farrar and Chen 1987). The hybrid element numerical techniques used in the formulation are discussed in greater detail in Chen and Mei (1974).

35. The HARBD model is intended to simulate waves which can be adequately described by the mild slope equation (Equation 6). Model accuracy decreases as wave conditions approach those outside the validity of this governing equation. HARBD does not simulate nonlinear processes such as wave breaking, wave transformation and overtopping of structures, and wave current interaction, however, the model predicts wave heights accurately if these processes are not dominant.

Finite Element Grids for Plan 1 and Plan 2

36. The finite element grids used to model Plan 1 and Plan 2 are shown in Figures 10 and 11. Both grids cover the same offshore and harbor areas with the exception of the modified west mole breakwater tip of Plan 2. The total number of elements (triangles), nodes (triangular corners), and boundary elements are 8674, 4561, and 348, respectively, for Plan 1 and 8703, 4571, and 339, respectively, for Plan 2. An approximate 6 elements per wavelength resolution is obtained for each grid. The wavelength is determined from linear wave theory using the design wave period of 8 seconds and a water depth of 8 feet.

37. The orientation and seaward extension of the artificial semicircular boundary is sufficient to adequately model the incident wave climate from pertinent directions into the study area. The semicircle diameter is approximately 1600 ft and is designed to be approximately twice the distance between the east and west breakwater tips. The entire seaward sides of the breakwaters were not enclosed since these areas would not affect the response inside the harbor.

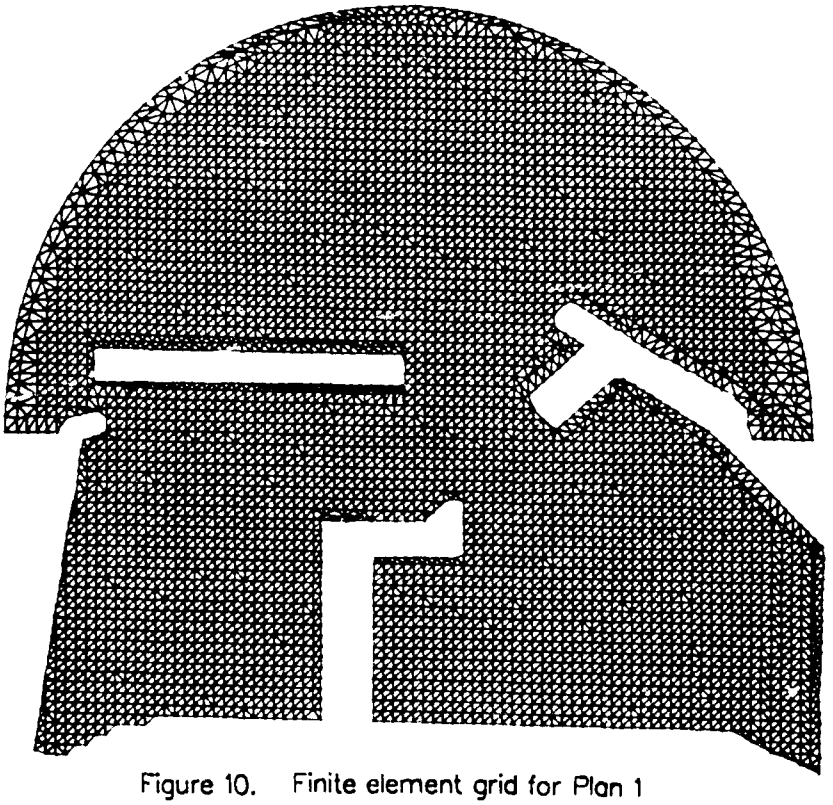

Figure 10. Finite element grid for Plan 1

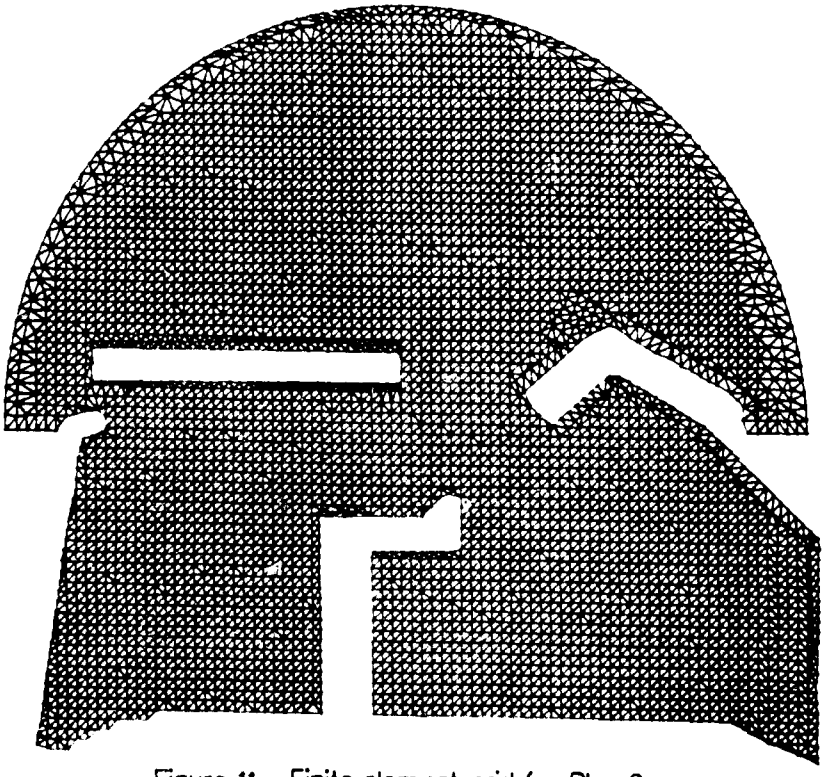

Figure 11. Finite element grid for Plan 2

38. The grid bathymetry was obtained from District hydrographic surveys of the study area based on conditions determined in 1989. A portion of the reef located south of the west mole breakwater was included in the bathymetry. A tide level of 5.5 ft (POD recommendation) was added to the Mean Lower Low Water Level (MLLW) of the hydrographic survey for all tests. The reflection coefficients were calculated using methods in the Shore Protection Manual (SPM 1984), and were refined upon recommendation from POD. The assigned reflection coefficients were 0.25 for the 1:2 sloped detached breakwater and 1:2 sloped seaward sides of the east and west mole breakwaters, 0.35 for the 1:1.5 sloped harbor sides of the east and west mole breakwaters, 0.30 for the wave absorber and interior mole, and 0.1 for the beach. The boundaries along the diameter of the semicircle were fully transmissive. The bottom friction factor (β) was set at 0.05 for all elements.

39. The grid for this study was initially developed at WES' Information Technology Laboratory (ITL). The grid was massaged and refined by CERC for application to HARBD. This procedure for HARBD grid generation was an original WES application.

Harbor Wave Response Simulation

40. Since 14 of the 39 deepwater wave period and direction combinations input to RCPWAVE refracted to duplicate angles at the HARBD boundary (Table 2), only 25 input wave period and direction combinations were necessary to establish the 39 refracted deepwater wave conditions at the harbor. The RCPWAVE-HARBD grid interface and the location of the selected RCPWAVE output cells are shown in Figure 12. The output cells selected were coincident with the HARBD outer boundary and were directed toward the harbor. A normalized unit wave height was used for all input combinations to establish a wave height to incident wave height amplification factor. The RCPWAVE

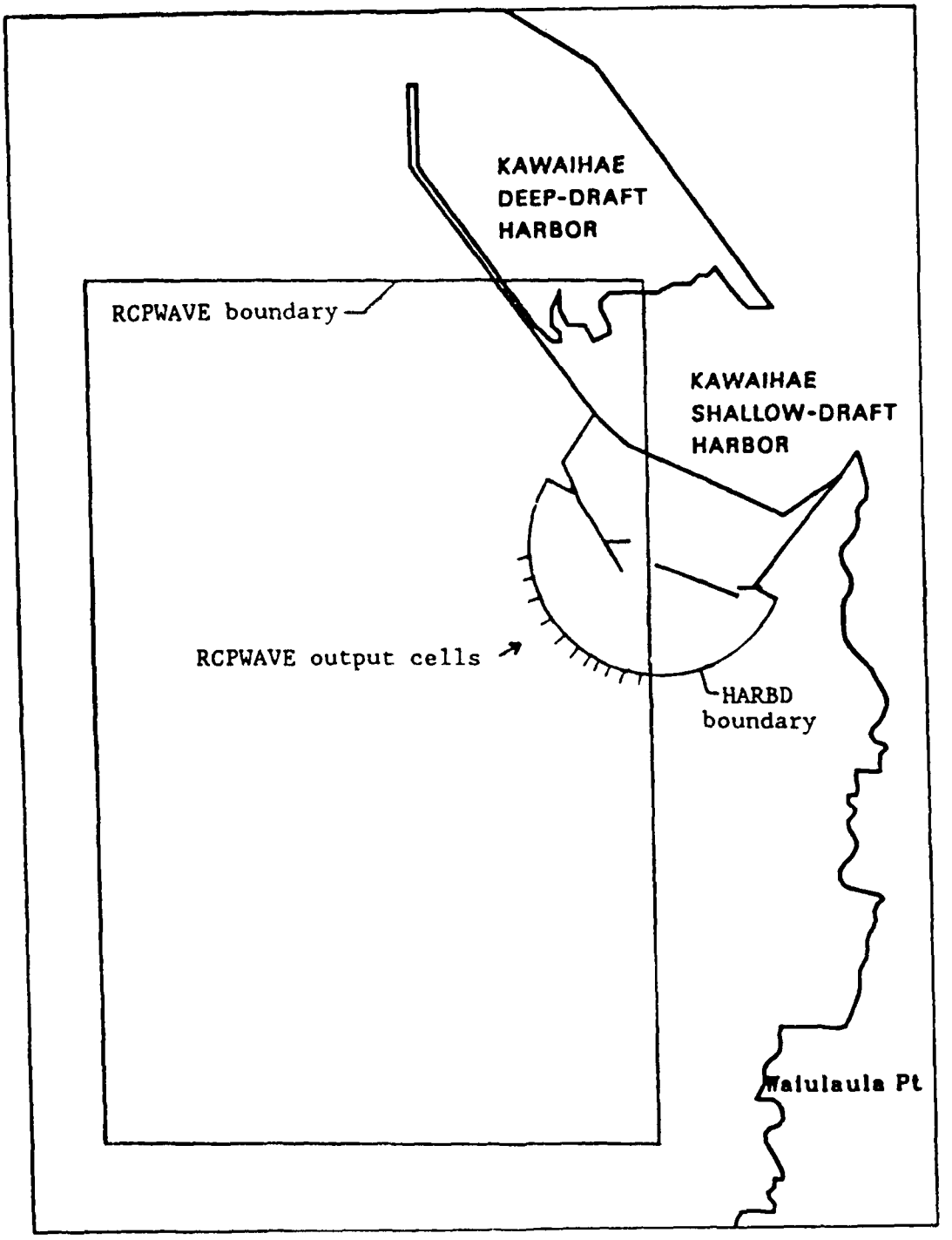

Figure 12. RCPWAVE-HARBD grid interface

amplification factors were multiplied with the HARBD amplification factors corresponding to each deepwater condition. The 25 wave period and direction combinations were tested for both Plans 1 and 2. All simulations were run on the WES CRAY Y-MP supercomputer facilities.

41. Nineteen output "basins" were selected to determine the wave response throughout the harbor. A basin is an area consisting of a specified number of elements from which the mean value of the results of those elements is calculated. The basin locations were the same for Plans 1 and 2 and selected by CERC, POD, and HQUSACE. They are shown in Figure 13. Basins 1 through 12 are located in the harbor berthing areas with a 1 ft maximum wave height criterion, and basins 13 through 19 are located throughout the harbor channels and turning basin with a 2 ft maximum wave height criterion. The resulting HARBD amplification factors at these basins for each deepwater wave condition were saved and tabulated for Plans 1 and 2 (Tables 3 through 16).

42. The percent occurrence of wave heights exceeding 1 ft in the berthing areas and 2 ft in the channel and turning basin were calculated for Plans 1 and 2. The procedure to calculate the percent occurrence of wave heights exceeding the 1 ft maximum criterion is as follows. The largest HARBD amplification factor of basins 1 through 12, was selected for each deepwater wave condition. The selected HARBD amplification factors were then multiplied by the RCPWAVE amplification factors corresponding to each deepwater wave condition. The wave conditions resulting in the largest wave heights were then calculated by multiplying the HARBD-RCPWAVE amplification factor for each deepwater condition by the wave height intervals of the corresponding percent occurrence table. The percent occurrence of those resulting wave heights which exceeded 1 ft were then tabulated. The same procedure was used to calculate the percent occurrence of wave heights exceeding the 2 ft criterion

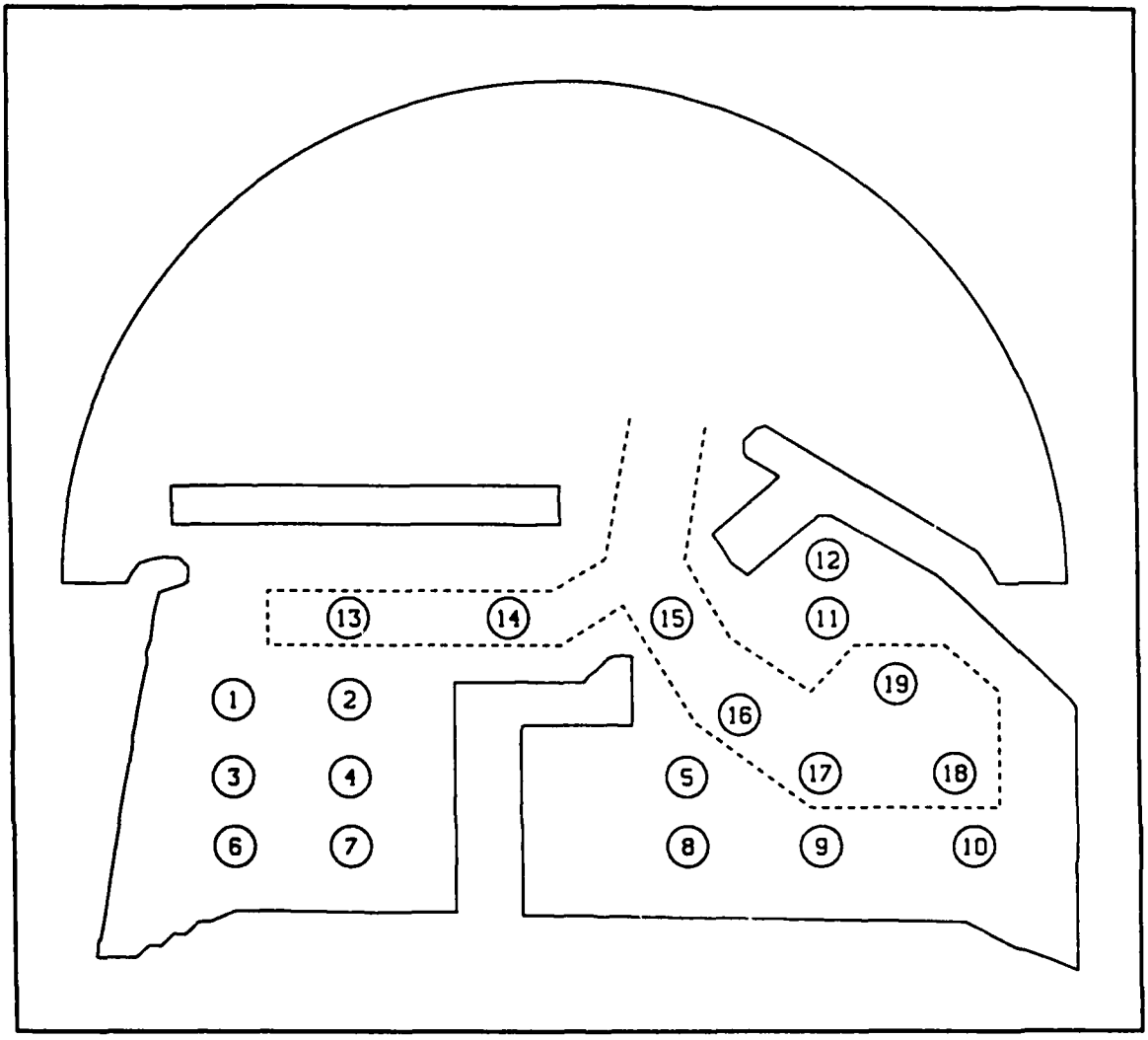

Figure 13. Output basin locations for Plans 1 and 2

in basins 13 through 19.

43. The resulting HARBD-RCPWAVE basin amplification factors of Plans 1 and 2 for each deepwater wave condition are plotted in Plates 1-39. The plots show that the amplification factors from Plan 2 exceed those of Plan 1 for 90 percent of the deepwater conditions.

44. Table 17 is a tabulation of the largest resulting HARBD-RCPWAVE amplification factors from each deepwater wave direction, the corresponding deepwater wave period, and the basin in which they occurred for the 1 and 2 ft maximum criteria of Plans 1 and 2. Table 17 shows that the largest wave amplification factors and thus largest wave heights occurring in the 1 ft maximum criterion berthing areas (basins 1 through 12) were caused by the 11 sec wave from directions of 202.5, 225.0, 247.5, and 292.5 deg, and the 7 sec wave from directions of 270.0, 315.0, and 337.5 deg. The largest wave heights from directions of 202.5, 225.0, 247.5, 270.0, and 292.5 deg occurred in basin 5 and those from 315.0 and 337.5 deg occurred in basin 2. Referring to Figure 13, basins 2 and 5 are located on the east and west sides of the wave absorber. The largest wave heights occurring in the 2 ft maximum criterion turning basin and channels (basins 13 through 19) resulted from the 11 sec wave from directions of 202.5, 225.0, and 247.5 deg, and the 7 sec wave from directions of 270.9, 292.5, 315.0, and 337.5 deg. The largest wave heights from 202.5, 225.0, 247.5, and 270.0 deg occurred in basin 15 and those from 292.5, 315.0 and 337.5 deg occurred in basin 14. Basin 14 is located in the access channel and basin 15 in the entrance channel. The worst case wave condition for both the maximum 1 and 2 ft criteria areas was the 7 sec wave from 315 deg.

45. In evaluating Table 17 for Plan 2, the largest amplification factors and thus largest wave heights occurring in the berthing areas (basins

1 through 12) are caused by the 11 sec wave from all directions with the exception of the 7 sec fetch limited wave from 337.5 deg. The 11 sec wave from 270.0 deg occurred in basin 8 and the remaining waves occurred in basin 5. Basin 8 is located at the back of the harbor, on the west side of the wave absorber, and below basin 5. The largest wave heights occurring in the turning basin and channels (basins 13 through 19) result from the 11 sec wave from directions of 202.5, 225.0, 247.5, 270.0, and 292.5 deg, and the 7 sec wave from 315.0 and 337.5 deg. The 11 sec waves occurred in basin 15 and the 7 sec waves occurred in basin 14. The worst case wave conditions for Plan 2 were the 11 sec 225.0 deg wave for the maximum 1 ft criterion and the 7 sec 315.0 deg wave for the maximum 2 ft criterion.

46. The percent occurrence of wave heights exceeding the maximum 1 and 2 ft criteria more than approximately 10 percent of the time were calculated using the percent occurrence tables of deepwater conditions and the largest HARBD-RCPWAVE amplifications factors for Plans 1 and 2. These results are given in Tables 18 through 21 and illustrated in Figures 14 and 15. Although wave breaking was not taken into account in Tables 18 through 20, the higher wave heights would most likely have broken over the reef, thus reducing the wave heights in the harbor. With a controlling water depth of 8 feet and a water level of 5.5 ft, those waves breaking over the reef may still result in sizable waves which exceed the design criteria.

47. In evaluating the resulting percent occurrences tables, Tables 18 through 21, and Figures 14 and 15, it is apparent that the waves approaching from the west southwest (202.5 to 270.0 deg) directions are insignificant in comparison to the waves approaching from the northwest (292.5 to 337.5 deg) directions. The percentage of wave heights exceeding the maximum 1 ft criterion for Plan 1 and 2 is 10.9 percent and 21.4 percent, respectively, and

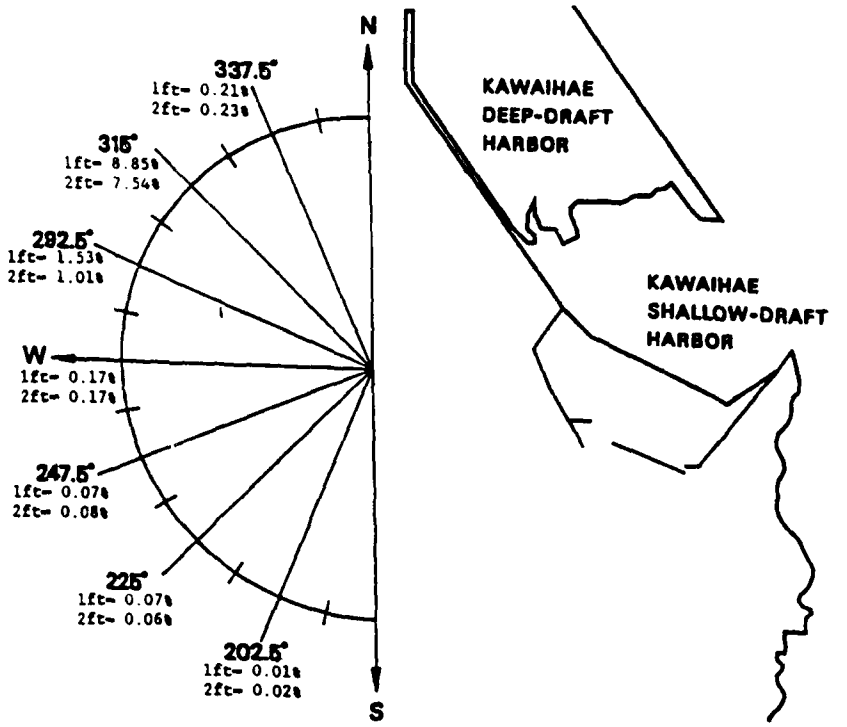

Figure 14. Plan 1 - Percent occurrence of wave heights exceeding 1 and 2 ft criteria

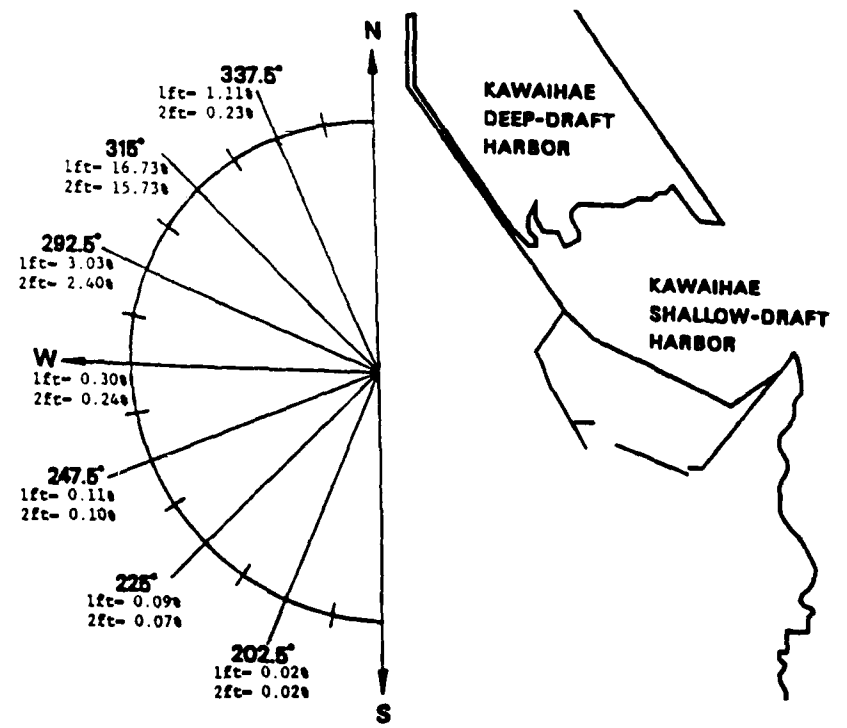

Figure 15. Plan 2 - Percent occurrence of wave heights exceeding 1 and 2 ft criteria

the percentage of wave heights exceeding the maximum 2 ft criterion for Plan 1 and 2 is 9.1 percent and 18.8 percent, respectively. These values are conservative since they represent the basins with the largest wave heights in the harbor. When one considers the uncertainties in augmenting the WIS deepwater data, approximating values in the RCPWAVE modeling, and estimating the harbor reflection coefficients, confidence can be held in the Plan 1 tolerance limits meeting the HQUSACE criteria of not exceeding 1 and 2 ft more than approximately 10 percent of the time. The Plan 2 values however, do exceed the HQUSACE criteria. The removal of the west breakwater tip reduces protection from a large percentage of waves occurring from the northwest and thus significantly increased wave heights inside the harbor.

PART V: CONCLUSIONS

48. The numerical model studies and results described in this report should be seen in light of the following considerations:

a. The deepwater waves were based on estimates from WIS and MCCP data. Generation of more accurate incident wave data would improve the validity of the overall results.

b. The input water level and revised SPM reflection coefficients were based on estimates from POD and were not re-evaluated. Research in this area continues at CERC for better guidance.

c. The following assumptions were made in the implementation of the HARBD numerical model used in this study. The model does not consider wave transmission through the breakwater, overtopping of structures, and wave breaking effects in the entrance channel; structure crest elevations were not tested or optimized; currents in the channel through the reef and nonlinear effects were neglected as well as other than depth-limited wave breaking over the reef; and diffraction around the structure ends was represented by diffraction around a blunt vertical wall with specified reflection coefficients. If wave transmission through the breakwater and overtopping of structures did occur in the harbor, the increased energy would result in larger wave heights than predicted. The presence of wave currents and breaking would increase hazardous navigation, however wave breaking would reduce the energy in the harbor and result in lower wave heights than predicted. The primary effects which must be considered within a harbor such as Kawaihae are wave refraction, diffraction, and dissipation effects for which the model has been well verified.

d. The HARBD model uses monochromatic waves only.

49. Based on the results of this study, the following conclusions were reached:

a. The POD plan based on the GDM (Plan 1) is satisfactory relative to the design criteria of the project for protecting the harbor from the incident wave climate. Plan 1 is recommended.

b. Plan 2, which is identical to Plan 1 with the exception of the reduced west mole breakwater tip, will not protect the harbor adequately from the deepwater waves which refract to incident angles from the northwest.

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Table 1

Percent Occurrence of Wave Heights Versus Direction**

Wave Height ft	Wave Direction, deg (from which waves approach) 202.5	225	247.5	270	292.5	315	337.5	Total
0-3	0.04	0.10	0.13	0.31	2.75	16.86	20.88	41.03
3-6	0.02	0.07	0.09	0.20	1.82	11.74	16.05	29.97
6-9	0.02	0.02	0.05	0.11	0.34	4.61	7.52	12.65
9-12	*	0.02	0.04	0.09	1.02	5.56	5.30	12.12
12-15	*	0.01	0.01	0.01	0.47	2.02	1.10	3.63
>15	0.00	0.02	0.01	0.02	0.06	0.45	*	0.56
TOTAL	0.08	0.24	0.33	0.74	6.46	41.31	50.85	100.0

** Percent occurrence is below table resolution

Table 2

RCPWAVE Offshore and Refracted Wave Conditions

Period (sec)	Offshore Direction (deg)	Refracted Direction (deg)	Amplification Factor
7	202.5	230.0	0.60
9	202.5	234.0	0.69
11	202.5	240.0	0.70
7	225.0	234.0	0.80
9	225.0	237.0	0.75
11	225.0	240.0	0.75
13	225.0	242.0	0.70
15	225.0	242.0	0.75
17	225.0	243.0	0.75
20	225.0	244.0	0.70
7	247.5	240.0	0.70
9	247.5	240.0	0.70
11	247.5	240.0	0.70
13	247.5	240.0	0.70
15	247.5	240.0	0.70
17	247.5	240.0	0.70
20	247.5	240.0	0.70
7	270.0	245.0	0.65
9	270.0	240.0	0.60
11	270.0	240.0	0.65
13	270.0	240.0	0.65
15	270.0	240.0	0.65
17	270.0	240.0	0.65
20	270.0	240.0	0.65
7	292.5	250.0	0.70
9	292.5	245.0	0.70
11	292.5	245.0	0.73
13	292.5	240.0	0.70
15	292.5	240.0	0.70
17	292.5	240.0	0.80
20	292.5	240.0	0.90
7	315.0	255.0	0.70
9	315.0	246.0	0.70
11	315.0	243.0	0.60
13	315.0	240.0	0.55
15	315.0	240.0	0.60
17	315.0	237.0	0.65
20	315.0	238.0	0.63
7	337.5	260.0	0.53

Table 3

HARBD Wave Amplification Factors for Proposed Improvements

Plan 1, Wave Angle = 202.5 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.08	0.18	0.12	*	*	*	*
2	0.09	0.22	0.11				
3	0.06	0.13	0.05				
4	0.08	0.17	0.07				
5	0.30	0.11	0.37				
6	0.06	0.12	0.08				
7	0.07	0.12	0.03				
8	0.22	0.09	0.29				
9	0.27	0.18	0.27				
10	0.19	0.13	0.22				
11	0.20	0.12	0.23				
12	0.10	0.07	0.11				
13	0.08	0.17	0.10				
14	0.21	0.49	0.27				
15	0.52	0.16	0.53				
16	0.38	0.20	0.32				
17	0.31	0.17	0.24				
18	0.17	0.13	0.13				
19	0.18	0.12	0.16				

* No data for these wave periods

Table 4

HARBD Wave Amplification Factors for Proposed Improvements

Plan 1, Wave Angle = 225 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.22	0.14	0.12	0.11	0.19	0.13	0.08
2	0.23	0.18	0.11	0.11	0.20	0.14	0.10
3	0.15	0.16	0.05	0.07	0.15	0.11	0.14
4	0.22	0.09	0.07	0.08	0.11	0.09	0.05
5	0.10	0.04	0.30	0.12	0.18	0.11	0.14
6	0.12	0.08	0.08	0.04	0.06	0.06	0.09
7	0.18	0.05	0.03	0.04	0.10	0.07	0.02
8	0.08	0.05	0.28	0.13	0.16	0.07	0.08
9	0.13	0.12	0.26	0.11	0.14	0.06	0.07
10	0.14	0.11	0.22	0.07	0.07	0.04	0.04
11	0.21	0.11	0.23	0.10	0.08	0.06	0.05
12	0.13	0.06	0.11	0.09	0.06	0.04	0.05
13	0.19	0.16	0.10	0.09	0.21	0.14	0.12
14	0.30	0.46	0.27	0.25	0.32	0.23	0.25
15	0.29	0.18	0.53	0.25	0.31	0.16	0.22
16	0.12	0.13	0.32	0.16	0.22	0.10	0.14
17	0.17	0.13	0.24	0.08	0.15	0.09	0.12
18	0.16	0.12	0.13	0.04	0.09	0.06	0.05
19	0.18	0.12	0.16	0.08	0.07	0.03	0.07

Table 5

HARBD Wave Amplification Factors for Proposed Improvements

Plan 1, Wave Angle = 247.5 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.15	0.16	0.12	0.11	0.19	0.12	0.08
2	0.19	0.22	0.11	0.13	0.20	0.14	0.10
3	0.13	0.21	0.05	0.08	0.15	0.13	0.12
4	0.14	0.13	0.07	0.09	0.11	0.09	0.05
5	0.14	0.13	0.29	0.06	0.18	0.16	0.12
6	0.12	0.10	0.08	0.04	0.07	0.09	0.09
7	0.06	0.08	0.03	0.05	0.10	0.07	0.02
8	0.12	0.14	0.27	0.07	0.16	0.11	0.08
9	0.16	0.15	0.26	0.07	0.15	0.10	0.07
10	0.14	0.15	0.21	0.06	0.07	0.06	0.04
11	0.13	0.19	0.23	0.09	0.09	0.10	0.06
12	0.09	0.10	0.11	0.07	0.07	0.07	0.06
13	0.14	0.20	0.10	0.11	0.22	0.15	0.12
14	0.35	0.43	0.27	0.26	0.31	0.30	0.25
15	0.33	0.32	0.53	0.16	0.33	0.25	0.22
16	0.21	0.20	0.32	0.09	0.22	0.16	0.14
17	0.22	0.16	0.24	0.06	0.15	0.15	0.12
18	0.12	0.17	0.13	0.03	0.10	0.09	0.05
19	0.14	0.18	0.16	0.07	0.07	0.05	0.07

Table 6

HARBD Wave Amplification Factors for Proposed Improvements

Plan 1, Wave Angle = 270 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.16	0.16	0.12	0.11	0.19	0.12	0.08
2	0.25	0.22	0.11	0.13	0.20	0.14	0.10
3	0.15	0.21	0.05	0.08	0.15	0.13	0.14
4	0.15	0.13	0.07	0.09	0.11	0.09	0.05
5	0.34	0.13	0.37	0.06	0.18	0.16	0.14
6	0.17	0.10	0.08	0.04	0.07	0.09	0.09
7	0.10	0.08	0.03	0.05	0.10	0.07	0.02
8	0.27	0.14	0.29	0.07	0.16	0.11	0.08
9	0.27	0.15	0.27	0.07	0.15	0.10	0.07
10	0.21	0.15	0.22	0.06	0.07	0.06	0.04
11	0.22	0.19	0.23	0.09	0.09	0.10	0.06
12	0.12	0.10	0.11	0.07	0.07	0.07	0.06
13	0.18	0.20	0.10	0.11	0.22	0.15	0.12
14	0.42	0.43	0.27	0.26	0.31	0.30	0.25
15	0.63	0.32	0.53	0.16	0.33	0.25	0.22
16	0.42	0.20	0.32	0.09	0.22	0.16	0.14
17	0.36	0.16	0.24	0.06	0.15	0.15	0.12
18	0.19	0.17	0.13	0.03	0.10	0.09	0.05
19	0.23	0.18	0.16	0.07	0.07	0.05	0.07

Table 7

HARBD Wave Amplification Factors for Proposed Improvements

Plan 1, Wave Angle = 292.5 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.19	0.18	0.08	0.11	0.19	0.12	0.08
2	0.32	0.24	0.13	0.13	0.20	0.14	0.10
3	0.23	0.23	0.08	0.08	0.15	0.13	0.14
4	0.22	0.13	0.08	0.09	0.11	0.09	0.05
5	0.32	0.27	0.32	0.06	0.18	0.16	0.14
6	0.15	0.10	0.08	0.04	0.07	0.09	0.09
7	0.17	0.08	0.06	0.05	0.10	0.07	0.02
8	0.25	0.26	0.26	0.07	0.16	0.11	0.08
9	0.28	0.28	0.24	0.07	0.15	0.10	0.07
10	0.19	0.22	0.18	0.06	0.07	0.06	0.04
11	0.20	0.27	0.18	0.09	0.09	0.10	0.06
12	0.13	0.14	0.08	0.07	0.07	0.07	0.06
13	0.23	0.21	0.08	0.11	0.22	0.15	0.12
14	0.60	0.40	0.27	0.26	0.31	0.30	0.25
15	0.57	0.53	0.44	0.16	0.33	0.25	0.22
16	0.42	0.37	0.28	0.09	0.22	0.16	0.14
17	0.34	0.26	0.20	0.06	0.15	0.15	0.12
18	0.17	0.25	0.10	0.03	0.10	0.09	0.05
19	0.19	0.26	0.12	0.07	0.07	0.05	0.07

Table 8

HARBD Wave Amplification Factors for Proposed Improvements

Plan 1, Wave Angle = 315 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.22	0.17	0.09	0.11	0.19	0.12	0.08
2	0.39	0.21	0.11	0.13	0.20	0.14	0.10
3	0.27	0.20	0.06	0.08	0.15	0.13	0.14
4	0.24	0.10	0.06	0.09	0.11	0.09	0.05
5	0.15	0.30	0.35	0.06	0.18	0.16	0.14
6	0.22	0.09	0.08	0.04	0.07	0.09	0.09
7	0.15	0.05	0.03	0.05	0.10	0.07	0.02
8	0.12	0.29	0.28	0.07	0.16	0.11	0.08
9	0.10	0.33	0.26	0.07	0.15	0.10	0.07
10	0.09	0.24	0.20	0.06	0.07	0.06	0.04
11	0.08	0.28	0.20	0.09	0.09	0.10	0.06
12	0.05	0.14	0.09	0.07	0.07	0.07	0.06
13	0.29	0.19	0.08	0.11	0.22	0.15	0.12
14	0.79	0.38	0.27	0.26	0.31	0.30	0.25
15	0.29	0.59	0.49	0.16	0.33	0.25	0.22
16	0.17	0.42	0.30	0.09	0.22	0.16	0.14
17	0.15	0.30	0.22	0.06	0.15	0.15	0.12
18	0.08	0.28	0.12	0.03	0.10	0.09	0.05
19	0.09	0.28	0.14	0.07	0.07	0.05	0.07

Table 9

HARBD Wave Amplification Factors for Proposed Improvements

Plan 1, Wave Angle = 337 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.19	*	*	*	*	*	*
2	0.31						
3	0.20						
4	0.18						
5	0.24						
6	0.19						
7	0.10						
8	0.19						
9	0.15						
10	0.10						
11	0.13						
12	0.06						
13	0.24						
14	0.52						
15	0.39						
16	0.25						
17	0.18						
18	0.09						
19	0.11						

* No data for these wave periods

Table 10

HARBD Wave Amplification Factors for Proposed Improvements

Plan 2, Wave Angle = 202.5 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.13	0.15	0.12	*	*	*	*
2	0.16	0.18	0.12				
3	0.09	0.10	0.08				
4	0.11	0.15	0.10				
5	0.37	0.18	0.51				
6	0.11	0.09	0.05				
7	0.07	0.11	0.09				
8	0.28	0.15	0.41				
9	0.33	0.21	0.39				
10	0.23	0.13	0.32				
11	0.22	0.11	0.34				
12	0.11	0.07	0.16				
13	0.12	0.15	0.10				
14	0.29	0.39	0.17				
15	0.65	0.21	0.76				
16	0.48	0.25	0.45				
17	0.38	0.18	0.34				
18	0.19	0.12	0.20				
19	0.21	0.10	0.23				

* No data for these wave periods

Table 11

HARBD Wave Amplification Factors for Proposed Improvements

Plan 2, Wave Angle = 225 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.25	0.11	0.12	0.18	0.24	0.19	0.13
2	0.29	0.13	0.12	0.19	0.26	0.20	0.20
3	0.17	0.14	0.08	0.13	0.21	0.18	0.24
4	0.24	0.07	0.10	0.14	0.14	0.13	0.11
5	0.15	0.04	0.51	0.17	0.21	0.20	0.25
6	0.18	0.05	0.05	0.06	0.10	0.11	0.15
7	0.19	0.04	0.09	0.07	0.14	0.10	0.05
8	0.11	0.03	0.41	0.18	0.19	0.14	0.14
9	0.13	0.09	0.39	0.16	0.18	0.12	0.13
10	0.13	0.11	0.32	0.10	0.09	0.07	0.07
11	0.21	0.11	0.34	0.15	0.11	0.11	0.09
12	0.13	0.06	0.16	0.13	0.08	0.08	0.10
13	0.22	0.13	0.10	0.17	0.28	0.20	0.21
14	0.34	0.41	0.17	0.39	0.36	0.33	0.40
15	0.34	0.15	0.76	0.36	0.38	0.30	0.40
16	0.15	0.09	0.45	0.24	0.26	0.19	0.24
17	0.16	0.11	0.34	0.11	0.18	0.17	0.21
18	0.15	0.11	0.20	0.05	0.12	0.11	0.09
19	0.17	0.12	0.23	0.12	0.08	0.06	0.13

Table 12

HARBD Wave Amplification Factors for Proposed Improvements

Plan 2, Wave Angle = 247.5 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.13	0.15	0.12	0.18	0.24	0.16	0.11
2	0.14	0.21	0.12	0.22	0.26	0.19	0.19
3	0.11	0.19	0.08	0.15	0.21	0.19	0.23
4	0.12	0.15	0.10	0.16	0.14	0.13	0.10
5	0.18	0.16	0.51	0.07	0.22	0.26	0.25
6	0.09	0.10	0.05	0.07	0.11	0.13	0.15
7	0.07	0.11	0.09	0.08	0.13	0.09	0.04
8	0.15	0.17	0.41	0.07	0.19	0.18	0.14
9	0.17	0.16	0.39	0.07	0.19	0.15	0.13
10	0.16	0.17	0.32	0.06	0.09	0.10	0.07
11	0.15	0.22	0.34	0.11	0.12	0.15	0.10
12	0.11	0.12	0.16	0.08	0.09	0.11	0.10
13	0.13	0.18	0.10	0.19	0.30	0.20	0.19
14	0.25	0.40	0.17	0.44	0.36	0.38	0.37
15	0.38	0.35	0.76	0.18	0.40	0.39	0.40
16	0.23	0.21	0.45	0.09	0.27	0.25	0.25
17	0.25	0.17	0.34	0.05	0.19	0.23	0.22
18	0.14	0.19	0.20	0.03	0.13	0.14	0.09
19	0.16	0.21	0.23	0.08	0.09	0.08	0.14

Table 13

HARBD Wave Amplification Factors for Proposed Improvements

Plan 2, Wave Angle = 270 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.14	0.15	0.12	0.18	0.24	0.16	0.11
2	0.15	0.21	0.12	0.22	0.26	0.19	0.19
3	0.10	0.19	0.08	0.15	0.21	0.19	0.23
4	0.12	0.15	0.10	0.16	0.14	0.13	0.10
5	0.35	0.16	0.51	0.07	0.22	0.26	0.25
6	0.12	0.10	0.05	0.07	0.11	0.13	0.15
7	0.08	0.11	0.09	0.08	0.13	0.09	0.04
8	0.27	0.17	0.41	0.07	0.19	0.18	0.14
9	0.32	0.16	0.39	0.07	0.19	0.15	0.13
10	0.26	0.17	0.32	0.06	0.09	0.10	0.07
11	0.28	0.22	0.34	0.11	0.12	0.15	0.10
12	0.16	0.12	0.16	0.08	0.09	0.11	0.10
13	0.14	0.18	0.10	0.19	0.30	0.20	0.19
14	0.27	0.40	0.17	0.44	0.36	0.38	0.37
15	0.68	0.35	0.76	0.18	0.40	0.39	0.40
16	0.47	0.21	0.45	0.09	0.27	0.25	0.25
17	0.42	0.17	0.34	0.05	0.19	0.23	0.22
18	0.24	0.19	0.20	0.03	0.13	0.14	0.09
19	0.28	0.21	0.23	0.08	0.09	0.08	0.14

Table 14

HARBD Wave Amplification Factors for Proposed Improvements

Plan 2, Wave Angle = 292.5 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.14	0.14	0.15	0.18	0.24	0.16	0.11
2	0.24	0.21	0.18	0.22	0.26	0.19	0.19
3	0.18	0.18	0.12	0.15	0.21	0.19	0.23
4	0.20	0.15	0.10	0.16	0.14	0.13	0.10
5	0.35	0.31	0.49	0.07	0.22	0.26	0.25
6	0.11	0.10	0.10	0.07	0.11	0.13	0.15
7	0.15	0.12	0.08	0.08	0.13	0.09	0.04
8	0.28	0.30	0.40	0.07	0.19	0.18	0.14
9	0.32	0.32	0.36	0.07	0.19	0.15	0.13
10	0.24	0.26	0.27	0.06	0.09	0.10	0.07
11	0.25	0.33	0.29	0.11	0.12	0.15	0.10
12	0.16	0.17	0.13	0.08	0.09	0.11	0.10
13	0.17	0.16	0.13	0.19	0.30	0.20	0.19
14	0.56	0.33	0.36	0.14	0.36	0.38	0.37
15	0.66	0.59	0.69	0.18	0.40	0.39	0.40
16	0.48	0.42	0.42	0.09	0.27	0.25	0.25
17	0.41	0.30	0.30	0.05	0.19	0.23	0.22
18	0.21	0.30	0.16	0.03	0.13	0.14	0.09
19	0.24	0.32	0.19	0.08	0.09	0.08	0.14

Table 15

HARBD Wave Amplification Factors for Proposed Improvements

Plan 2, Wave Angle = 315 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.20	0.11	0.13	0.18	0.24	0.16	0.11
2	0.39	0.16	0.13	0.22	0.26	0.19	0.19
3	0.27	0.15	0.09	0.15	0.21	0.19	0.23
4	0.25	0.09	0.07	0.16	0.14	0.13	0.10
5	0.21	0.33	0.52	0.07	0.22	0.26	0.25
6	0.23	0.08	0.06	0.07	0.11	0.13	0.15
7	0.17	0.06	0.07	0.08	0.13	0.09	0.04
8	0.17	0.33	0.42	0.07	0.19	0.18	0.14
9	0.12	0.38	0.39	0.07	0.19	0.15	0.13
10	0.11	0.29	0.31	0.06	0.09	0.10	0.07
11	0.08	0.34	0.32	0.11	0.12	0.15	0.10
12	0.06	0.17	0.15	0.08	0.09	0.11	0.10
13	0.26	0.12	0.10	0.19	0.30	0.20	0.19
14	0.86	0.35	0.27	0.44	0.36	0.38	0.37
15	0.39	0.67	0.75	0.18	0.40	0.39	0.40
16	0.21	0.48	0.45	0.09	0.27	0.25	0.25
17	0.17	0.35	0.33	0.05	0.19	0.23	0.22
18	0.09	0.33	0.19	0.03	0.13	0.14	0.09
19	0.10	0.34	0.22	0.08	0.09	0.08	0.14

Table 16

HARBD Wave Amplification Factors for Proposed Improvements

Plan 2, Wave Angle = 337 deg

	Wave Period, sec						
Basin	7	9	11	13	15	17	20
1	0.19	*	*	*	*	*	*
2	0.33						
3	0.21						
4	0.20						
5	0.36						
6	0.20						
7	0.13						
8	0.28						
9	0.18						
10	0.11						
11	0.12						
12	0.05						
13	0.22						
14	0.60						
15	0.55						
16	0.32						
17	0.20						
18	0.10						
19	0.11						

* No data for these wave periods

Table 17

Largest Resulting HARBD-RCPWAVE Amplification Factors
(Deepwater Wave Conditions)

	Plan 1						Plan 2					
	1 ft criteria			2 ft criteria			1 ft criteria			2 ftcriteria		
Dir. (deg)	Per. (sec)	Amp. Fac.	Basin #	Per. (sec)	Amp. Fac.	Basin #	Per. (sec)	Amp. Fac.	Basin #	Per. (sec)	Amp. Fac.	Basin #
202.5	11	0.26	5	11	0.37	15	11	0.36	5	11	0.53	15
225.0	11	0.23	5	11	0.40	15	11	0.38	5	11	0.57	15
247.5	11	0.20	5	11	0.37	15	11	0.36	5	11	0.53	15
270.0	7	0.22	5	7	0.41	15	11	0.27	8	11	0.49	15
292.5	11	0.23	5	7	0.42	14	11	0.36	5	11	0.50	15
315.0	7	0.27	2	7	0.55	14	11	0.31	5	7	0.60	14
337.5	7	0.16	2	7	0.28	14	7	0.19	5	7	0.31	14

Table 18

Percent Occurrence of Wave Heights Versus Direction*

Plan 1 - Wave Heights Exceeding 1 ft

Wave Height ft	Wave Direction, deg (from which waves approach) 202.5	225	247.5	270	292.5	315	337.5	Total
0-3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3-6	*	*	*	0.03	0.36	3.27	0.00	3.66
6-9	0.01	0.02	0.03	0.07	0.18	2.69	0.20	3.20
9-12	*	0.02	0.03	0.05	0.47	1.46	0.01	2.04
12-15	*	0.01	0.01	0.01	0.46	1.09	0.00	1.58
>15	0.00	0.02	*	0.01	0.06	0.34	*	0.43
TOTAL	0.01	0.07	0.07	0.17	1.53	8.85	0.21	10.91

Table 19

Percent Occurrence of Wave Heights Versus Direction*

Plan 1 - Wave Heights Exceeding 2 ft

Wave Height ft	Wave Direction, deg (from which waves approach) 202.5	225	247.5	270	292.5	315	337.5	Total
0-3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3-6	0.02	0.00	*	0.00	0.00	2.05	0.22	2.29
6-9	*	0.01	0.02	0.08	0.16	2.64	0.01	2.92
9-12	*	0.02	0.04	0.06	0.32	1.51	0.00	1.95
12-15	*	0.01	0.02	0.02	0.47	0.89	0.00	1.41
>15	0.00	0.02	*	0.01	0.06	0.45	0.00	0.54
TOTAL	0.02	0.06	0.08	0.17	1.01	7.54	0.23	9.10

* Percent occurrence is below significance for tabulation

Table 20

Percent Occurrence of Wave Heights Versus Direction*

Plan 2 - Wave Heights Exceeding 1 ft

Wave Height ft	Wave Direction, deg (from which waves approach) 202.5	225	247.5	270	292.5	315	337.5	Total
0-3	*	0.00	0.00	0.00	0.04	0.00	0.00	0.04
3-6	0.01	0.02	0.03	0.06	1.12	5.15	0.88	7.27
6-9	0.01	0.02	0.03	0.12	0.32	3.64	0.22	4.36
9-12	*	0.02	0.04	0.09	1.02	5.47	0.01	6.64
12-15	*	0.01	0.01	0.02	0.47	2.02	0.00	2.53
>15	0.02	0.02	*	0.01	0.06	0.45	0.00	0.54
TOTAL	0.02	0.09	0.11	0.30	3.03	16.73	1.10	21.39

Table 21

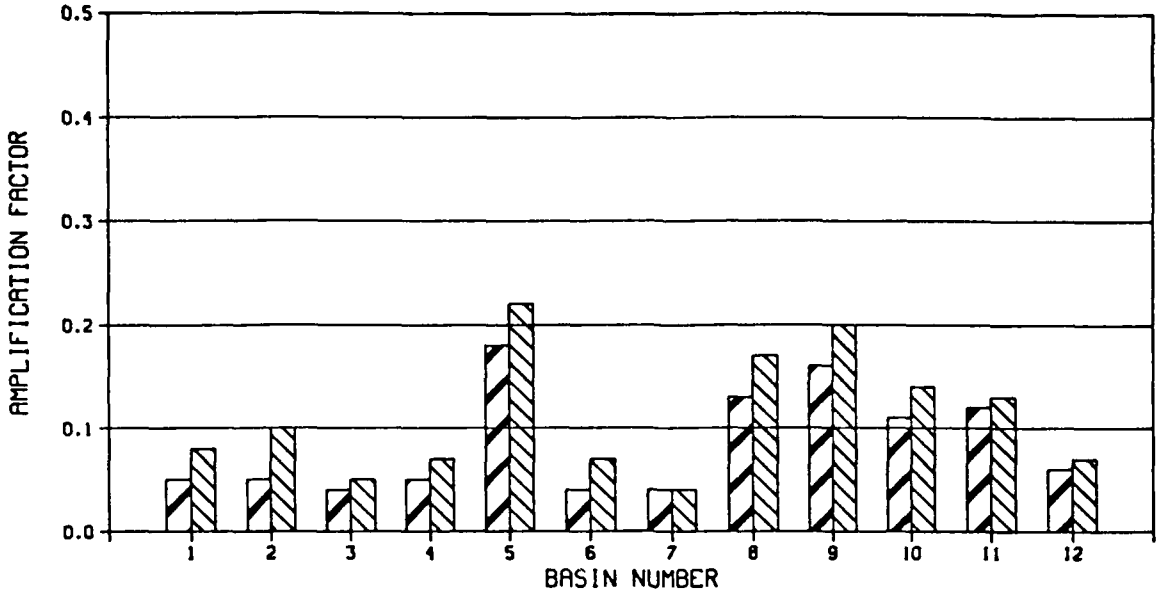
Percent Occurrence of Wave Heights Versus Direction*

Plan 2 - Wave Heights Exceeding 2 ft

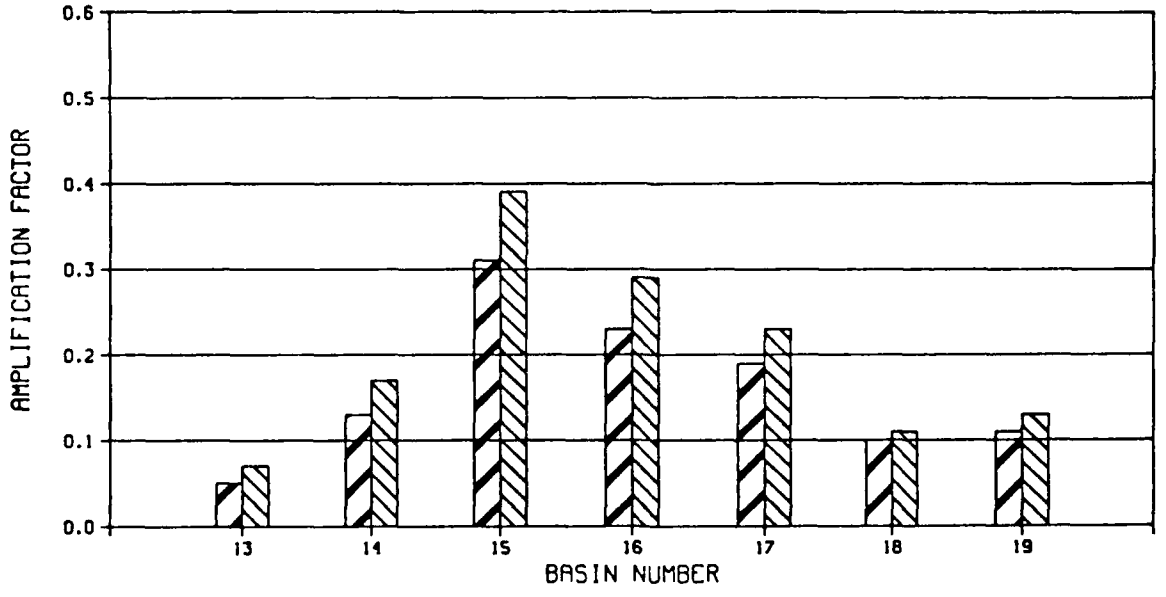
Wave Height ft	Wave Direction, deg (from which waves approach) 202.5	225	247.5	270	292.5	315	337.5	Total
0-3	0.00	0.00	*	0.00	0.00	0.00	0.00	*
3-6	*	*	0.01	0.04	0.54	4.36	0.00	4.95
6-9	0.01	0.02	0.04	0.08	0.32	3.43	0.22	4.12
9-12	*	0.02	0.04	0.09	1.02	5.47	0.01	6.66
12-15	*	0.01	0.01	0.02	0.46	2.02	0.00	2.52
>15	0.00	0.02	*	0.01	0.06	0.45	0.00	0.54
TOTAL	0.02	0.07	0.10	0.24	2.40	15.73	0.23	18.79

* Percent occurrence is below significance for tabulation

HARBOR BERTHING AREAS



HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 7 sec
WAVE DIRECTION - 202.5 deg

PLATE 1

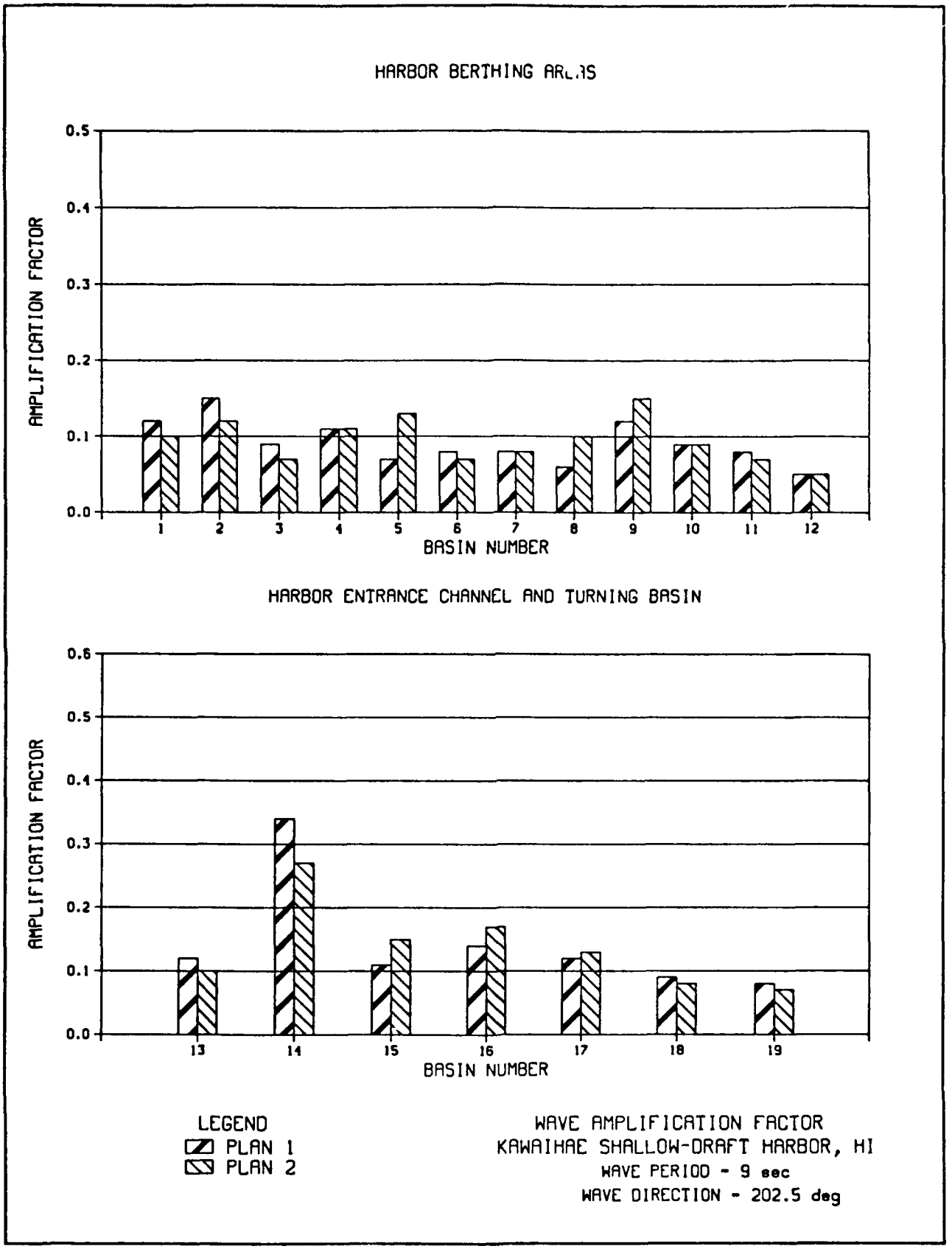
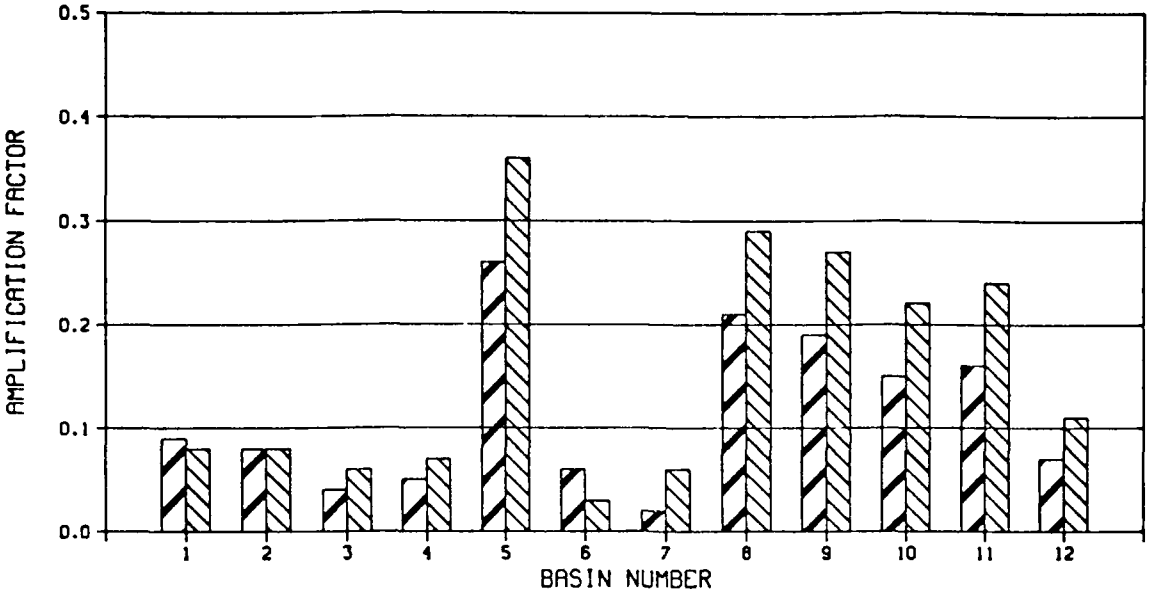
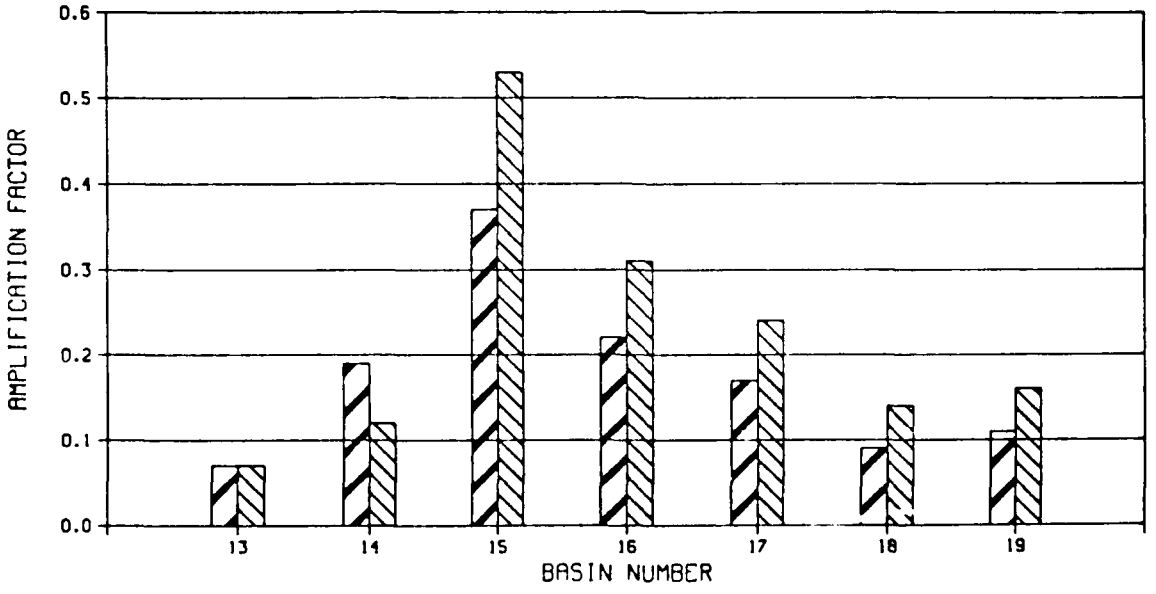

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 9 sec
WAVE DIRECTION - 202.5 deg

PLATE 2

HARBOR BERTHING AREAS



HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 11 sec
WAVE DIRECTION - 202.5 deg

PLATE 3

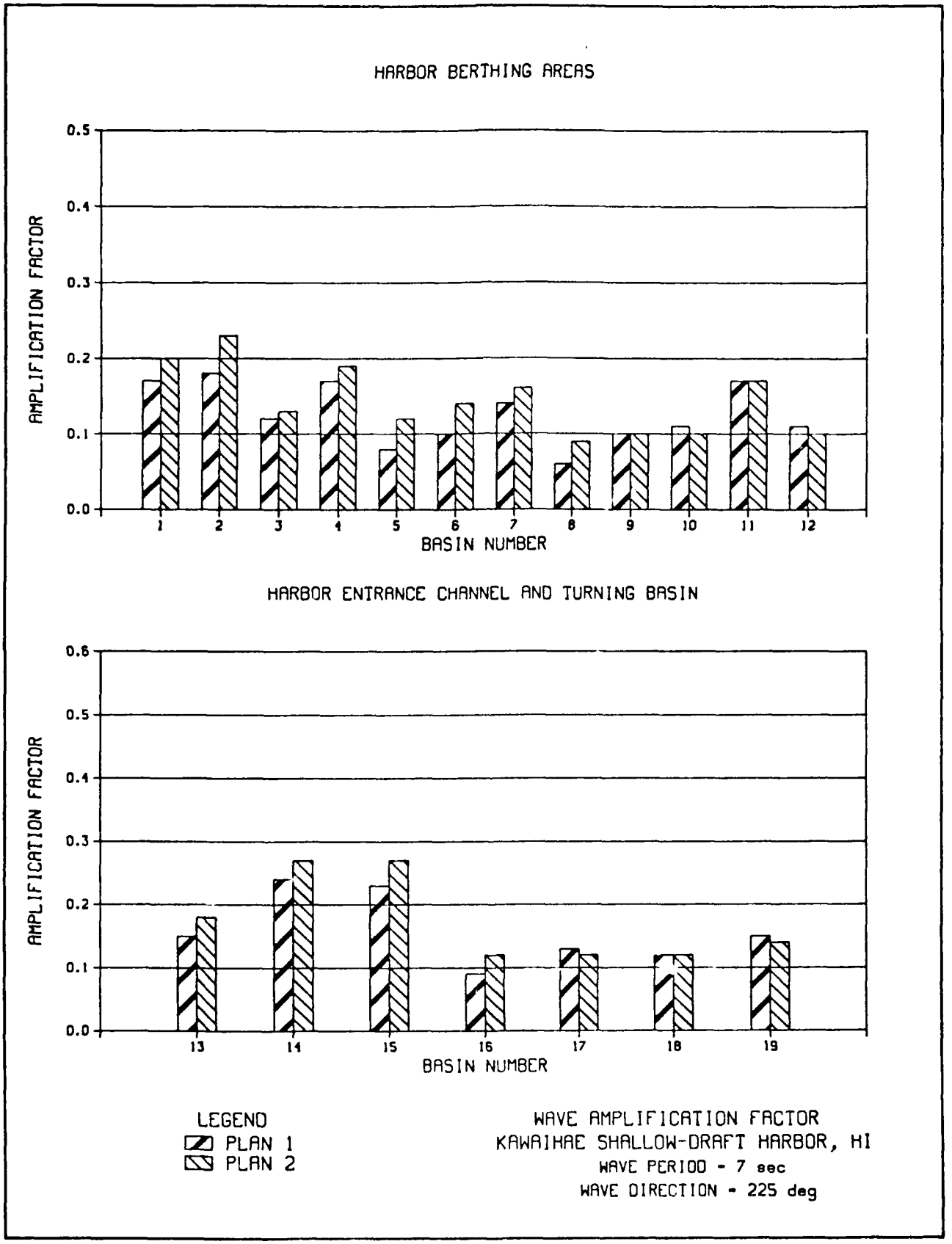
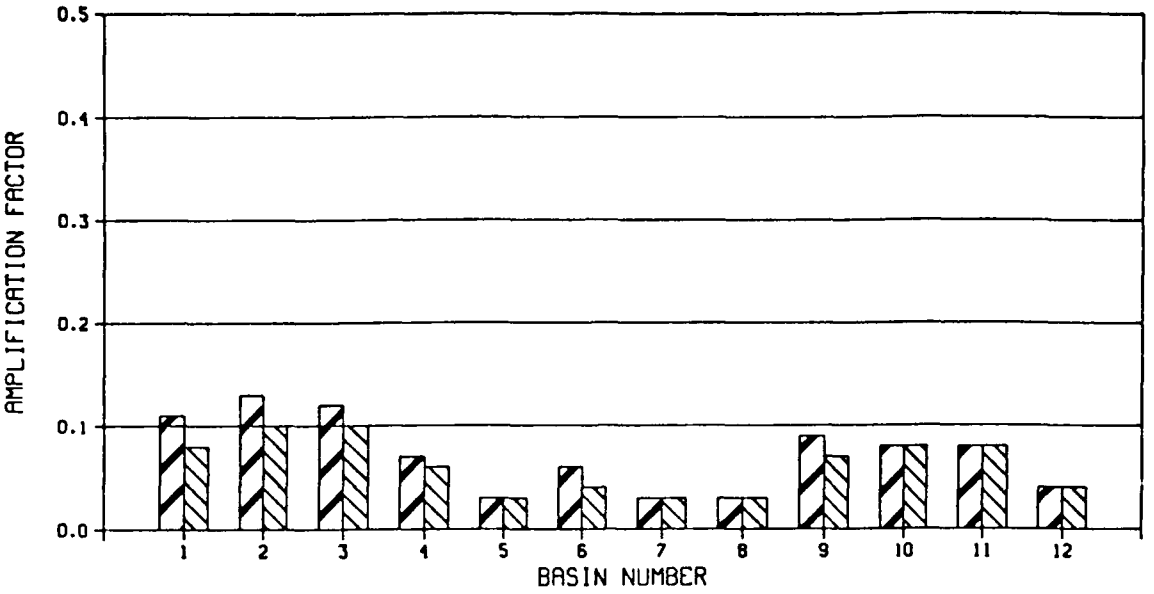
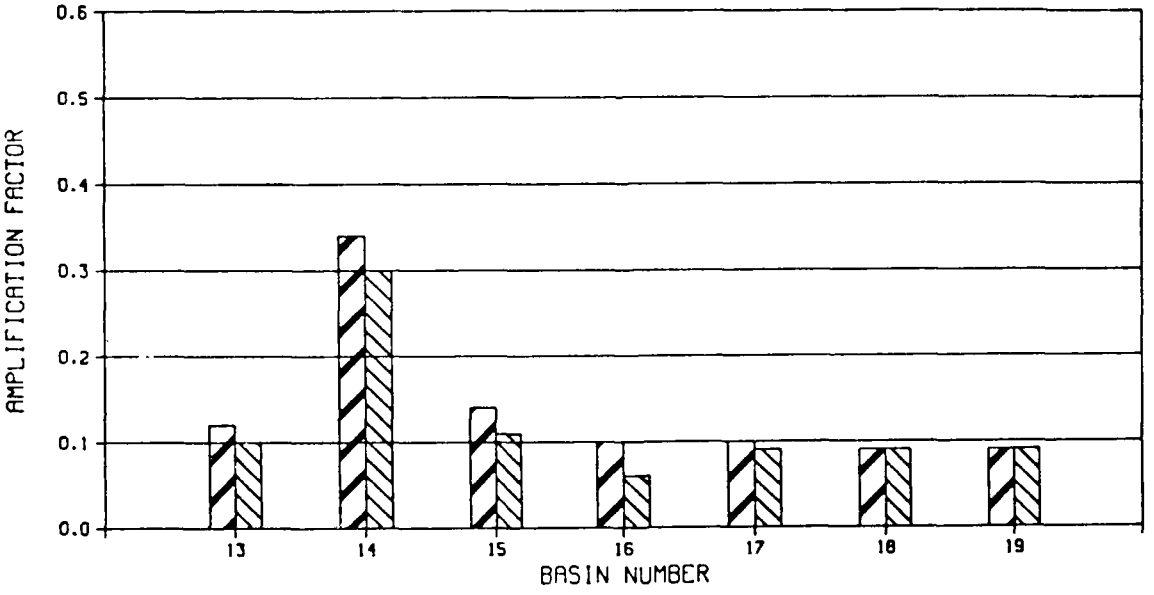

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 7 sec
WAVE DIRECTION - 225 deg

PLATE 4

HARBOR BERTHING AREAS



HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 9 sec
WAVE DIRECTION - 225 deg

PLATE 5

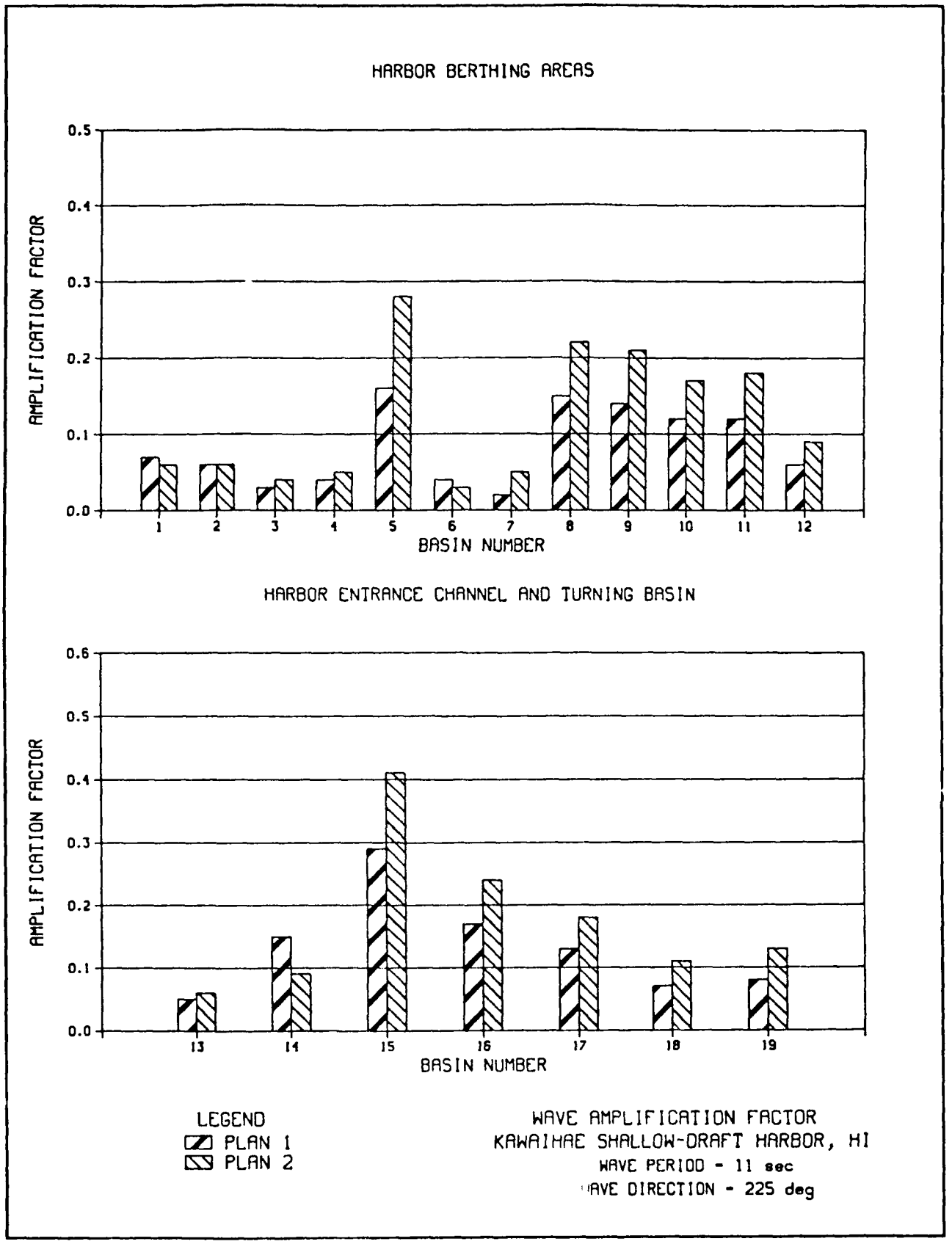

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 11 sec
WAVE DIRECTION - 225 deg

PLATE 6

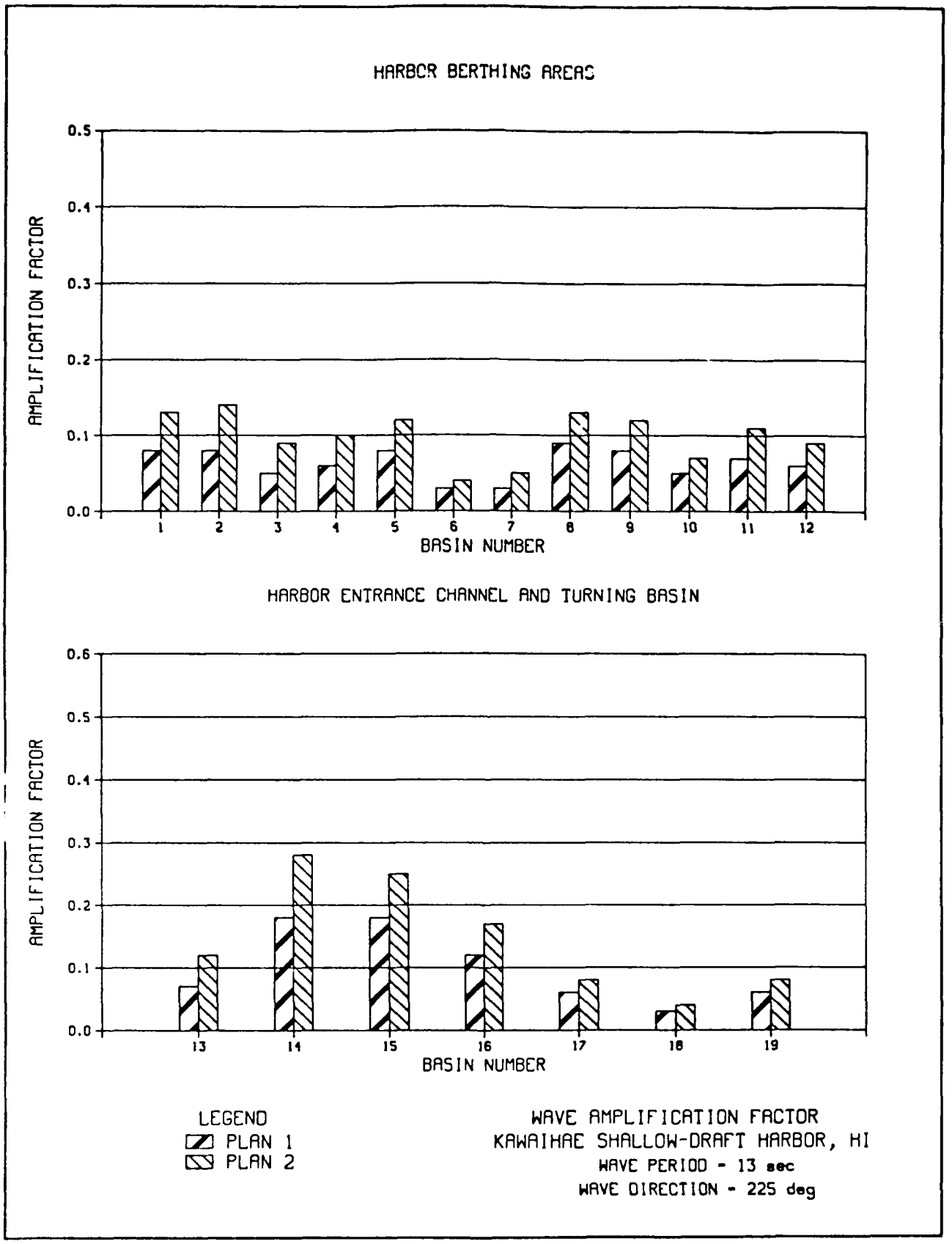

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 13 sec
WAVE DIRECTION - 225 deg

PLATE 7

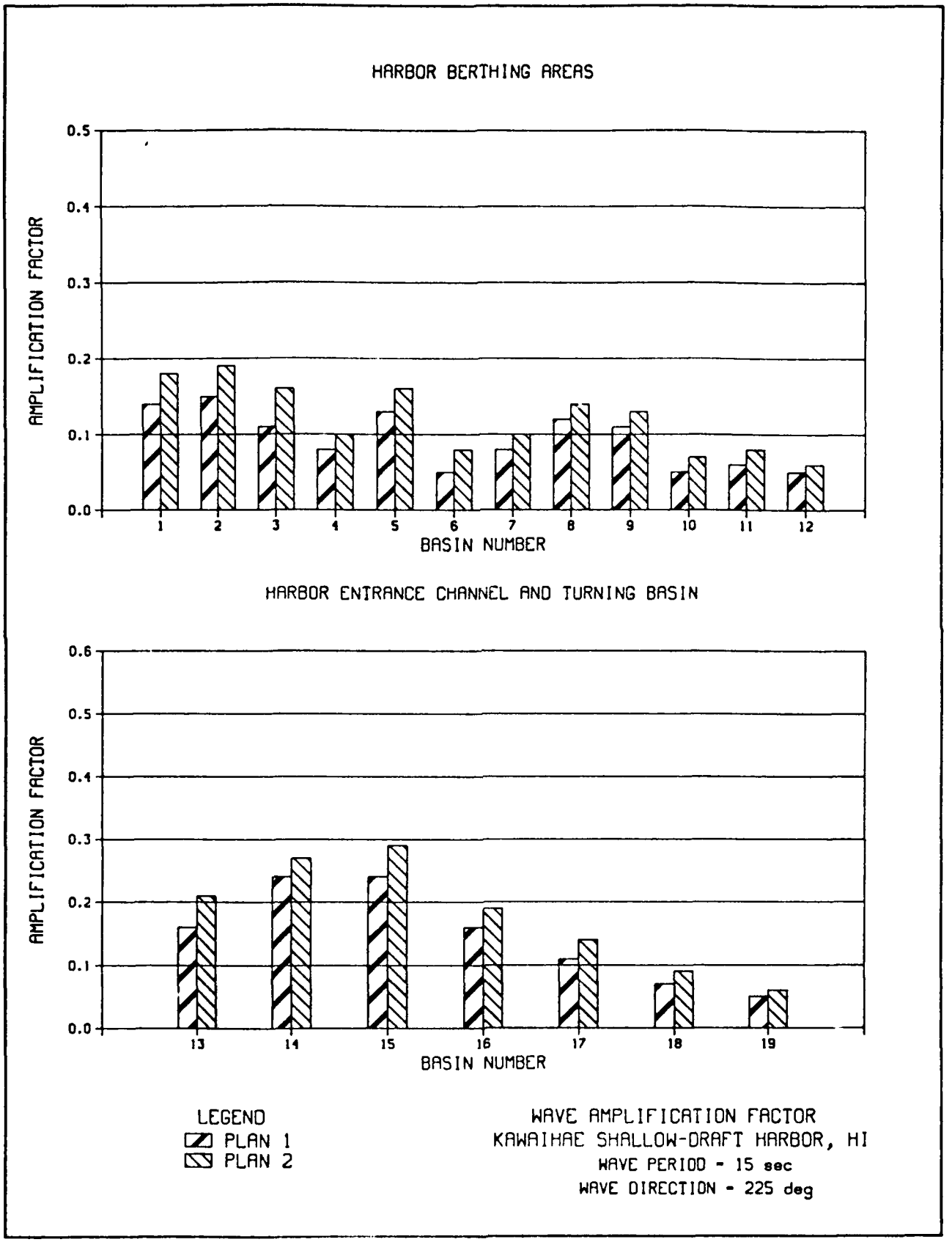

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 15 sec
WAVE DIRECTION - 225 deg

PLATE 8

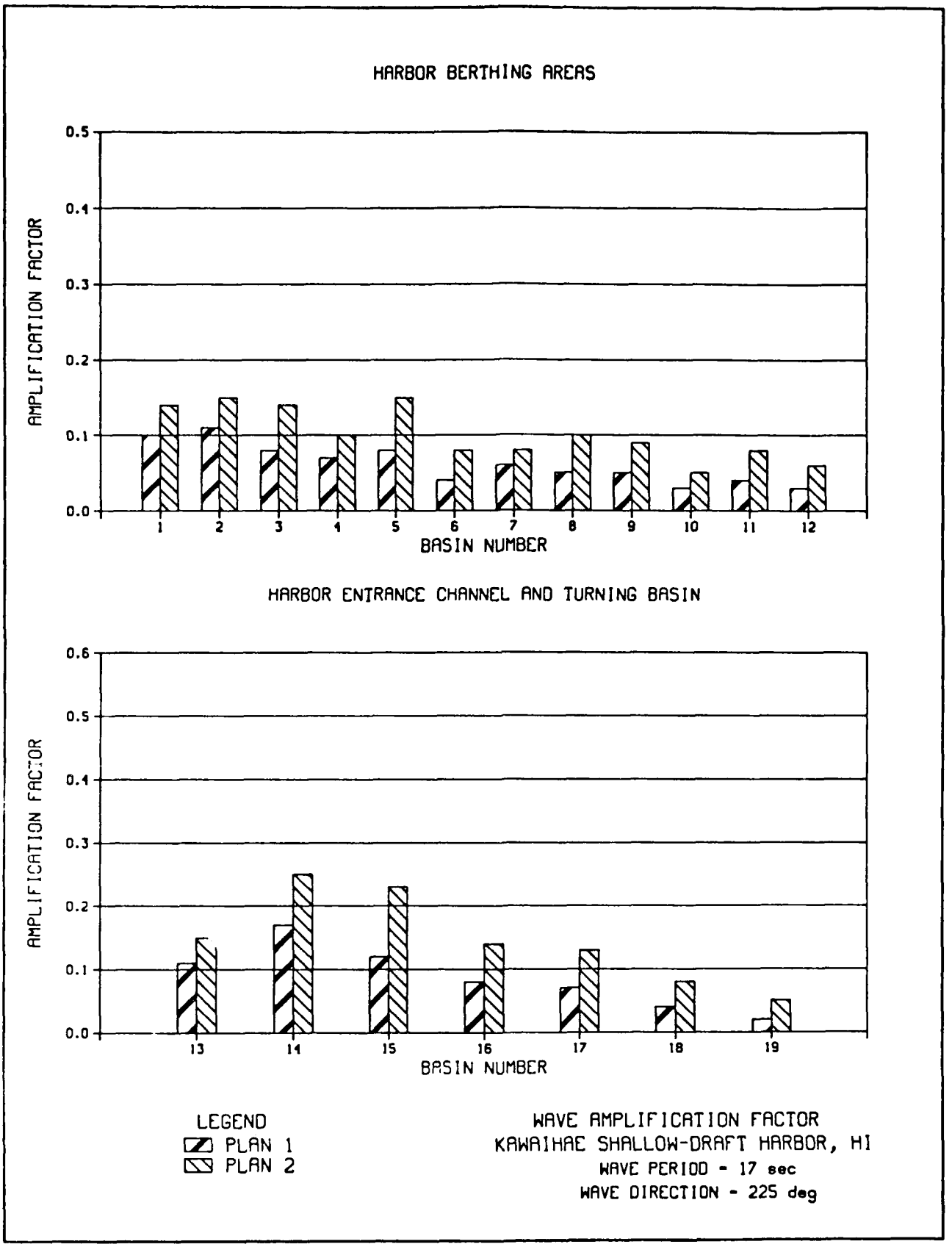

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 17 sec
WAVE DIRECTION - 225 deg

PLATE 9

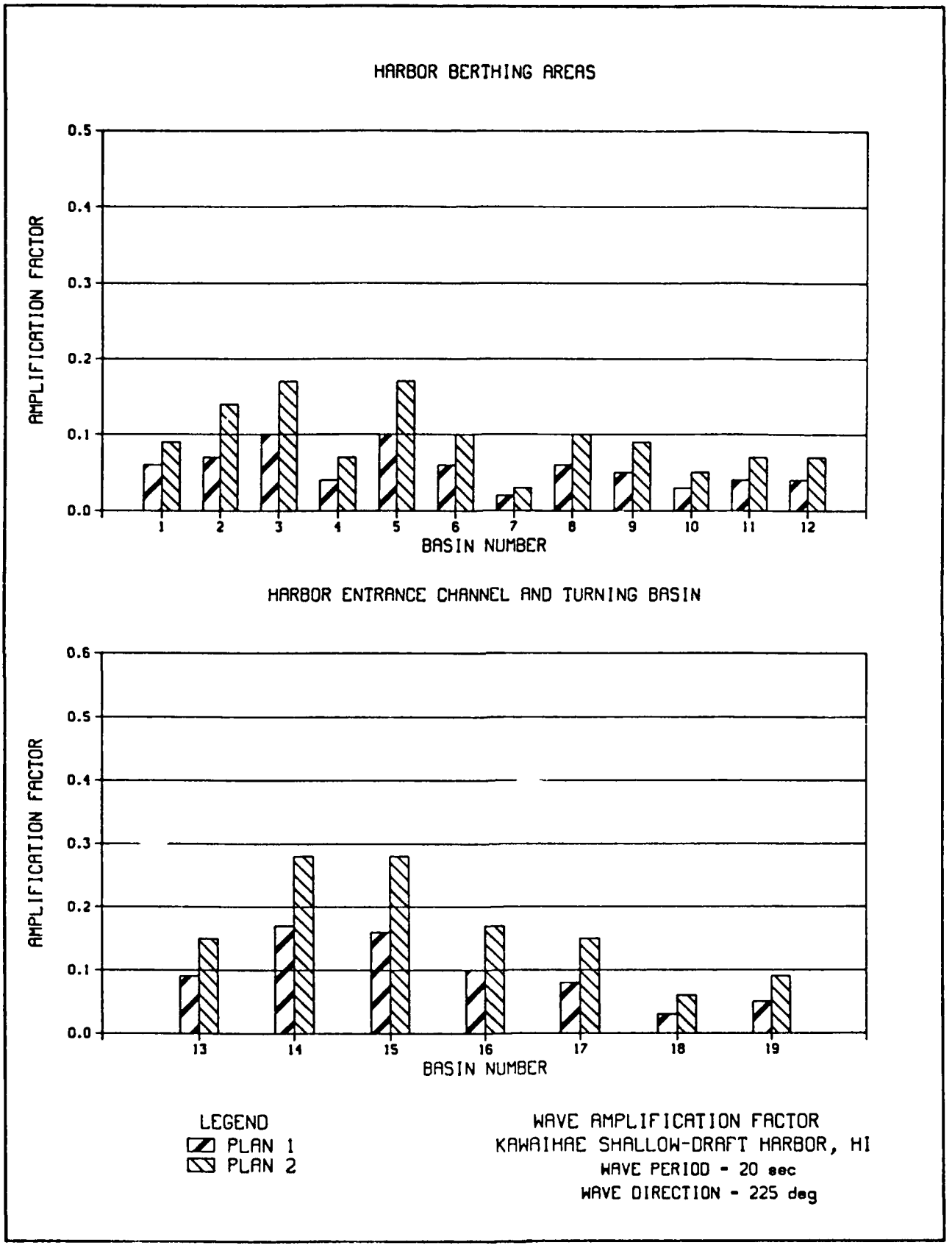
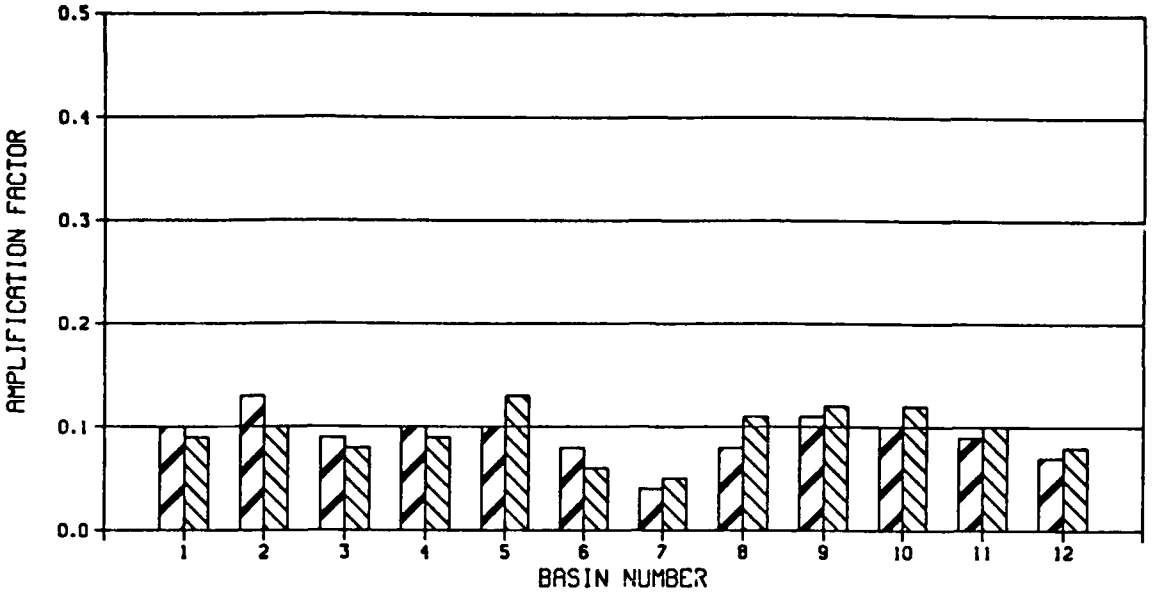
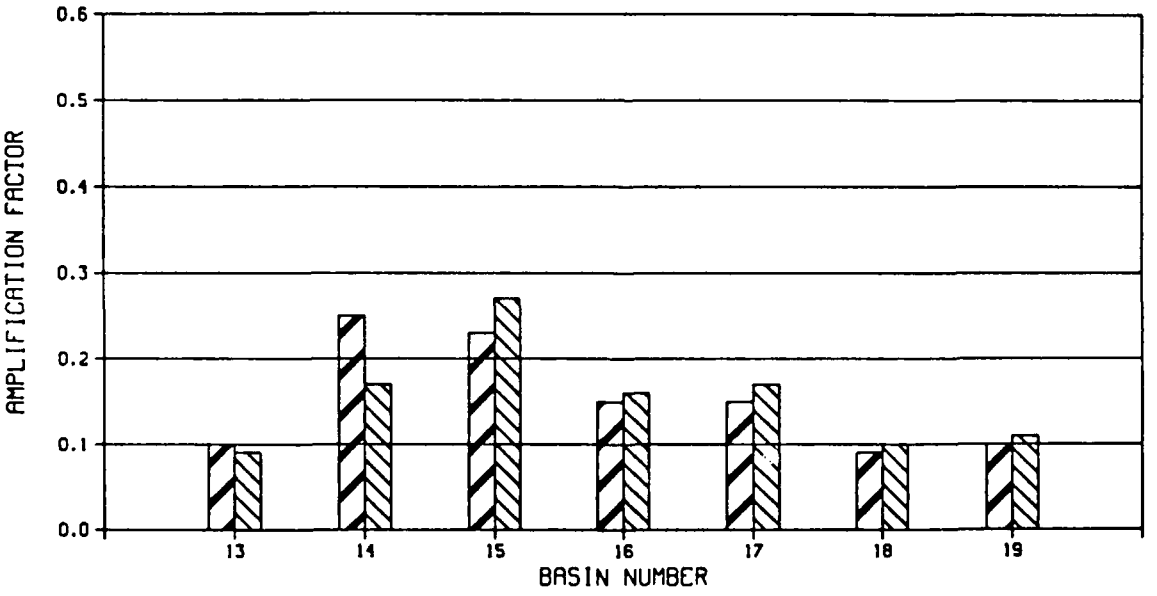

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 20 sec
WAVE DIRECTION - 225 deg

PLATE 10

HARBOR BERTHING AREAS



HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 7 sec
WAVE DIRECTION - 247.5 deg

PLATE 11

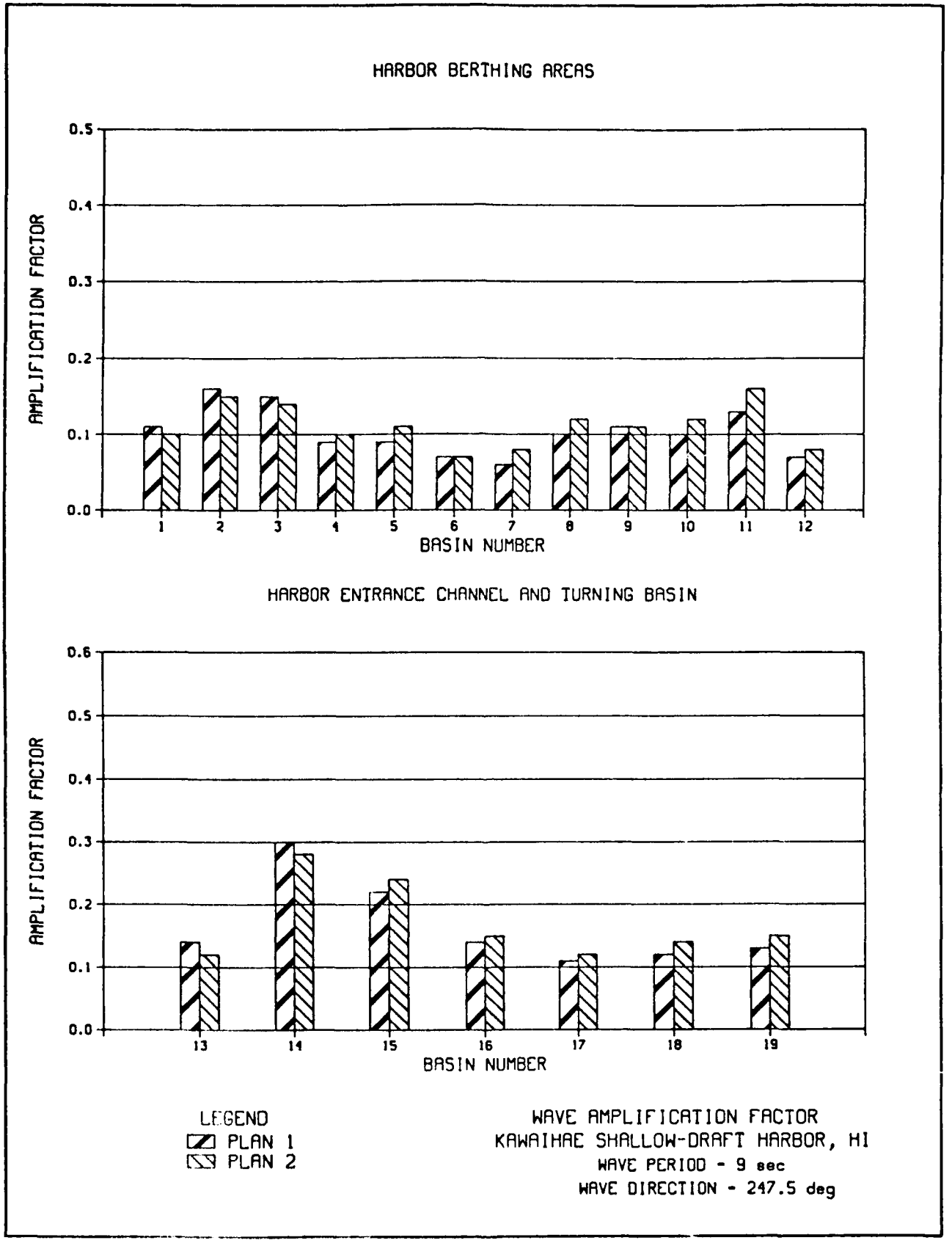
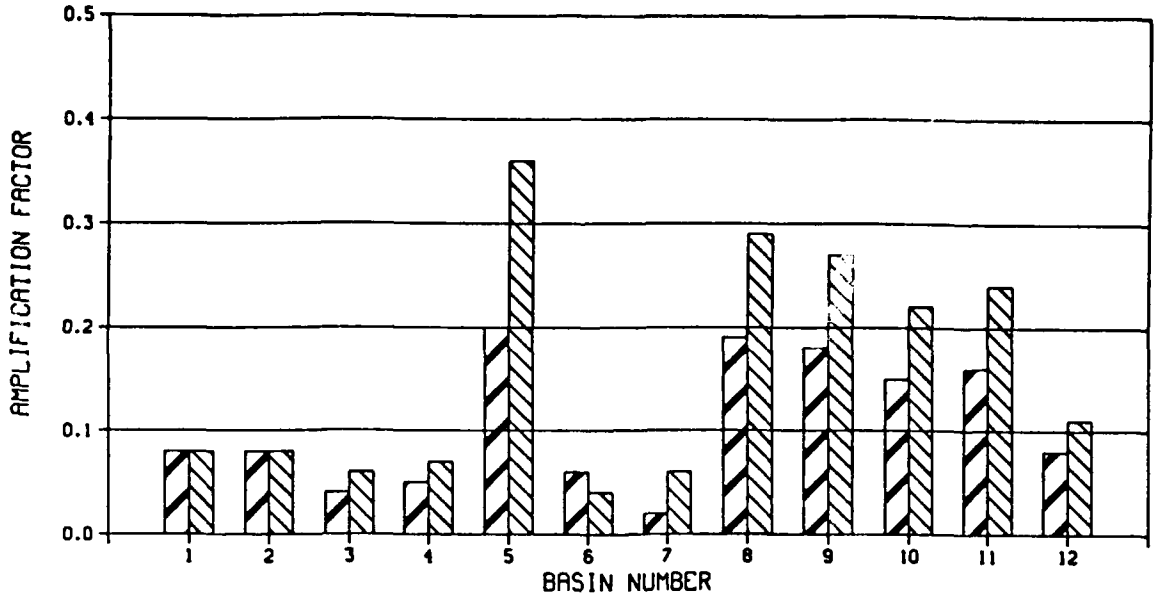
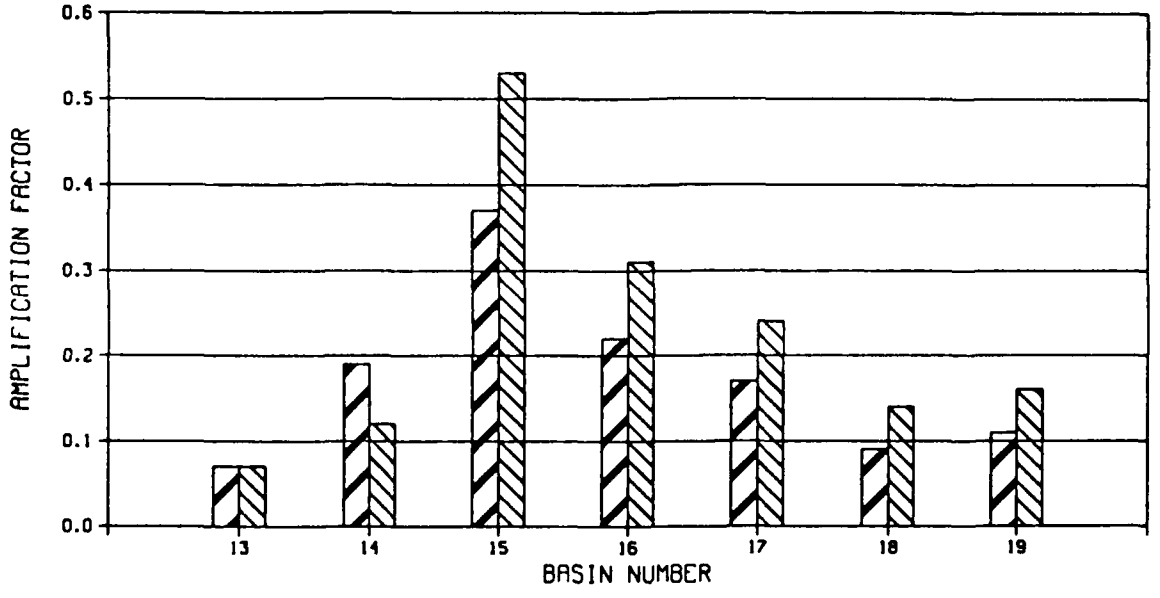

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 9 sec
WAVE DIRECTION - 247.5 deg

PLATE 12

HARBOR BERTHING AREAS



HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 11 sec
WAVE DIRECTION - 247.5 deg

PLATE 13

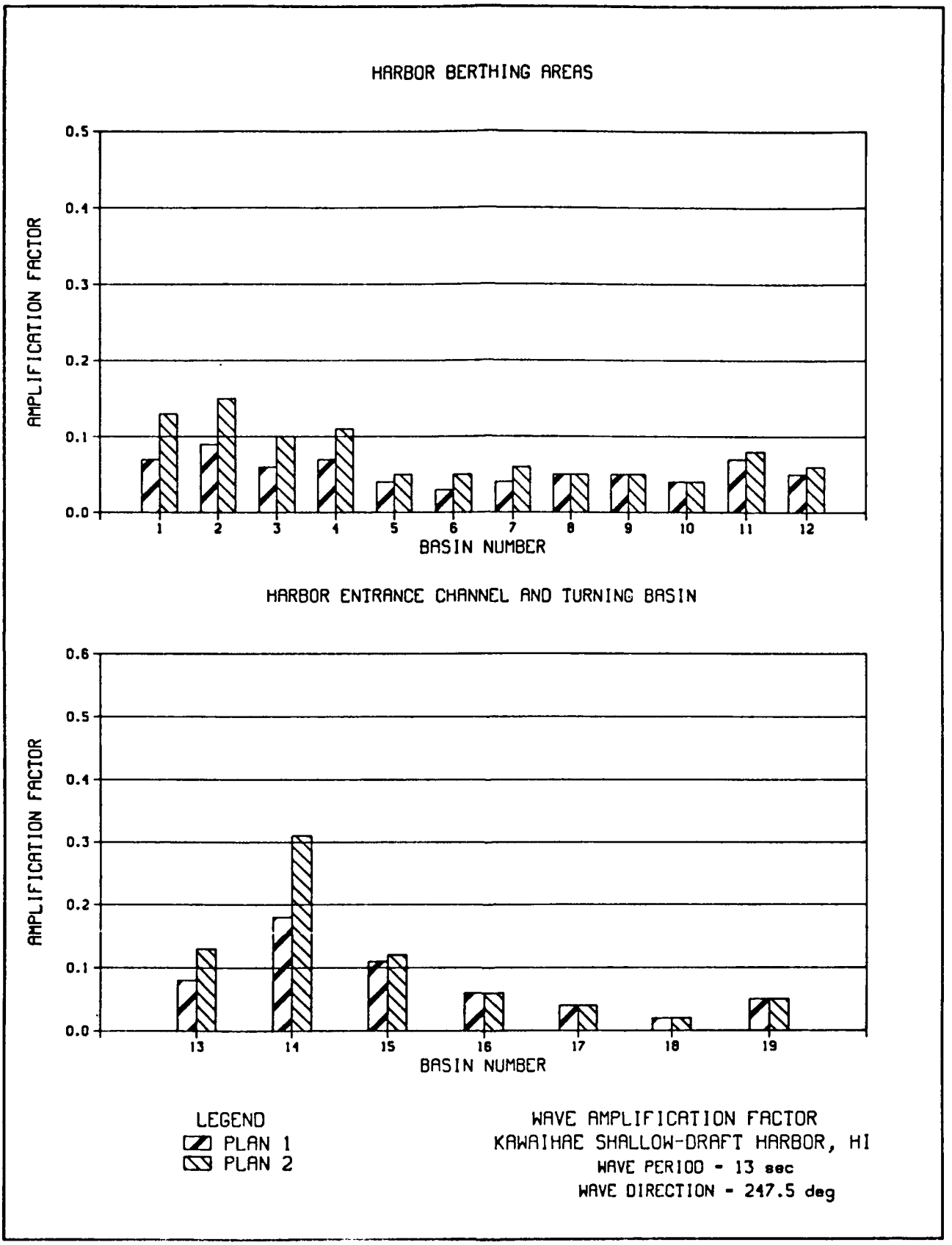
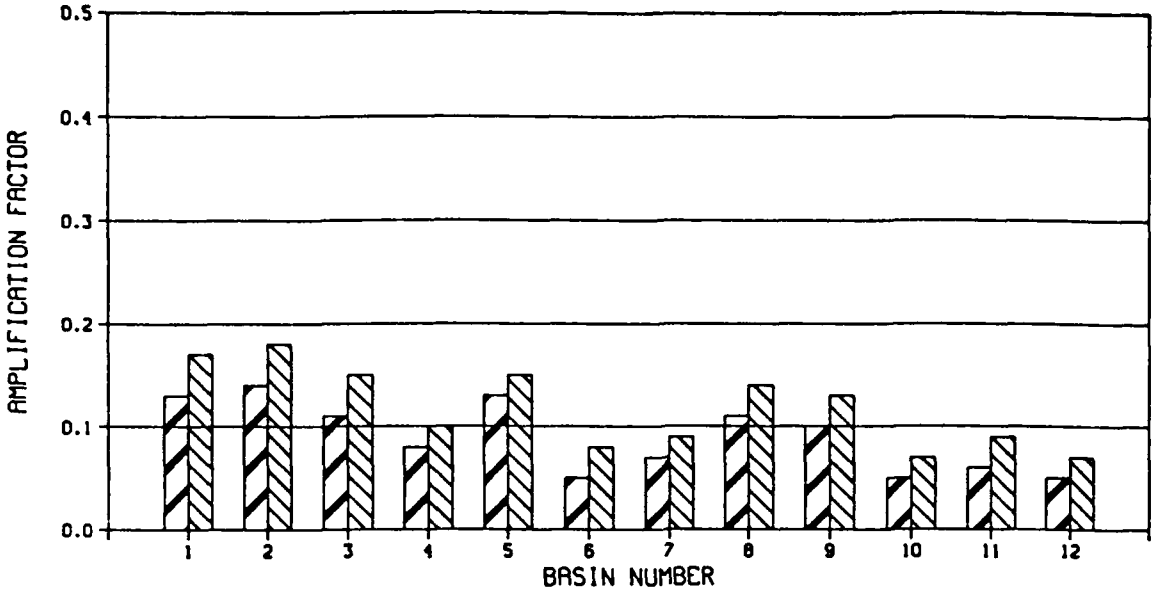
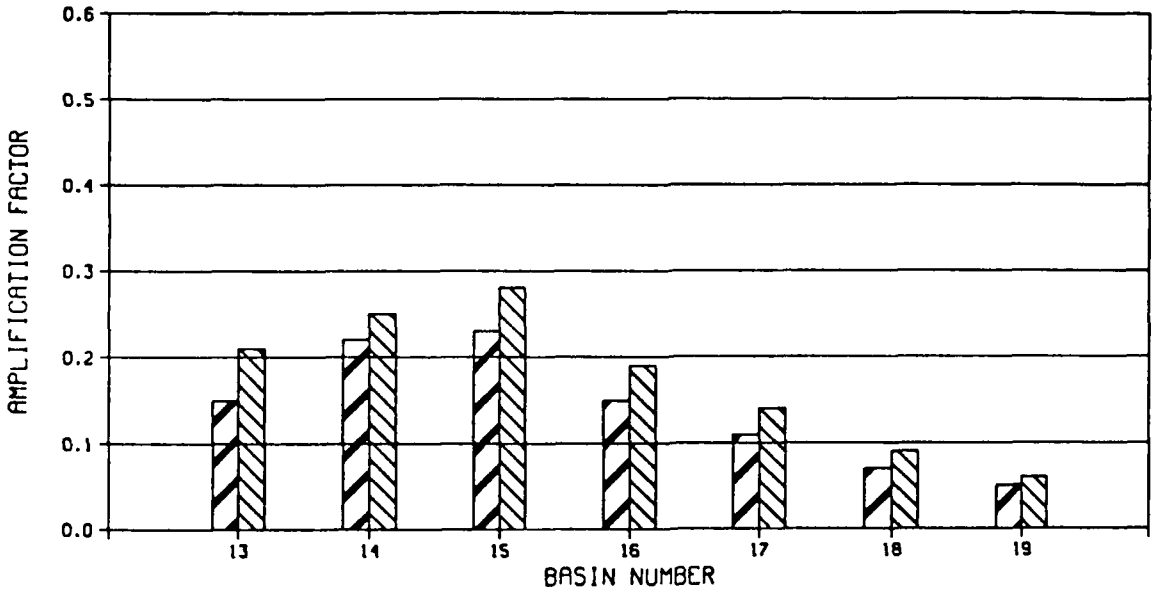

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 13 sec
WAVE DIRECTION - 247.5 deg

PLATE 14

HARBOR BERTHING AREAS



HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 15 sec
WAVE DIRECTION - 247.5 deg

PLATE 15

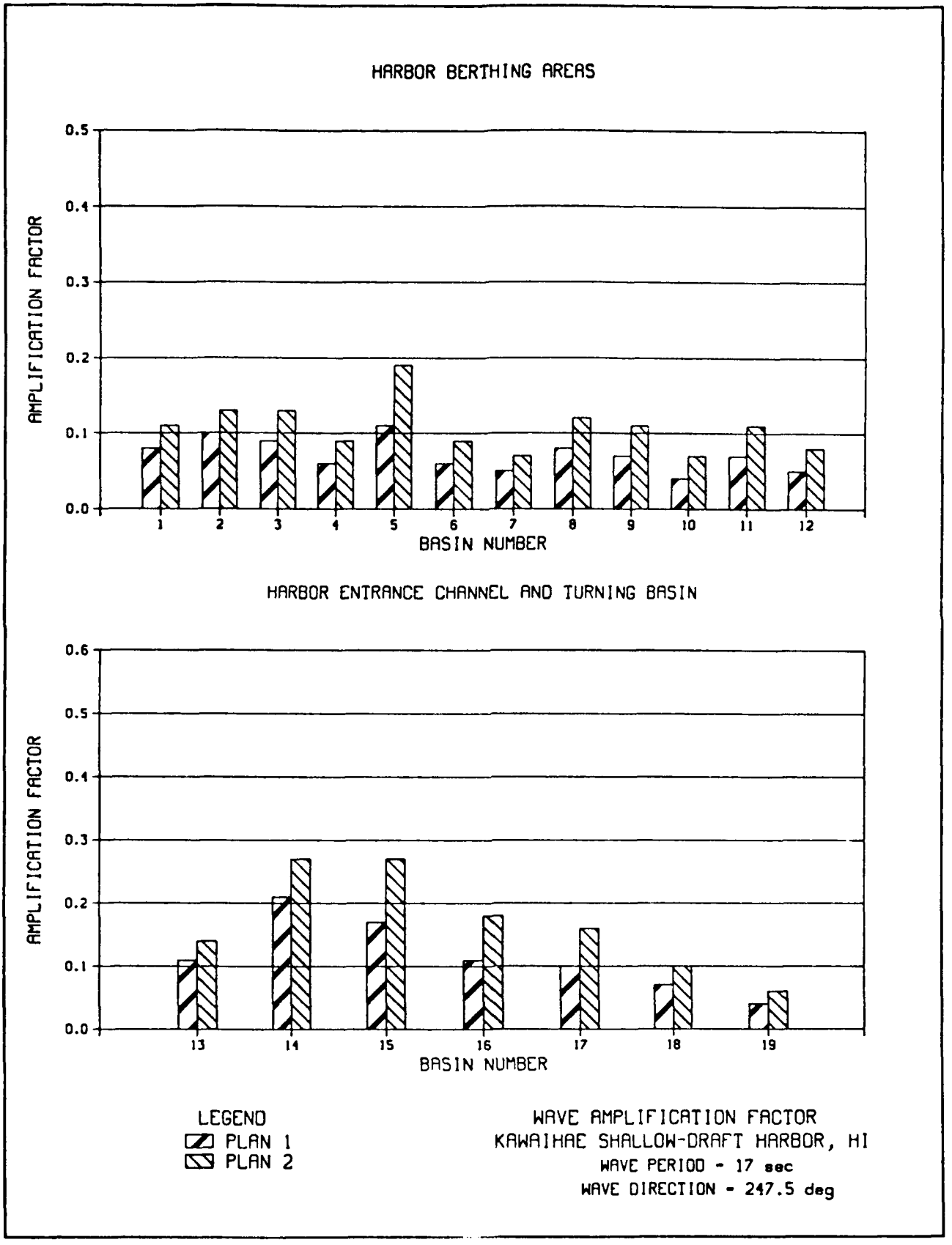
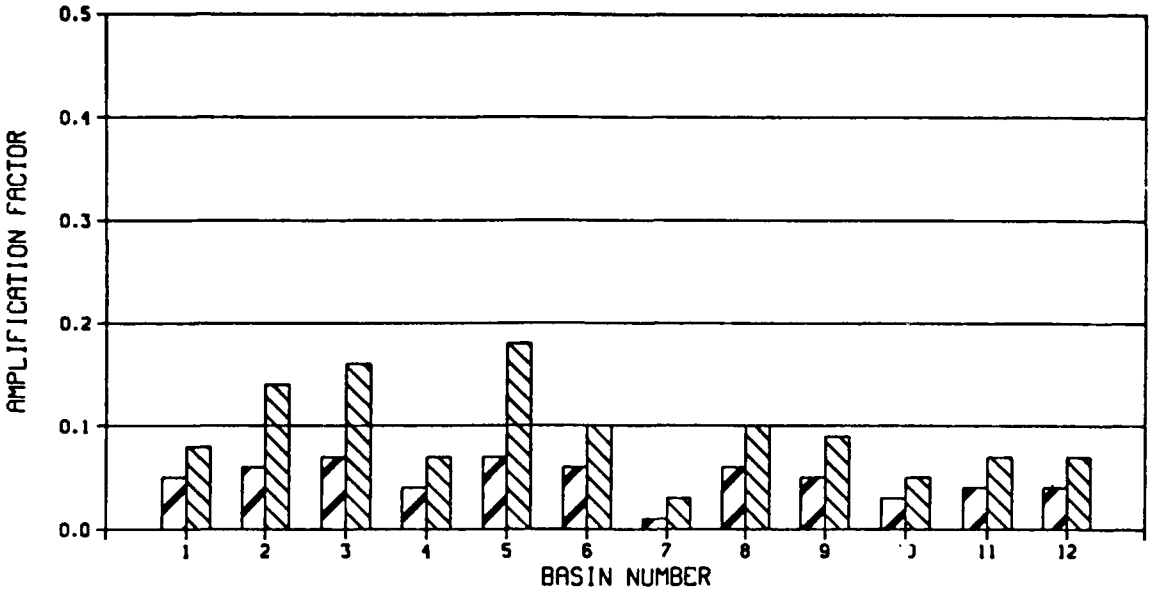
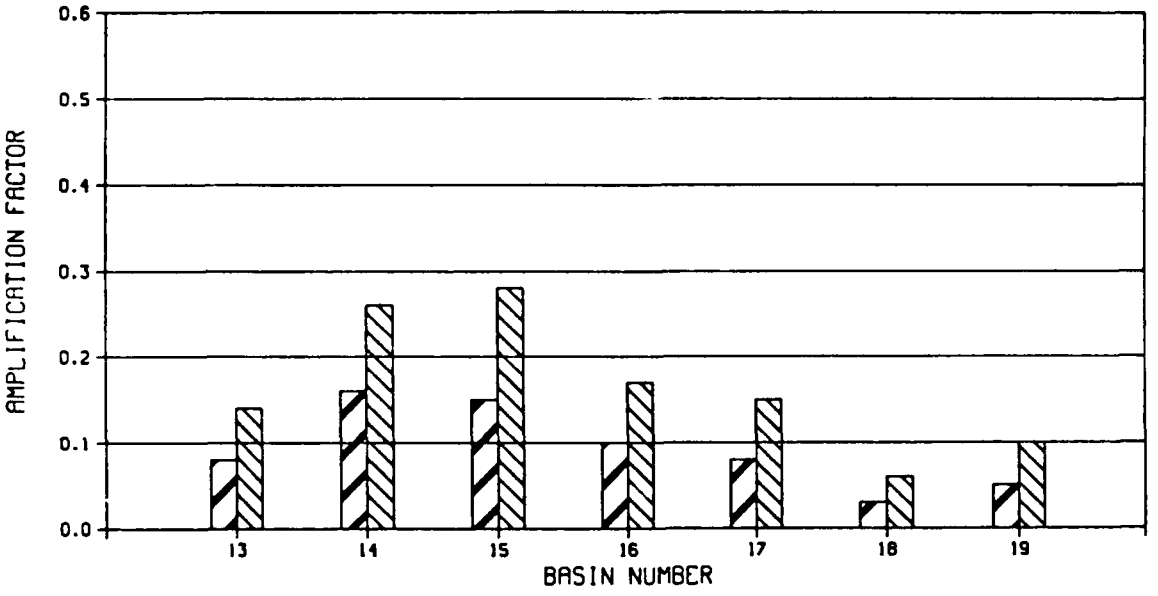

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 17 sec
WAVE DIRECTION - 247.5 deg

PLATE 16

HARBOR BERTHING AREAS



HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 20 sec
WAVE DIRECTION - 247.5 deg

PLATE 17

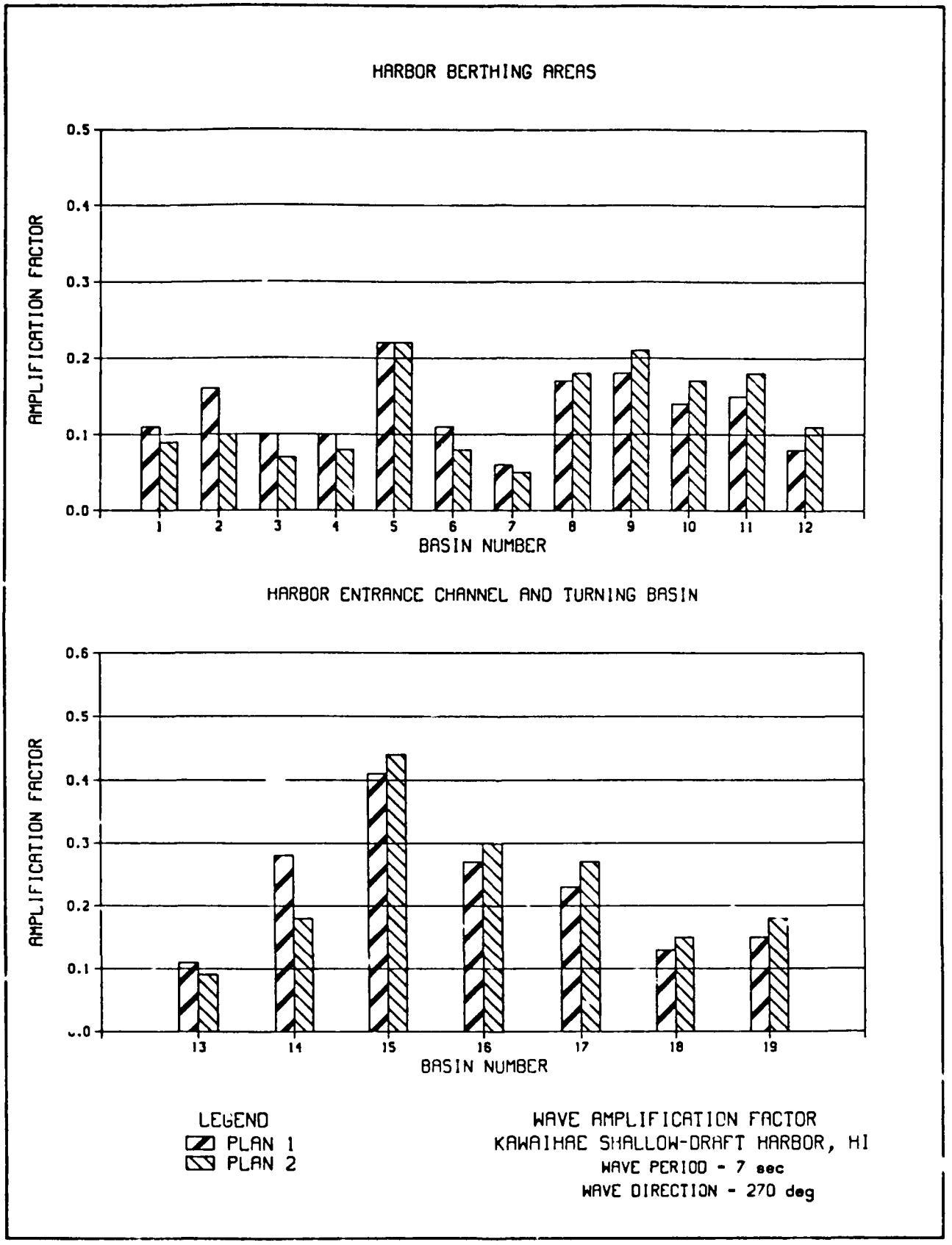
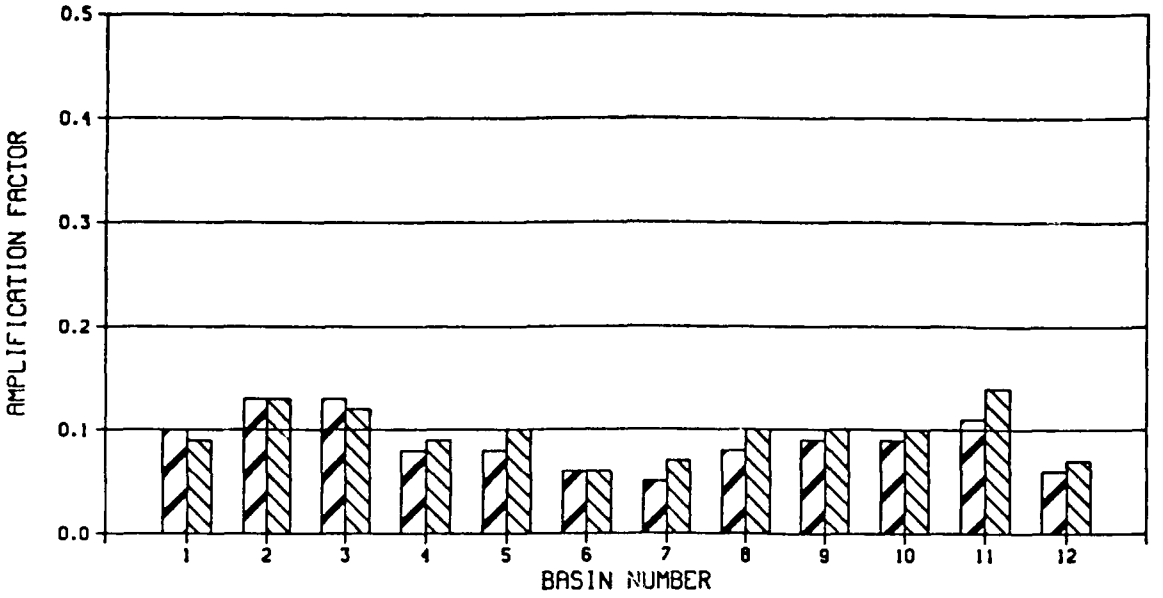
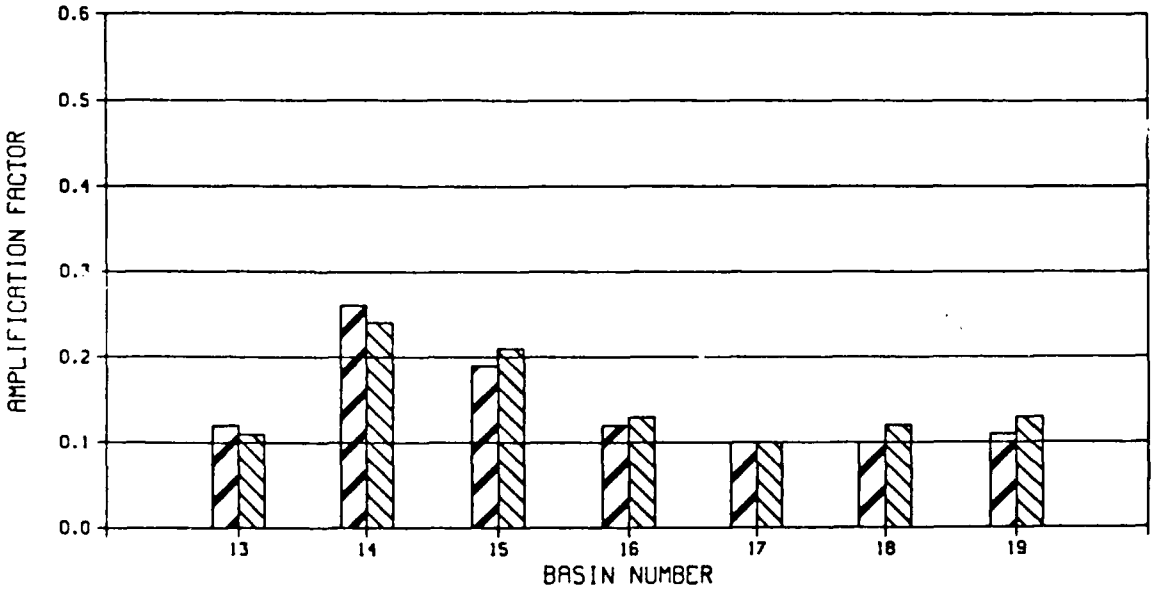

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 7 sec
WAVE DIRECTION - 270 deg

PLATE 18

HARBOR BERTHING AREAS



HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 9 sec
WAVE DIRECTION - 270 deg

PLATE 19

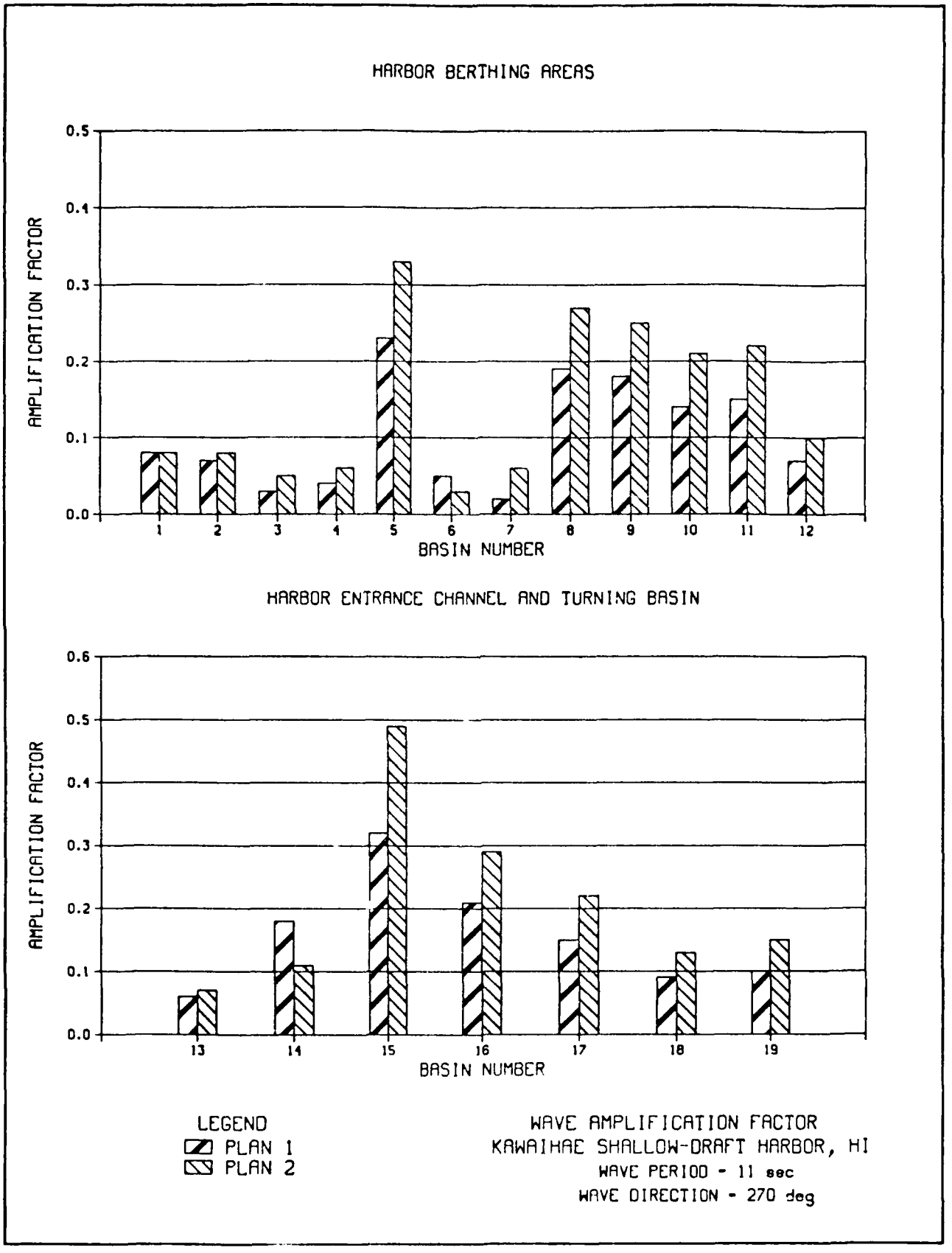
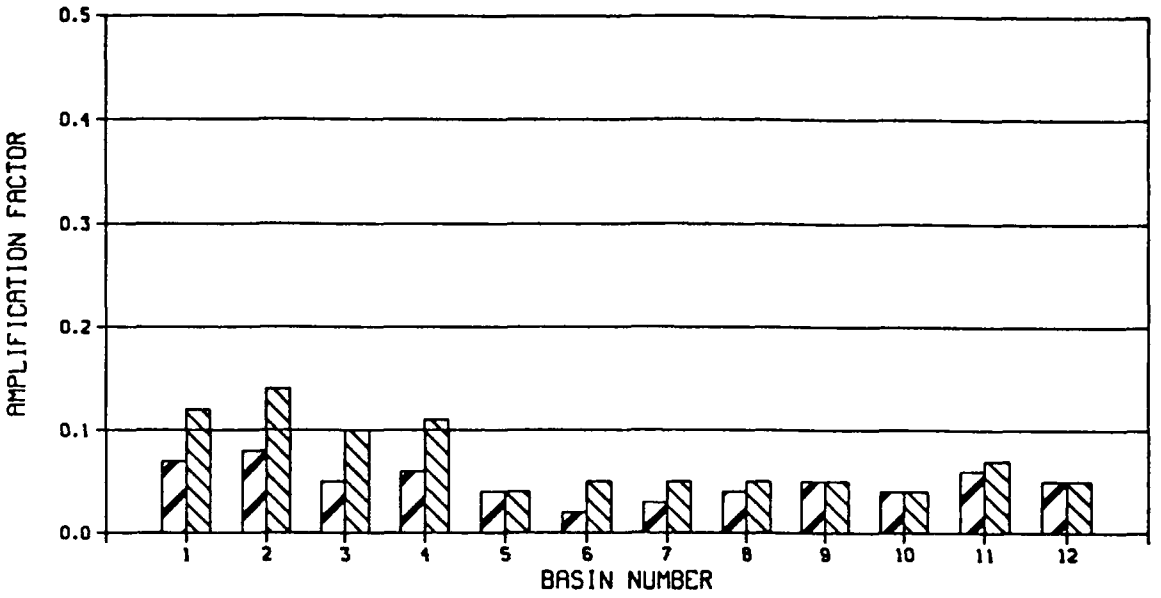
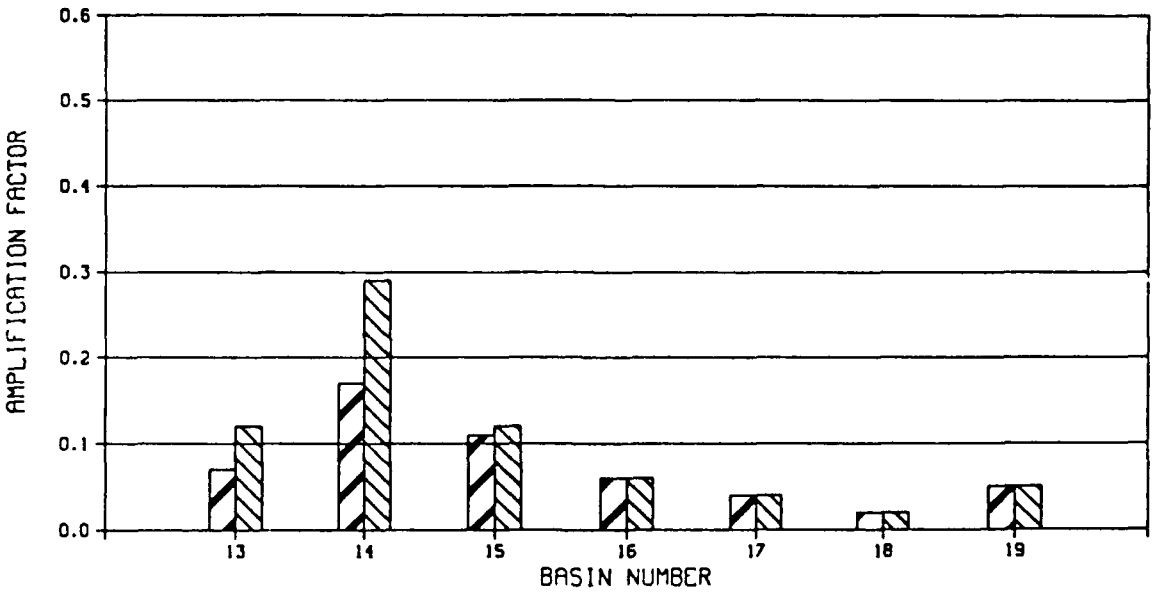

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 11 sec
WAVE DIRECTION - 270 deg

PLATE 20

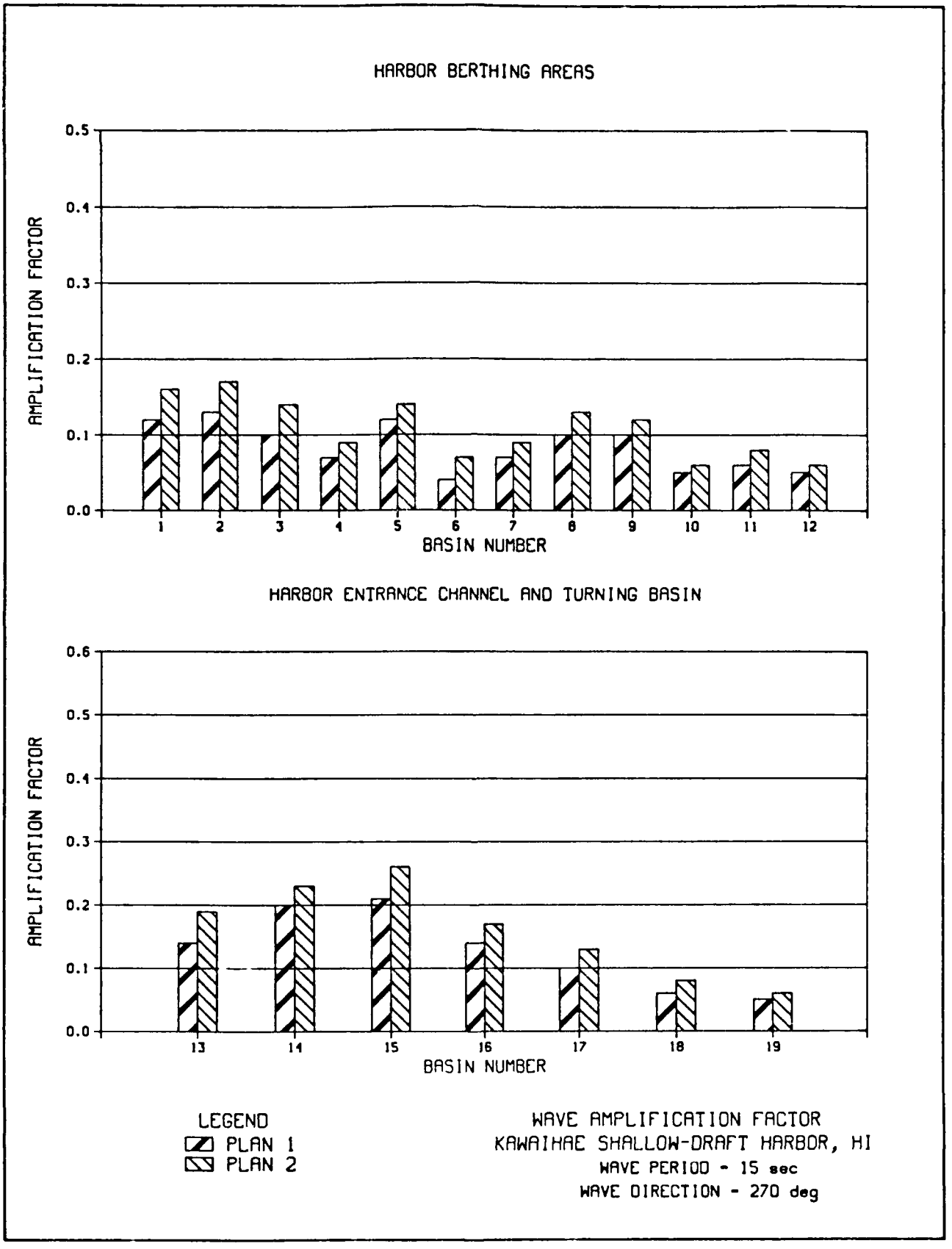




LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 13 sec
WAVE DIRECTION - 270 deg

PLATE 21


HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
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0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 15 sec
WAVE DIRECTION - 270 deg

PLATE 22

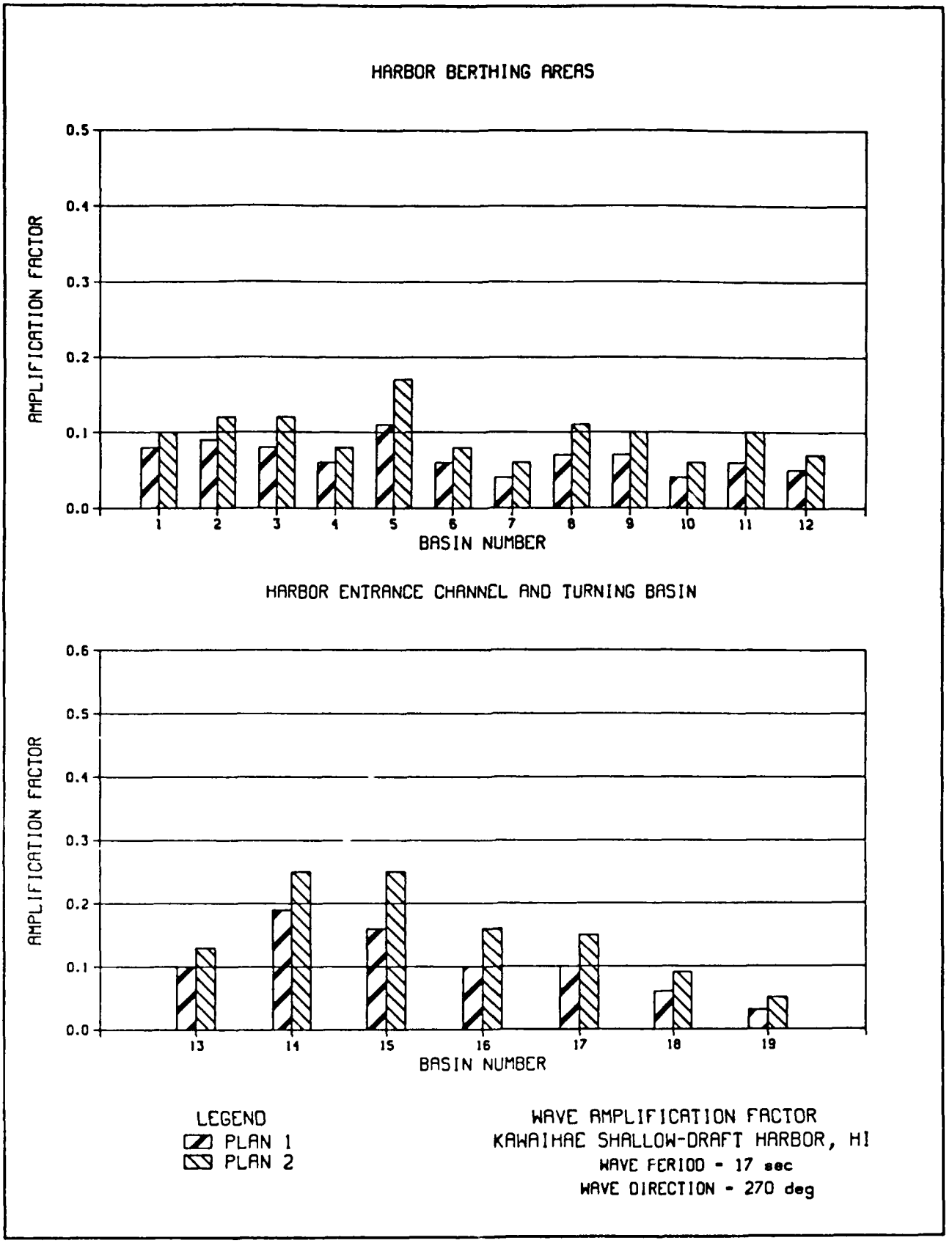

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 17 sec
WAVE DIRECTION - 270 deg

PLATE 23

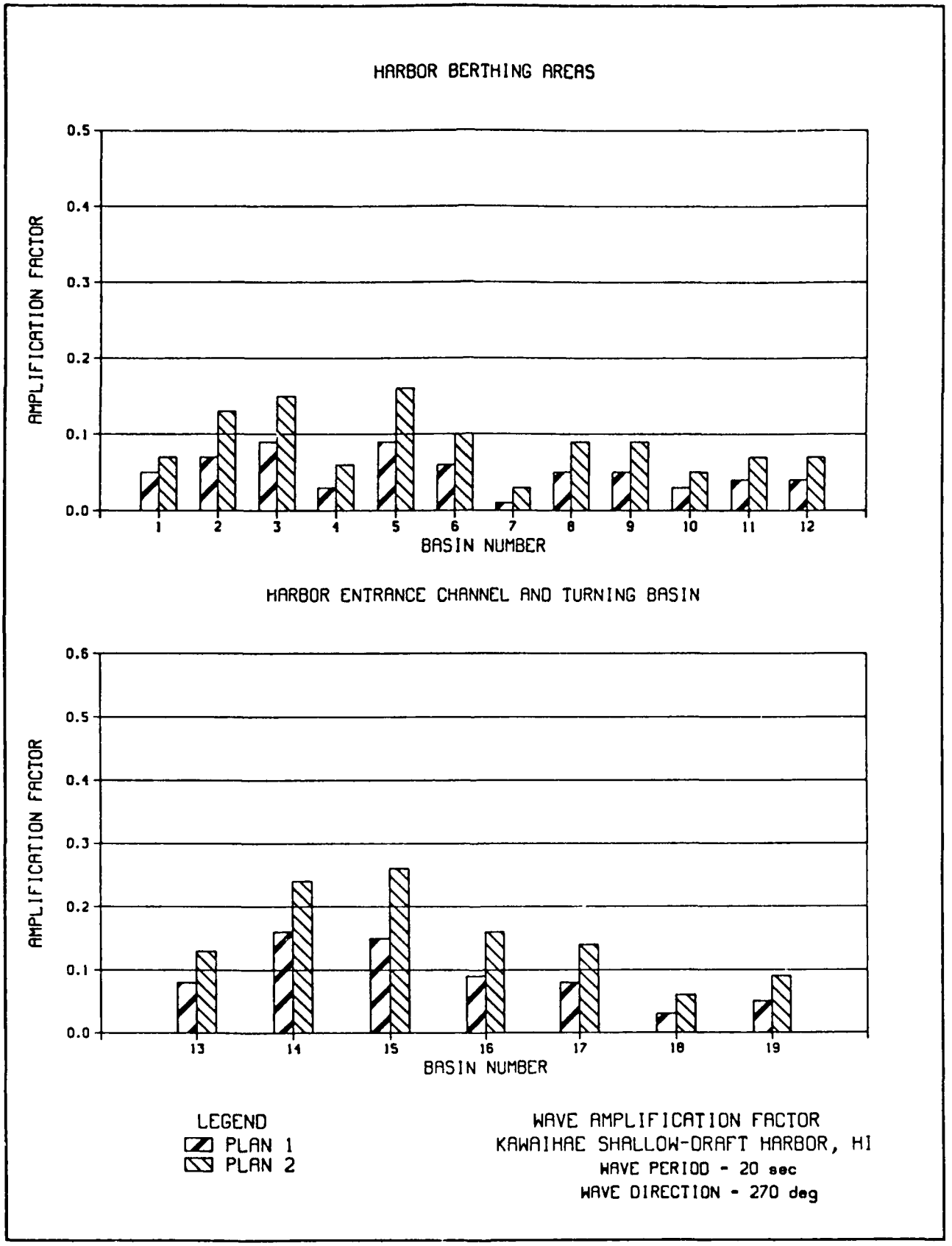
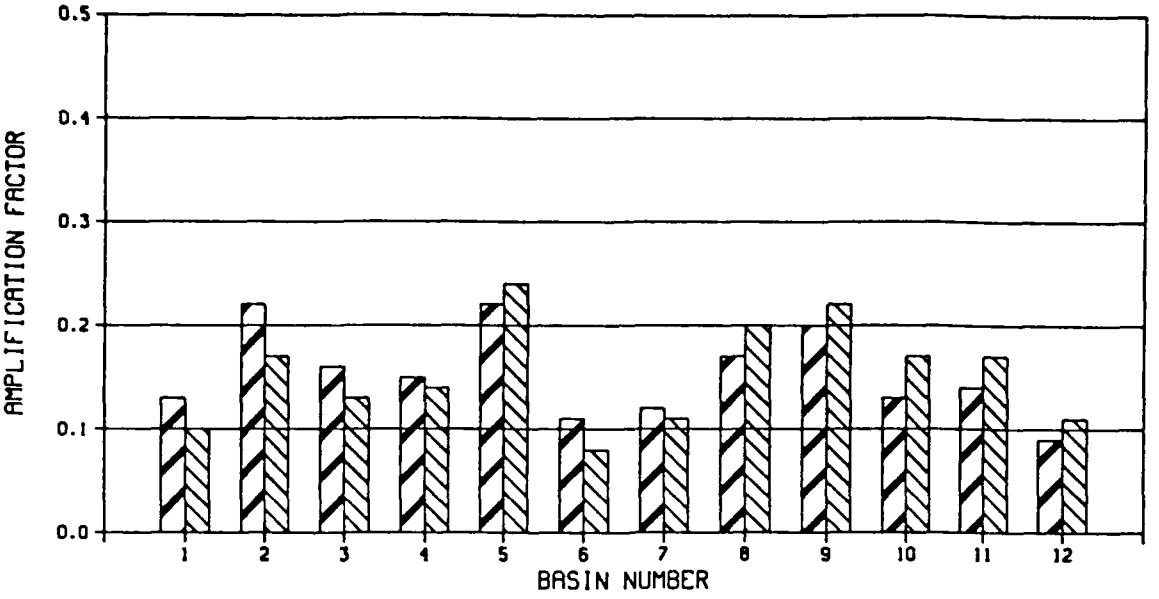
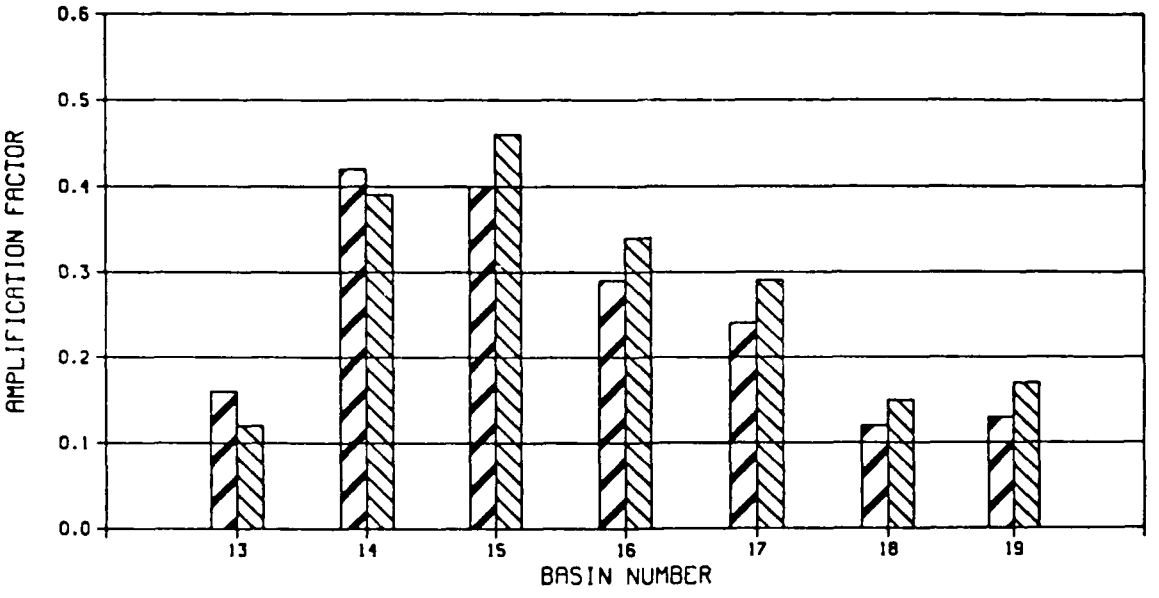

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 20 sec
WAVE DIRECTION - 270 deg

PLATE 24

HARBOR BERTHING AREAS



HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 7 sec
WAVE DIRECTION - 292.5 deg

PLATE 25

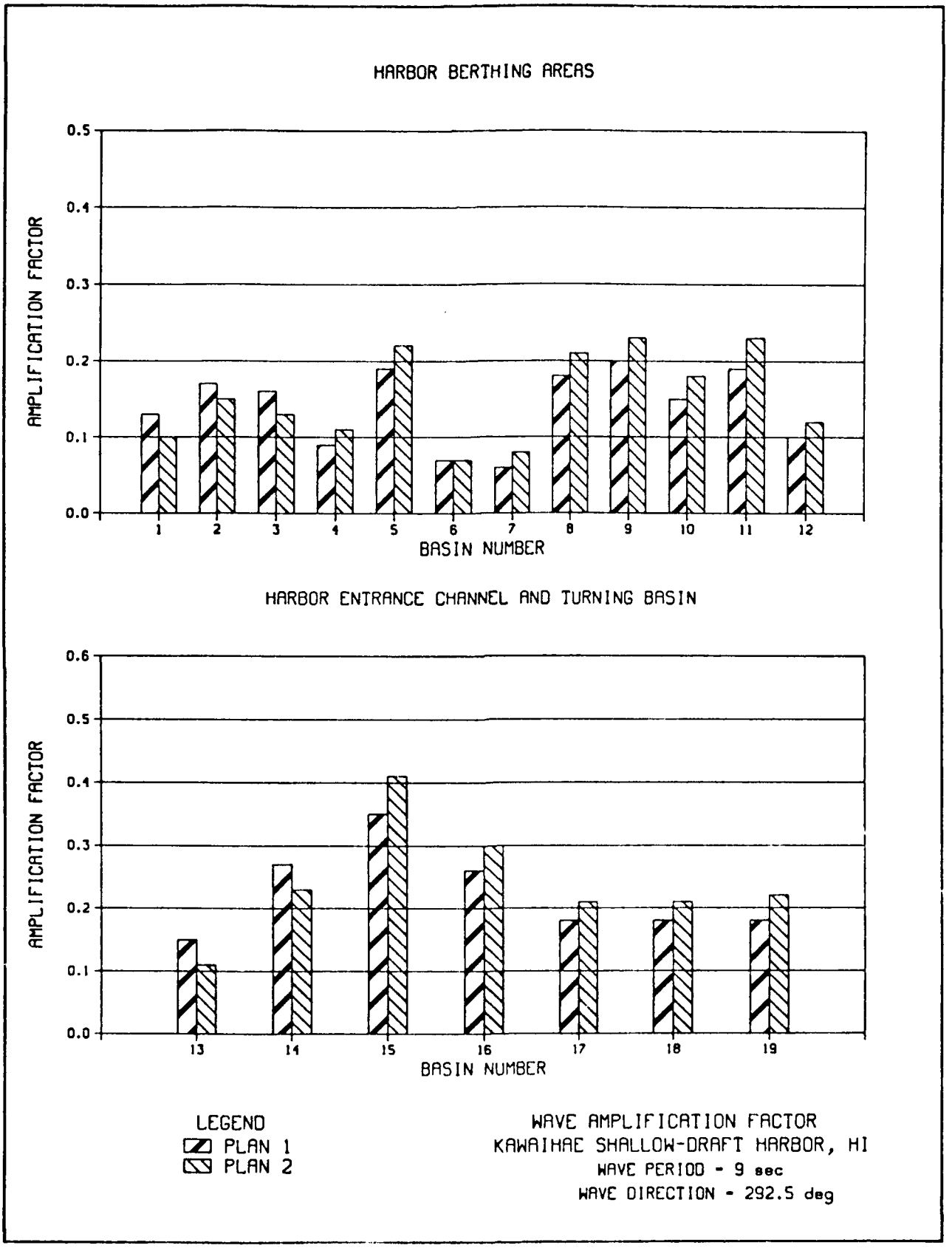
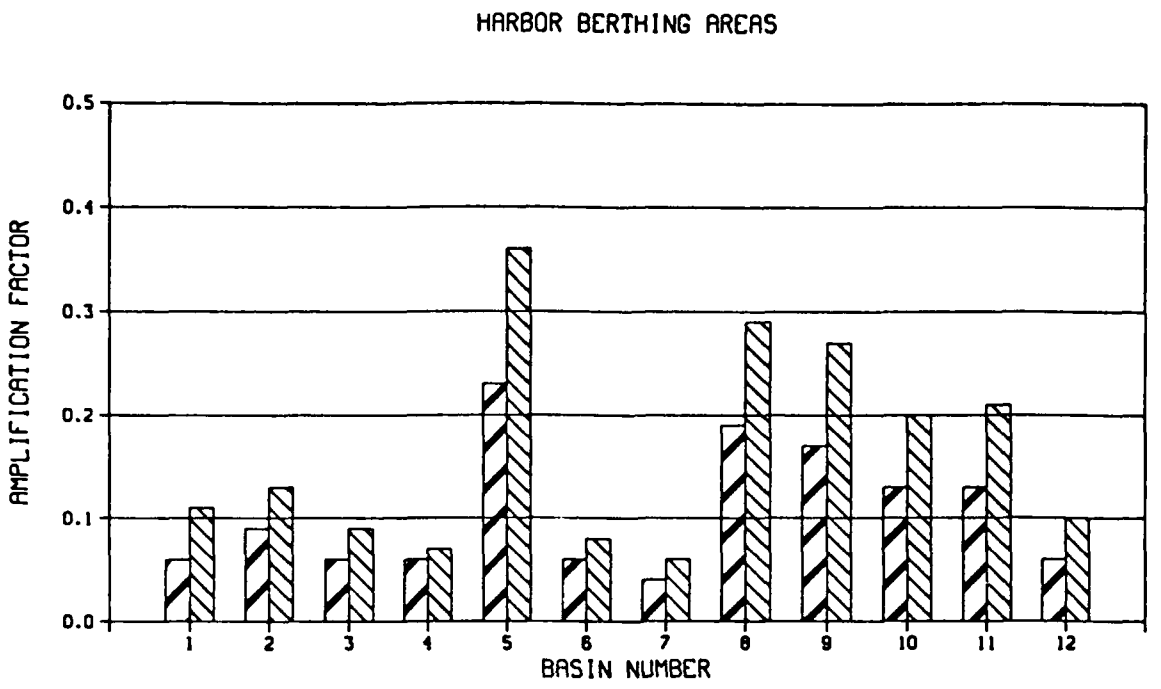
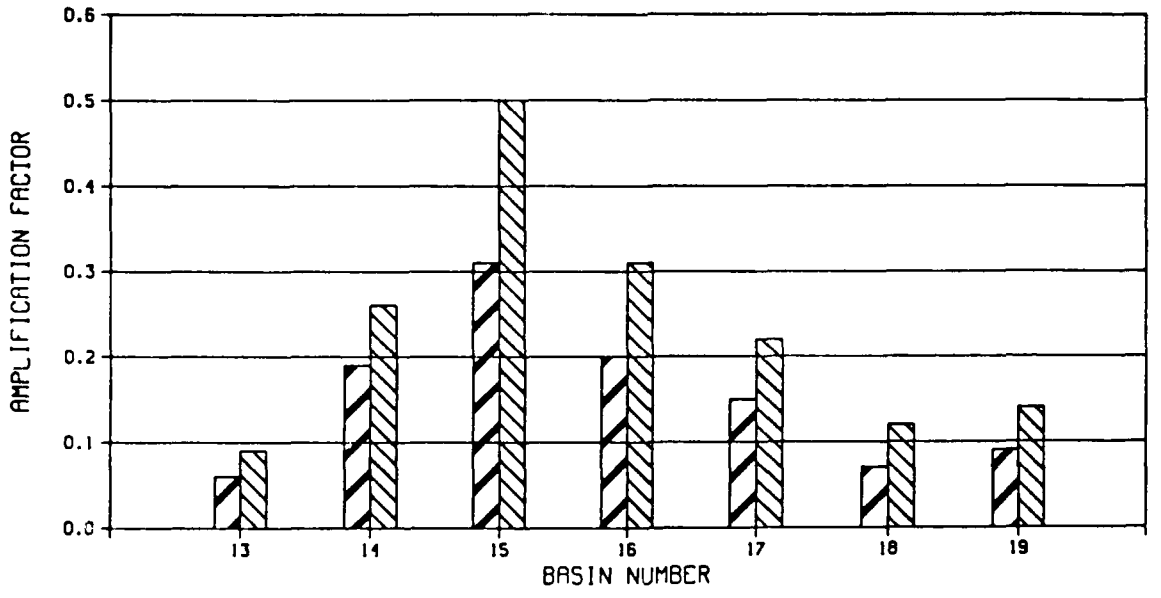

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.0
0.1
0.2
0.3
0.4
0.5
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.0
0.1
0.2
0.3
0.4
0.5
0.6
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 9 sec
WAVE DIRECTION - 292.5 deg

PLATE 26





LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 11 sec
WAVE DIRECTION - 292.5 deg

PLATE 27

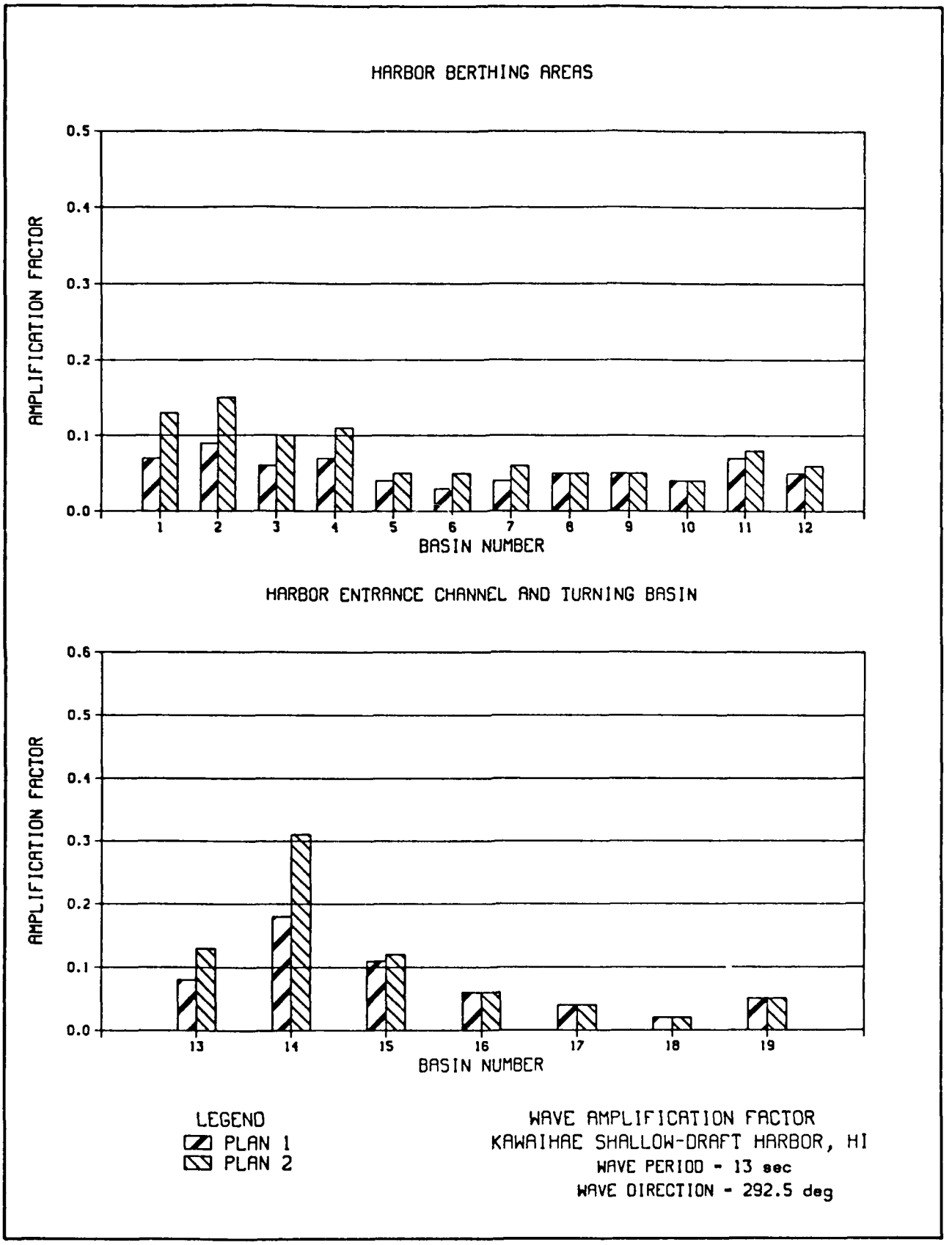
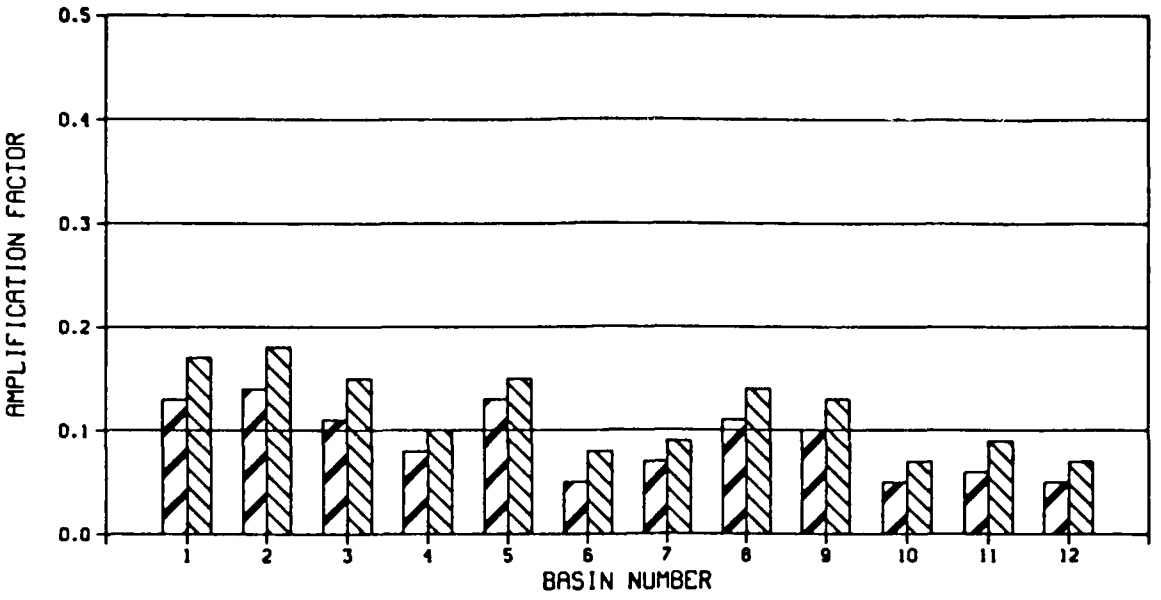
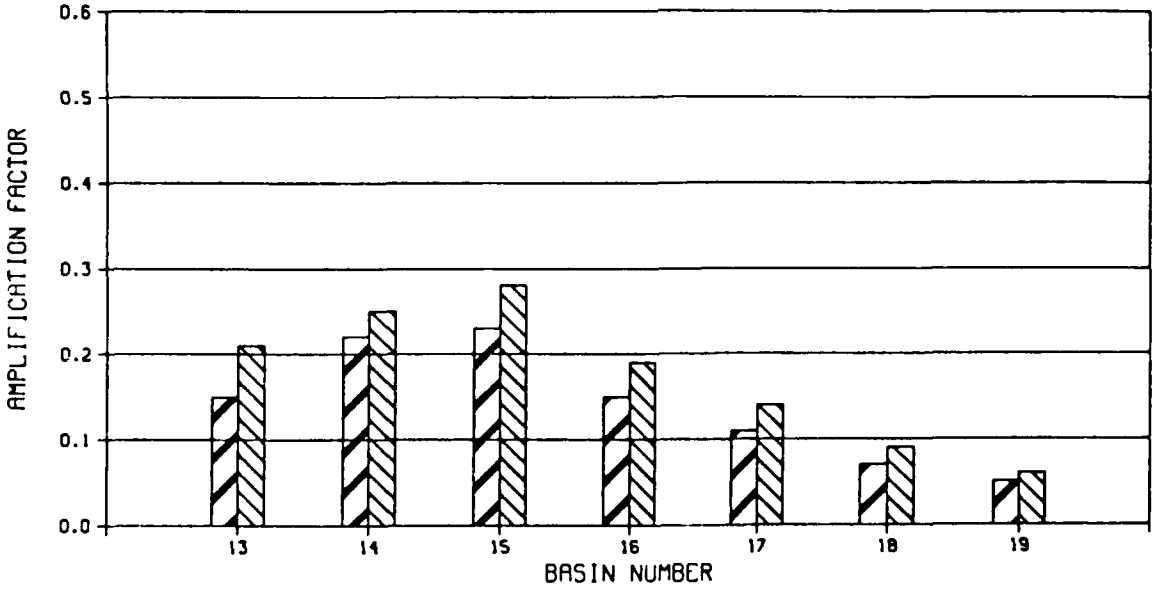

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 13 sec
WAVE DIRECTION - 292.5 deg

PLATE 28

HARBOR BERTHING AREAS



HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 15 sec
WAVE DIRECTION - 292.5 deg

PLATE 29

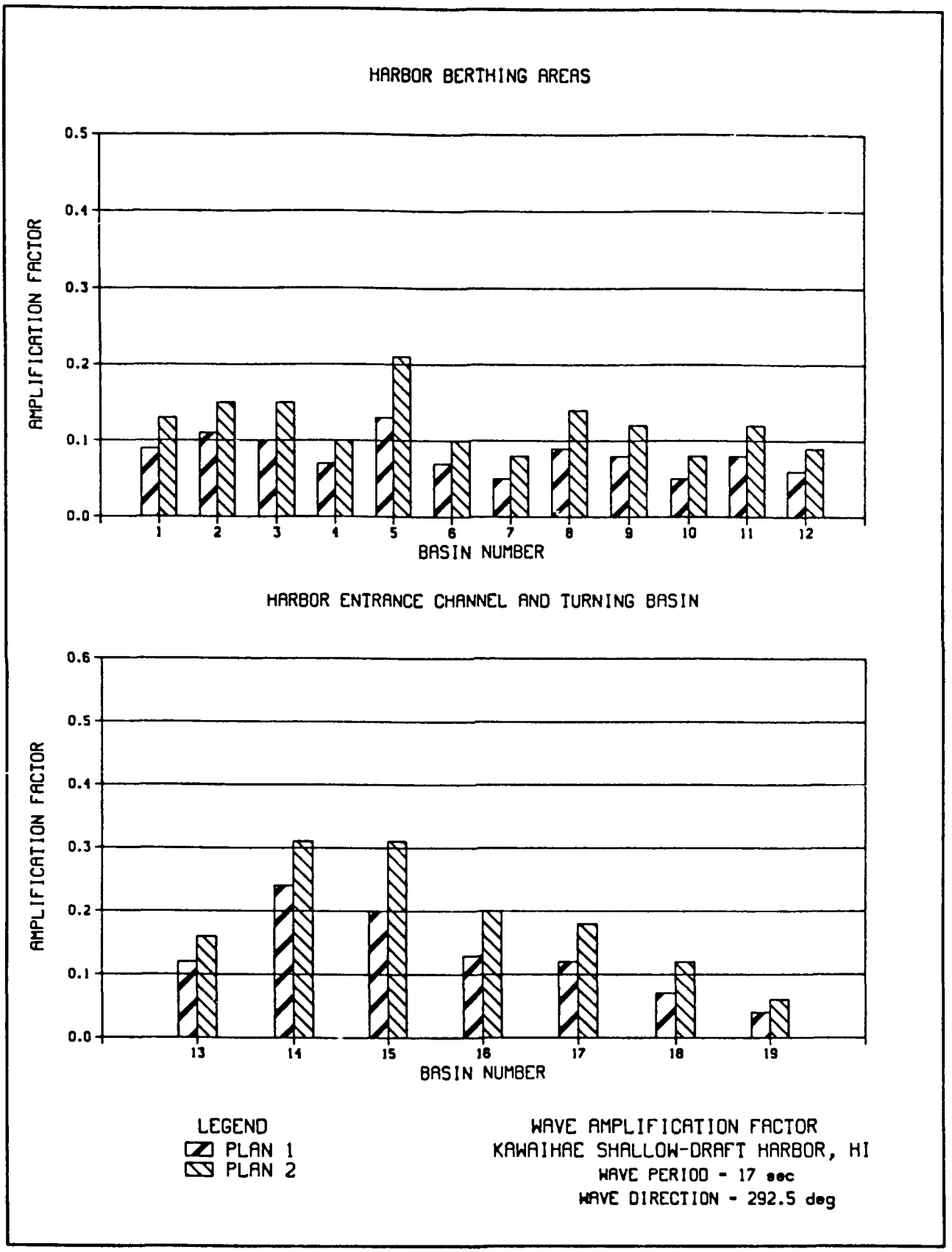
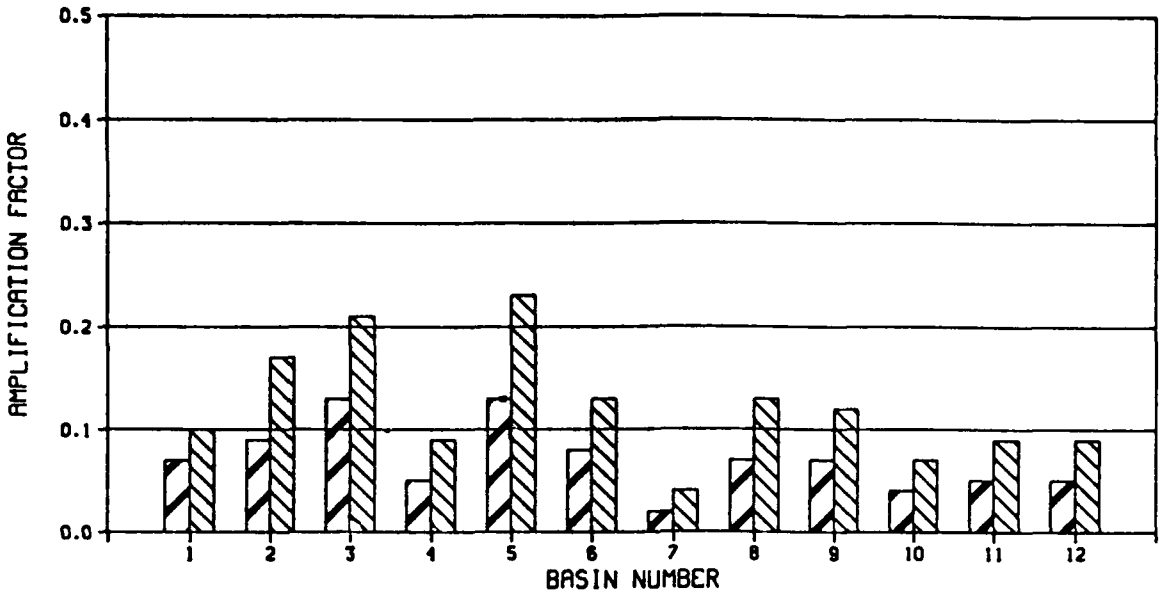
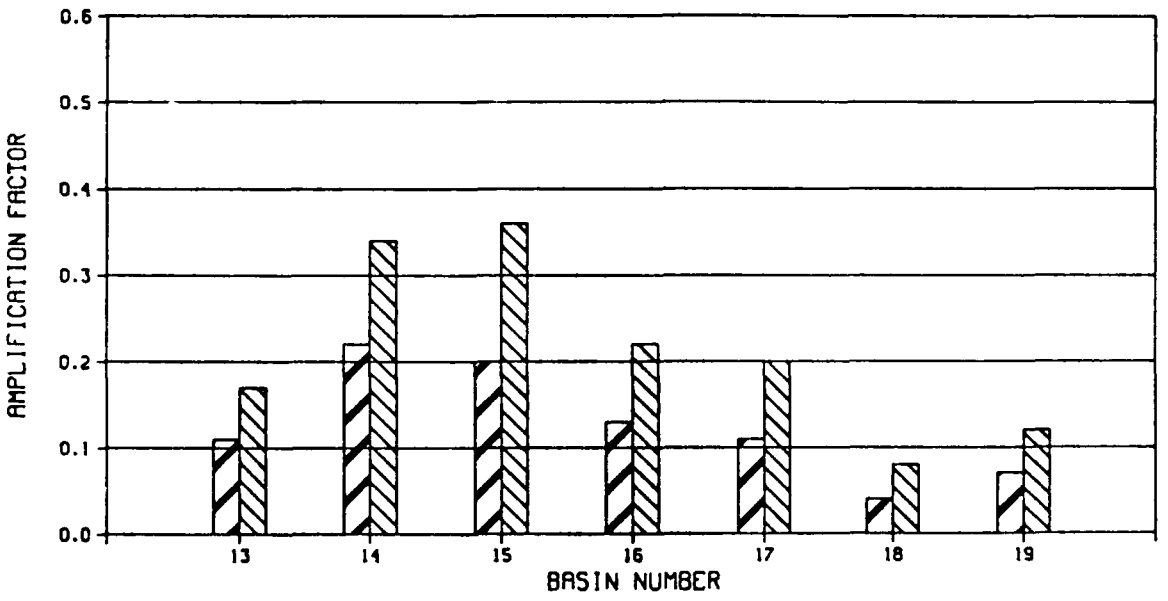

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 17 sec
WAVE DIRECTION - 292.5 deg

PLATE 30





LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 20 sec
WAVE DIRECTION - 292.5 deg

PLATE 31

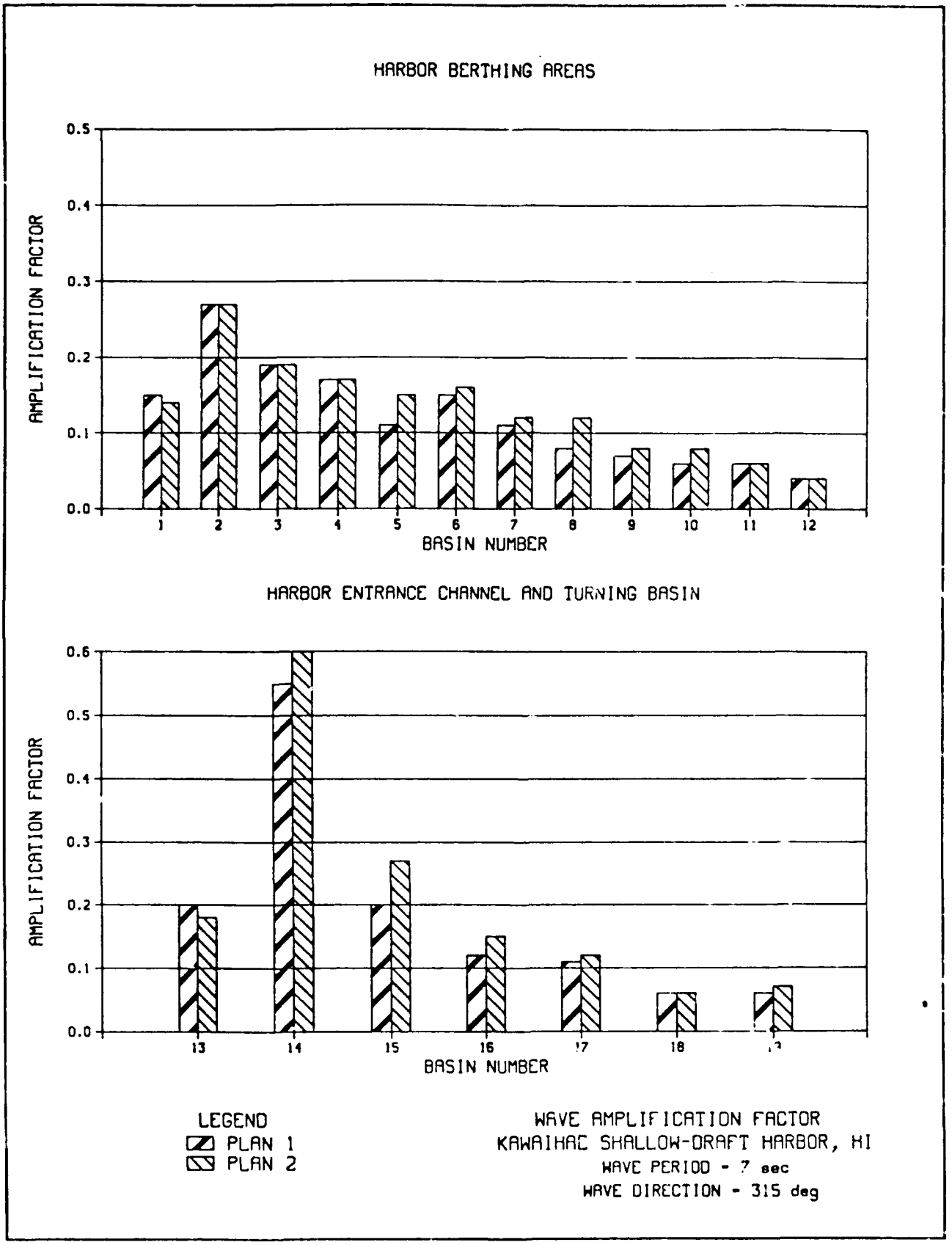
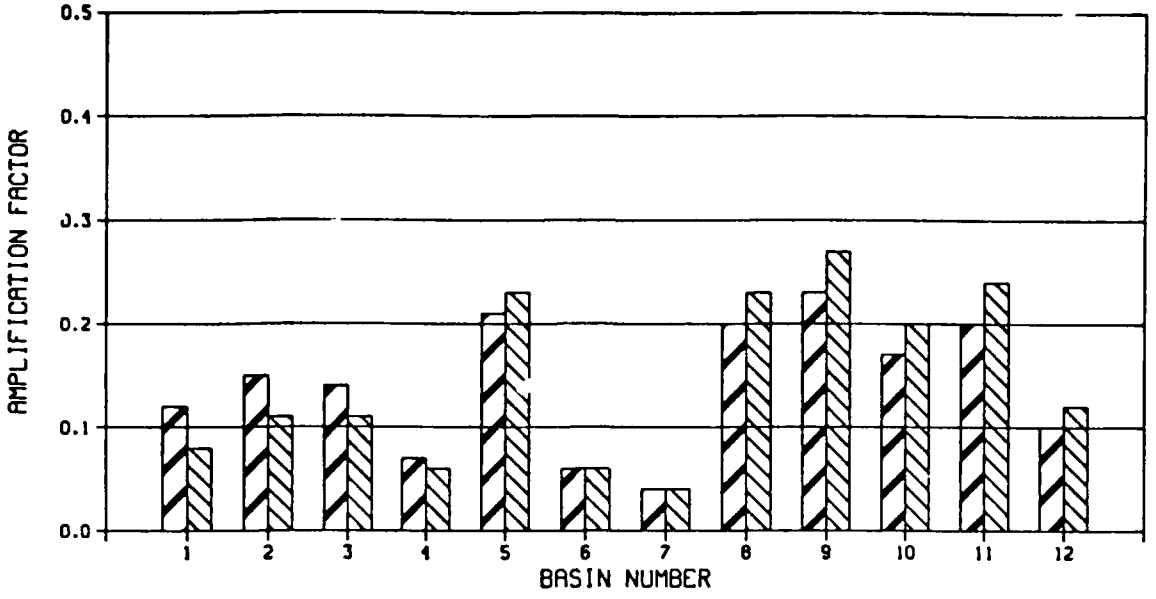
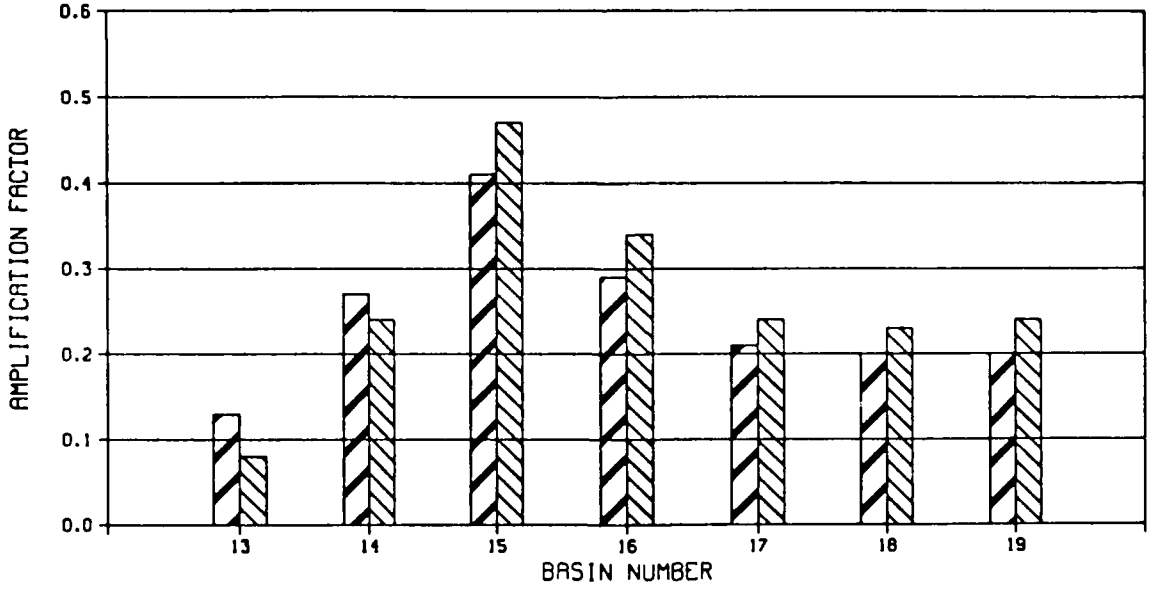

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 7 sec
WAVE DIRECTION - 315 deg

PLATE 32

HARBOR BERTHING AREAS



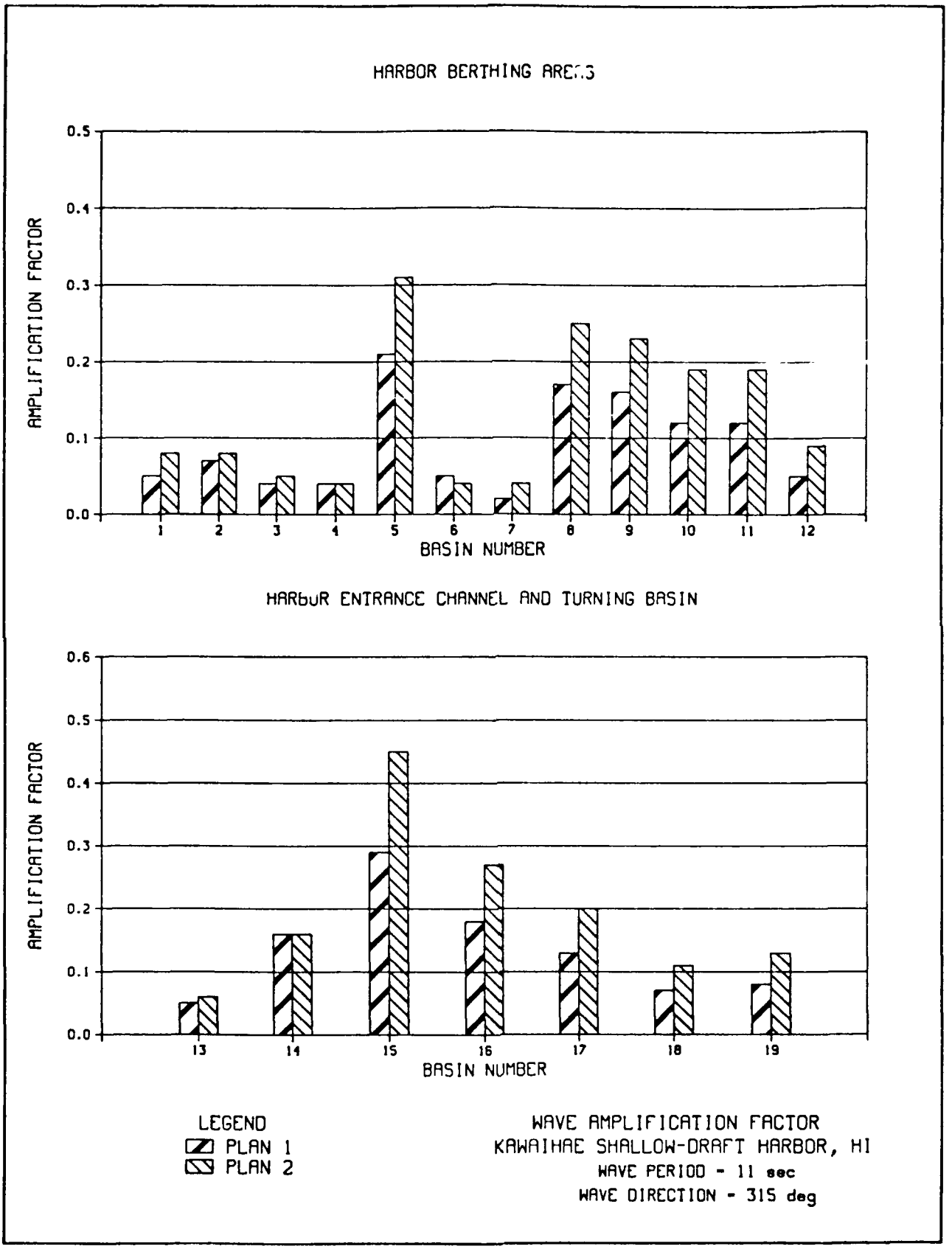
HARBOR ENTRANCE CHANNEL AND TURNING BASIN



LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 9 sec
WAVE DIRECTION - 315 deg

PLATE 33


HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
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0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 11 sec
WAVE DIRECTION - 315 deg

PLATE 34

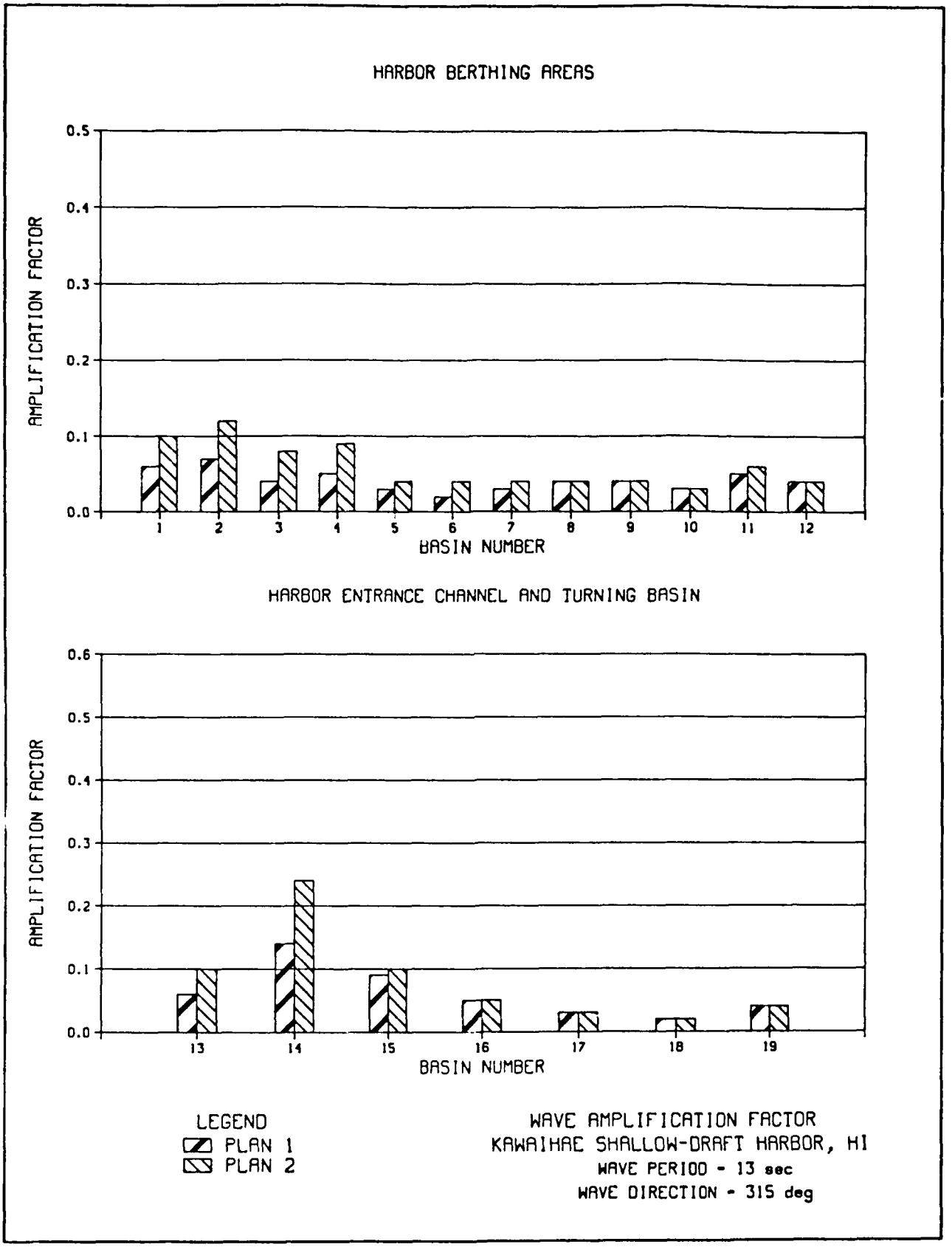

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 13 sec
WAVE DIRECTION - 315 deg

PLATE 35

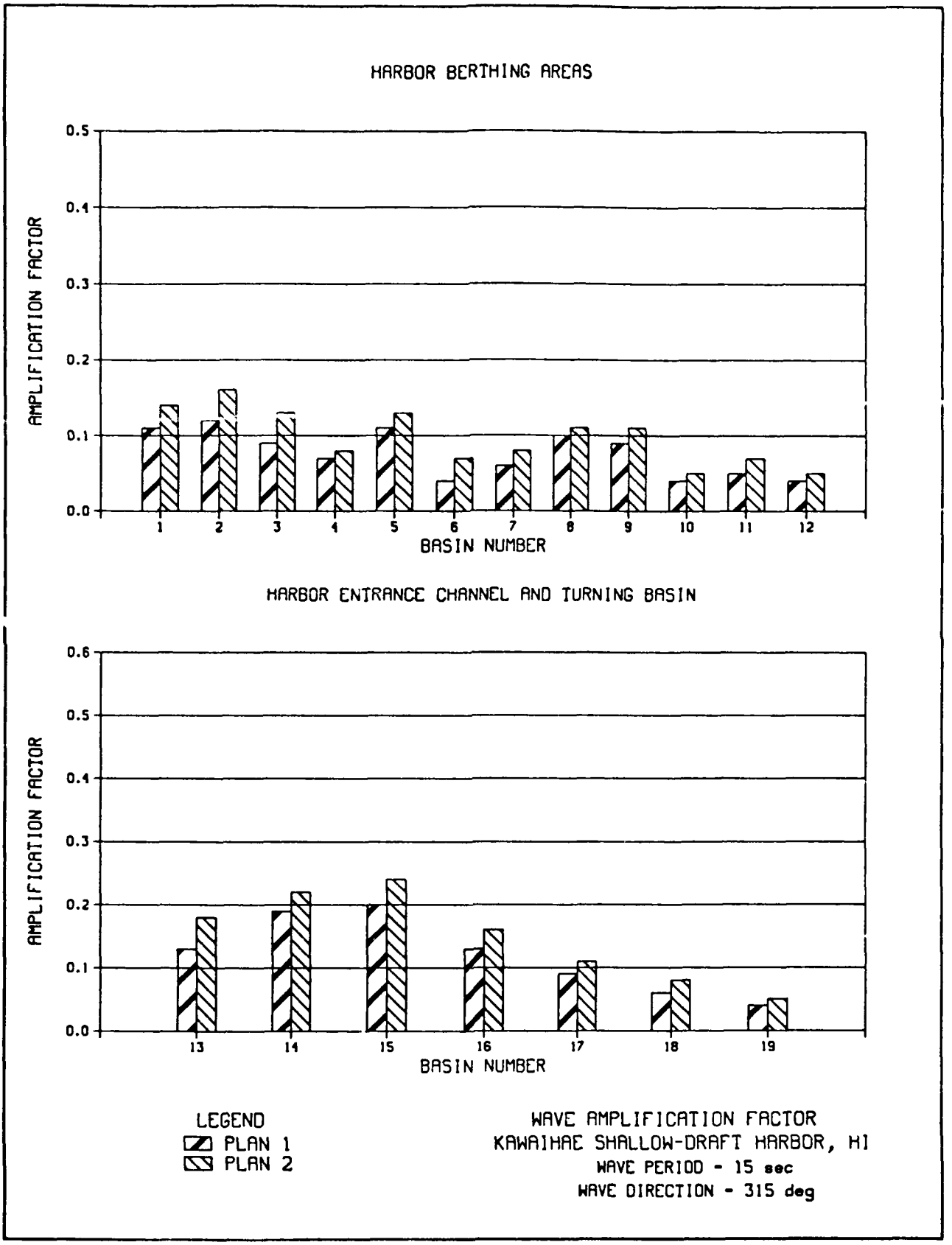
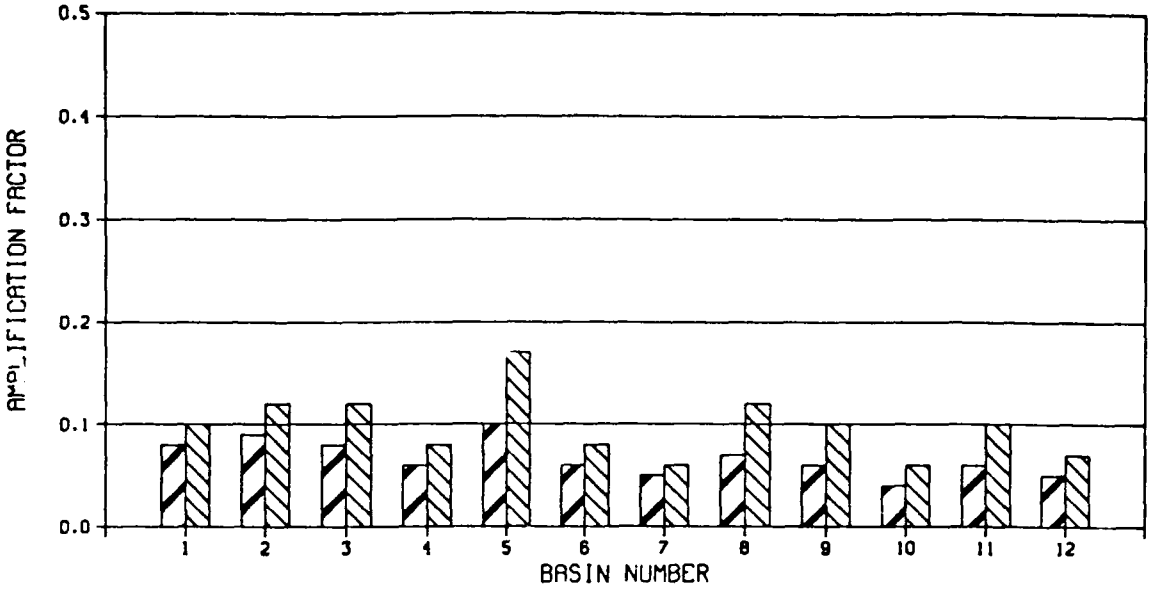
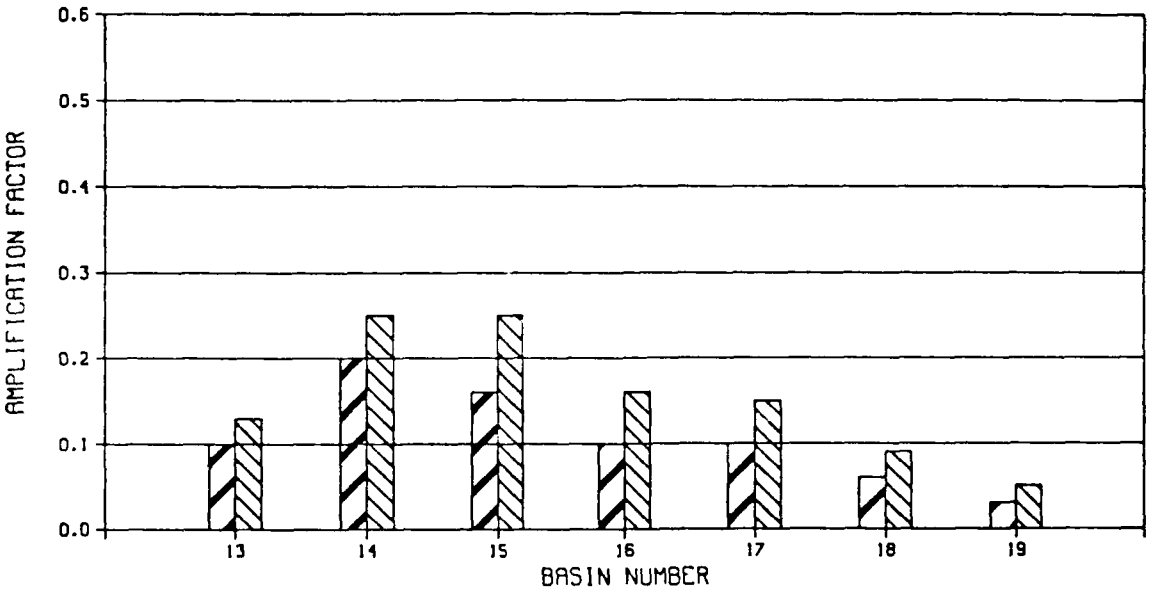

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 15 sec
WAVE DIRECTION - 315 deg

PLATE 36





LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 17 sec
WAVE DIRECTION - 315 deg

PLATE 37

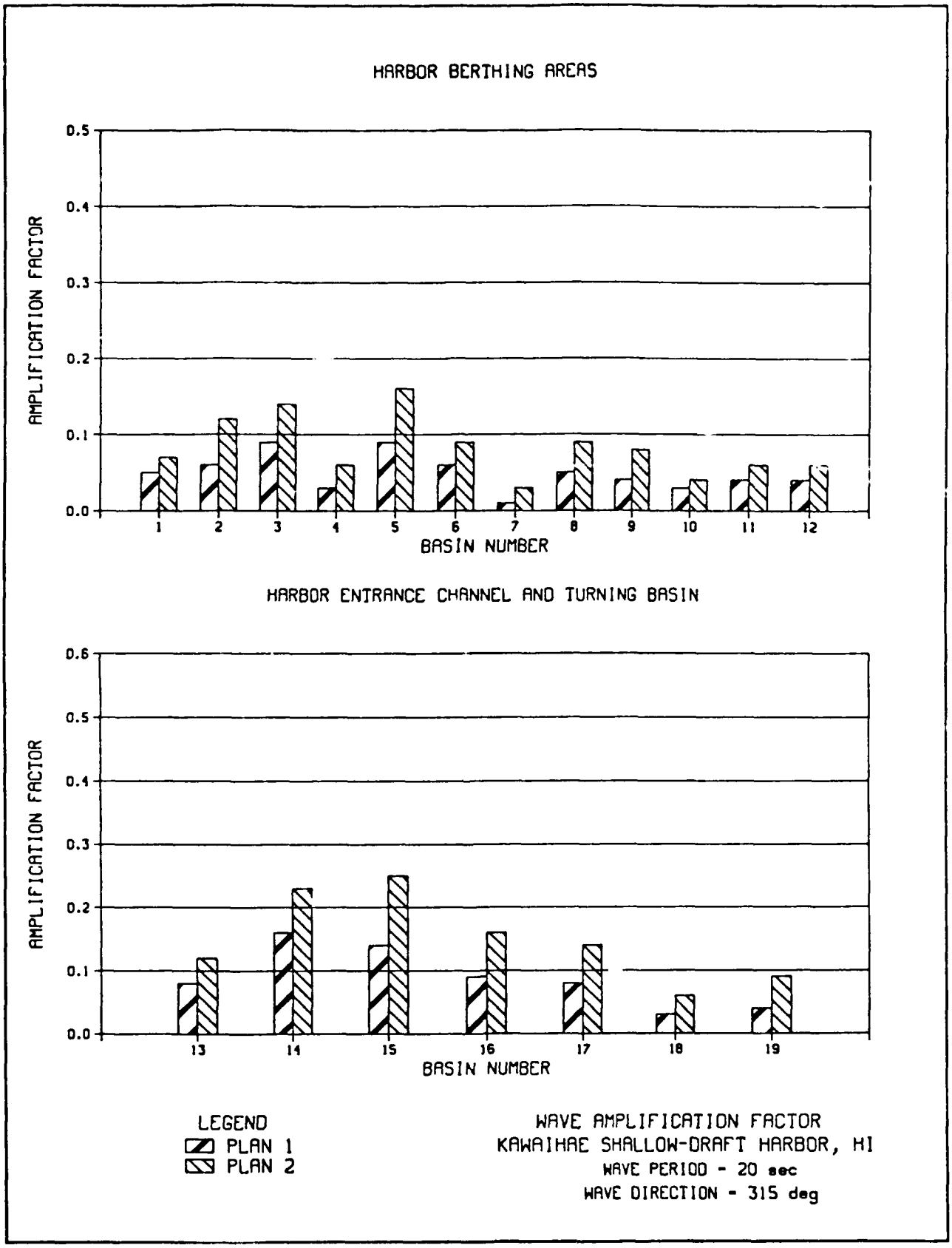
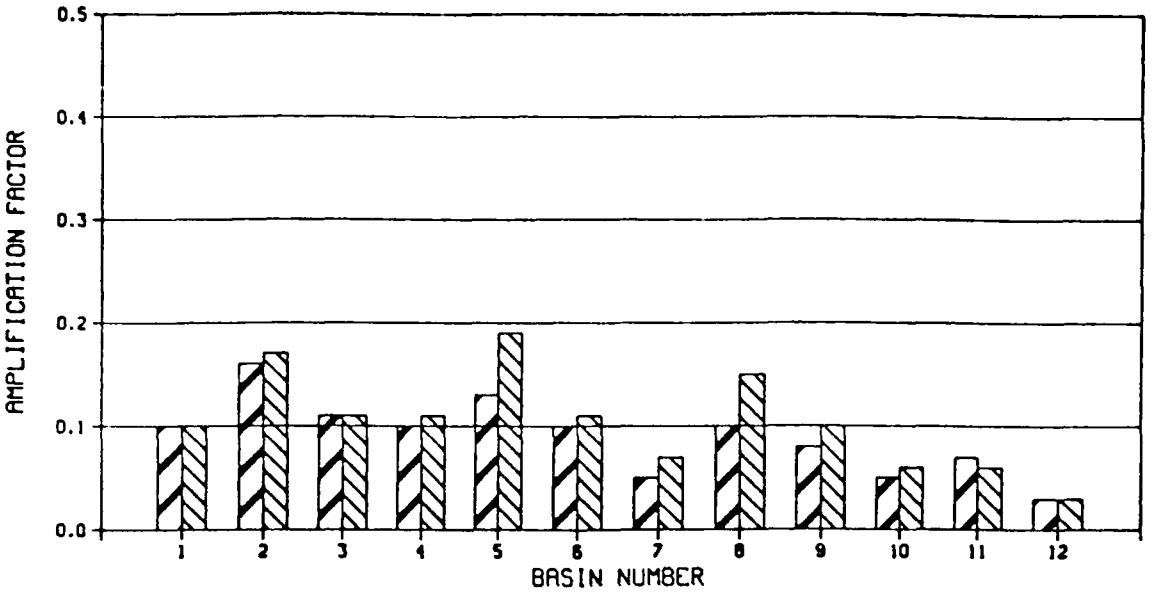
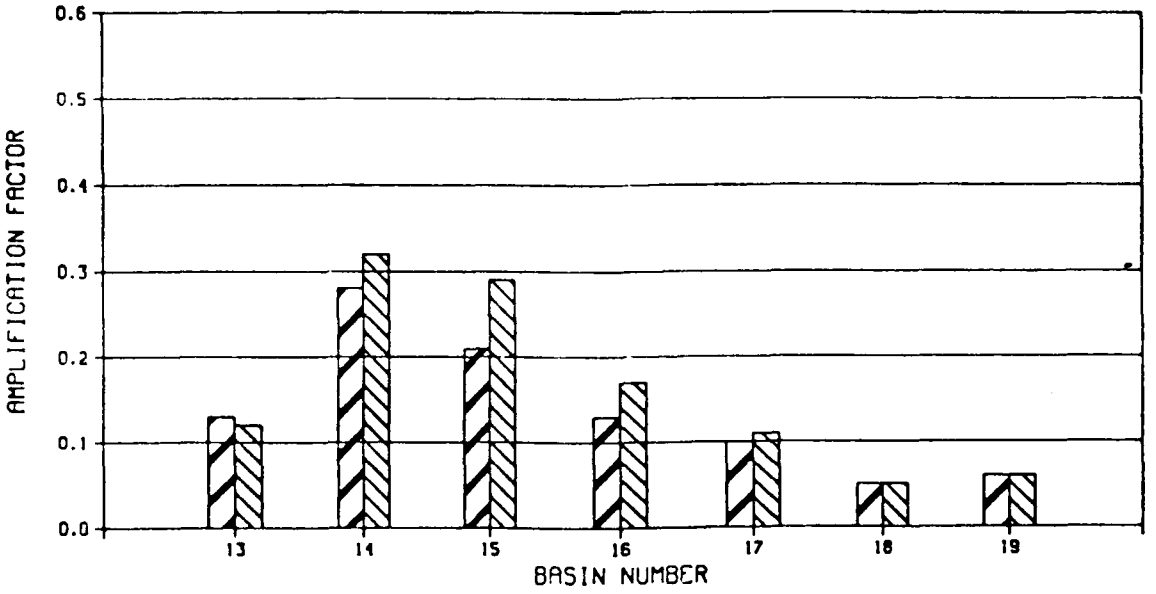

HARBOR BERTHING AREAS
AMPLIFICATION FACTOR
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
BASIN NUMBER
HARBOR ENTRANCE CHANNEL AND TURNING BASIN
AMPLIFICATION FACTOR
0.6
0.5
0.4
0.3
0.2
0.1
0.0
13
14
15
16
17
18
19
BASIN NUMBER
LEGEND
PLAN 1
PLAN 2
WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 20 sec
WAVE DIRECTION - 315 deg

PLATE 38





LEGEND
PLAN 1
PLAN 2

WAVE AMPLIFICATION FACTOR
KAWAIHAE SHALLOW-DRAFT HARBOR, HI
WAVE PERIOD - 7 sec
WAVE DIRECTION - 337.5 deg

PLATE 39

APPENDIX A: OFFSHORE WAVE CLIMATE PERCENT OCCURRENCE TABLES

Table A-1

Percent Occurence of Height and Period by Direction*

Wave Direction = 202.5 deg (from which waves approach)

Wave Height ft	Peak Period (sec) 5	7	9	11	13	15	17	20	Total
0-3	*	0.01	0.01	0.01	0.01	*	*	*	0.04
3-6	*	*	*	*	0.01	*	*	*	0.02
6-9	*	0.01	*	*	*	*	*	*	0.02
9-12	.	*	.	.	.	.	.	.	*
12-15	.	.	*	.	.	.	.	.	*
>15	.	.	.	.	.	.	.	.	0.00
Total	*	0.03	0.01	0.01	0.02	0.01	*	*	0.08

Table A-2

Percent Occurence of Height and Period by Direction

Wave Direction = 225.0 deg (from which waves approach)

Wave Height ft	Peak Period (sec) 5	7	9	11	13	15	17	20	Total
0-3	*	0.02	0.02	0.02	0.03	0.01	*	*	0.10
3-6	*	0.01	0.01	0.01	0.01	0.02	0.01	*	0.07
6-9	*	0.02	*	*	*	*	*	*	0.02
9-12	.	0.02	.	.	.	.	.	.	0.02
12-15	.	*	0.01	.	.	.	.	.	0.01
>15	.	.	0.02	.	.	.	.	.	0.02
Total	*	0.07	0.06	0.03	0.04	0.03	0.01	*	0.24

* Percent occurrence is below table resolution

Table A-3

Percent Occurence of Height and Period by Direction*

Wave Direction = 247.5 deg (from which waves approach)

Wave Height ft	Peak Period (sec) 5	7	9	11	13	15	17	20	Total
0-3	0.01	0.03	0.02	0.02	0.03	0.02	*	*	0.13
3-6	*	0.02	0.01	0.01	0.02	0.02	0.01	*	0.09
6-9	0.01	0.02	*	0.02	*	*	*	*	0.05
9-12	.	0.02	0.01	0.01	.	.	.	.	0.04
12-15	.	0.01	*	.	*	.	.	.	0.01
>15	.	.	0.01	.	.	.	.	.	*
Total	0.02	0.10	0.05	0.06	0.05	0.04	0.01	*	0.33

Table A-4

Percent Occurence of Height and Period by Direction

Wave Direction = 270.0 deg (from which waves approach)

Wave Height ft	Peak Period (sec) 5	7	9	11	13	15	17	20	Total
0-3	0.02	0.06	0.05	0.05	0.08	0.04	0.01	*	0.31
3-6	0.01	0.04	0.02	0.03	0.05	0.04	0.01	*	0.20
6-9	0.01	0.03	0.03	0.03	0.01	*	*	*	0.11
9-12	.	0.03	*	0.03	0.03	.	.	.	0.09
12-15	.	*	*	.	0.01	.	.	.	0.01
>15	.	.	0.01	*	0.01	.	.	.	0.02
Total	0.04	0.16	0.11	0.14	0.19	0.08	0.02	*	0.74

* Percent occurrence is below table resolution

Table A-5

Percent Occurence of Height and Period by Direction*

Wave Direction = 292.5 deg (from which waves approach)

Wave Height ft	Peak Period (sec) 5	7	9	11	13	15	17	20	Total
0-3	0.12	0.55	0.45	0.47	0.71	0.34	0.09	0.02	2.75
3-6	0.04	0.34	0.23	0.28	0.41	0.37	0.13	0.02	1.82
6-9	*	0.04	0.05	0.07	0.12	0.04	0.01	0.01	0.34
9-12	.	0.01	0.02	0.28	0.69	0.02	*	.	1.02
12-15	.	0.01	0.01	0.03	0.34	0.08	*	.	0.47
>15	.	.	.	*	0.03	0.03	.	.	0.06
Total	0.16	0.95	0.76	1.13	2.30	0.88	0.23	0.05	6.46

Table A-6

Percent Occurence of Height and Period by Direction

Wave Direction = 315.0 deg (from which waves approach)

Wave Height ft	Peak Period (sec) 5	7	9	11	13	15	17	20	Total
0-3	0.72	3.37	2.79	2.85	4.34	2.10	0.58	0.12	16.86
3-6	0.28	2.06	1.74	1.96	2.51	2.26	0.81	0.15	11.74
6-9	0.02	0.17	0.37	2.13	1.59	0.27	0.05	0.05	4.61
9-12	.	0.01	0.03	0.80	3.98	0.71	0.03	.	5.56
12-15	.	.	*	0.08	1.13	0.74	0.07	.	2.02
>15	.	.	.	.	0.11	0.22	0.12	.	0.45
Total	1.02	5.61	4.92	7.82	13.66	6.30	1.66	0.32	41.31

* Percent occurrence is below table resolution

Table A-7

Percent Occurence of Height and Period by Direction*

Wave Direction = 337.5 deg (from which waves approach)

Wave Height ft	Peak Period (sec) 5	7	9	11	13	15	17	20	Total
0-3	0.89	4.22	3.44	3.53	5.36	2.58	0.72	0.14	20.88
3-6	0.39	2.67	2.99	2.89	3.15	2.79	1.00	0.17	16.05
6-9	0.04	0.22	1.24	3.59	1.93	0.39	0.06	0.05	7.52
9-12	.	0.03	0.06	1.09	3.48	0.57	0.07	.	5.30
12-15	.	.	*	0.08	0.53	0.42	0.07	.	1.10
>15	.	.	.	.	.	.	.	.	*
Total	1.32	7.14	7.73	11.18	14.45	6.75	1.92	0.36	50.85

* Percent occurrence is below table resolution

APPENDIX B: NOTATION

a	Wave amplitude function
a_o	Incident wave amplitude
c	Wave celerity
c_g	Group celerity
g	Gravitational acceleration
H	Wave height
h	Water depth
i	imaginary unit = $(-1)^{1/2}$
K_r	Reflection coefficient
k	Wave number = $2\pi/L$
L	Wavelength
n	Independent variable in the direction of the unit vector
s	Wave phase function
T	Wave period
x	Horizontal coordinate
y	Horizontal coordinate
α	Reflective component of absorbing boundary
β	Dimensionless bottom friction coefficient
γ	Phase difference between bottom friction and flow velocity
θ	Wave approach angle
λ	Complex bottom friction factor
π	3.14159.....
ω	Radian wave frequency, intrinsic wave frequency
ϕ	Velocity potential
∂	Partial differentiation
∇	Gradient operator in two dimensions = $\partial/\partial x + \partial/\partial y$