US Army Corps
of Engineers
Waterways Experiment
Station

Technical Report CERC-95-1
February 1995

Reef Breakwater Design for Burns Waterway Harbor, Indiana

by Hugh F. Acuff, Robert R. Bottin, Jr.

Prepared for U.S. Army Engineer District, Chicago

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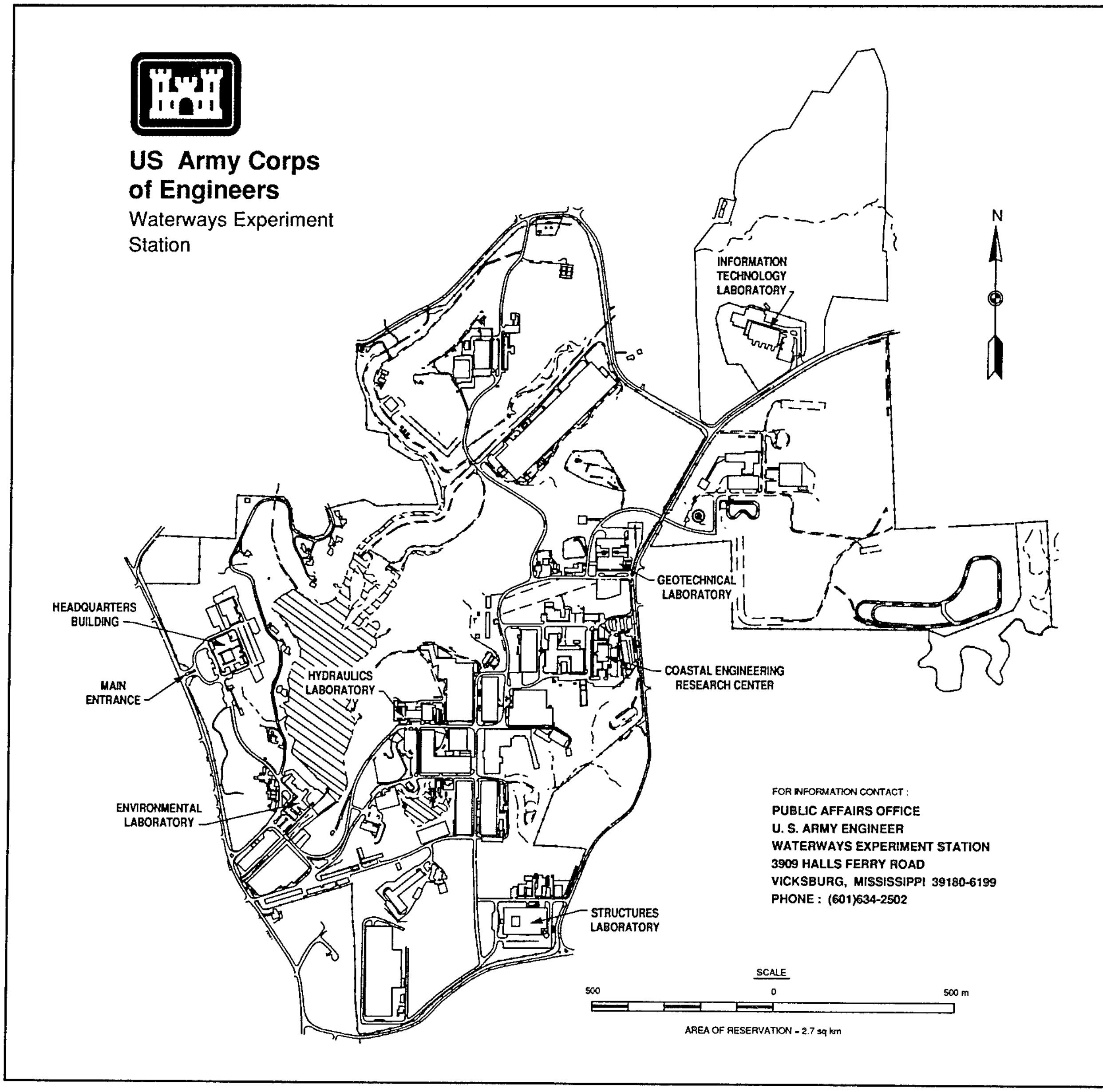
Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Engineer District, Chicago
Chicago, IL 14207



Waterways Experiment Station Cataloging-in-Publication Data

Acuff, Hugh F.
Reef breakwater design for Burns Waterway Harbor, Indiana / by Hugh F. Acuff, Robert R. Bottin, Jr. ; prepared for U.S. Army Engineer District, Chicago.
89 p. : ill. ; 28 cm. — (Technical report ; CERC-95-1)
Includes bibliographic references.
1. Breakwaters — Indiana — Design and construction. 2. Burns Harbor (Ind.) — Design and construction. 3. Hydrodynamics — Indiana. 4. Hydraulic models — Indiana — Design and construction. I. Bottin, Robert R. II. United States. Army. Corps of Engineers. Chicago District. III. U.S. Army Engineer Waterways Experiment Station. IV. Coastal Engineering Research Center (U.S.) V. Title. VI. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; CERC-95-1.
TA7 W34 no.CERC-95-1

Contents

Preface

A request for a model investigation of wave conditions at Burns Waterway Harbor, Indiana, was initiated by the U.S. Army Engineer District, Chicago (NCC), in a letter to the U.S. Army Engineer Division, North Central (NCD). Authorization for the U.S. Army Engineer Waterways Experiment Station (WES) to conduct the study was subsequently granted and funds were authorized by NCC on 15 September 1993.

Model tests were conducted at WES during the period February through June 1994 by personnel of the Wave Processes Branch (WPB) of the Wave Dynamics Division (WDD), Coastal Engineering Research Center (CERC) under the direction of Dr. James R. Houston, Director, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Director, CERC. Direct guidance was provided by Messrs. C. E. Chatham, Jr., Chief, WDD, and Dennis G. Markle, Chief, WPB. Tests were conducted by Mr. Hugh F. Acuff, Ms. Bettye E. Stephens, Mr. Larry R. Tolliver, Civil Engineering Technicians, and Mr. William G. Henderson, Computer Assistant, under the direction of Mr. Robert R. Bottin, Jr., Research Physical Scientist. This report was prepared by Messrs. Acuff and Bottin.

During the course of the investigation, liaison was maintained by means of telephone communication and monthly progress reports. Mr. Charlie Johnson, NCD, visited WES and observed model operation during the course of the investigation. Ms. Anne Smith and Mr. Eric Matthews were technical contacts at NCC.

Dr. Robert W. Whalin was Director of WES during model testing and the preparation and publication of this report. COL Bruce K. Howard, EN, was Commander.

Conversion Factors, Non-SI to SI 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	radians
feet	0.3048	meters
miles (U.S. statute)	1.609347	kilometers
square feet	0.09290304	square meters
square miles	2.589998	square kilometers
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

The Prototype

Burns Waterway Harbor, Indiana, is a man-made harbor located on the southern shoreline of Lake Michigan, approximately 20 miles[1] southeast of Chicago, Illinois (Figure 1). Burns Harbor was primarily constructed to facilitate shipping materials to and from the steel industry in northern Indiana. The Burns Harbor structure includes a 4,600 ft rubble-mound north breakwater with an east-west alignment, a 1,200 ft rubble-mound west breakwater with a north-south alignment, and a cellular steel sheetpile extension connecting the west breakwater to the shore (Figure 2).

The breakwater is a rubble-mound structure with a multi-layered random placement design and a toe elevation of approximately -40 ft low water datum (LWD)[2] and a crest elevation of +14 ft. Armor stones are cut Indiana Bedford limestone ranging from 10 to 16 tons on the trunk and 15 to 20 tons on the head of the breakwater. An aerial photo of the harbor is shown in Figure 3.

The Problem

Since completion of construction in 1968, the harbor has experienced two problems. Maintenance of the crest elevation and structure cross section has required the addition of large amounts of stone (average of 7,640 tons per year for the first 19 years of operation). Rehabilitation history of the structure can be found in Bottin (1988). In addition, unacceptable large wave conditions within the harbor (recorded data show transmission coefficients as high as 25 percent) have led to instances of extensive damage to harbor facilities and moored vessels.

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1 A table of factors for converting non-SI to SI units is presented on page v.

2 All elevations (el) cited herein are in feet referred to low water datum (LWD), el 576.8 ft above mean water level at Father Point, Quebec (International Great Lakes Datum, 1955).

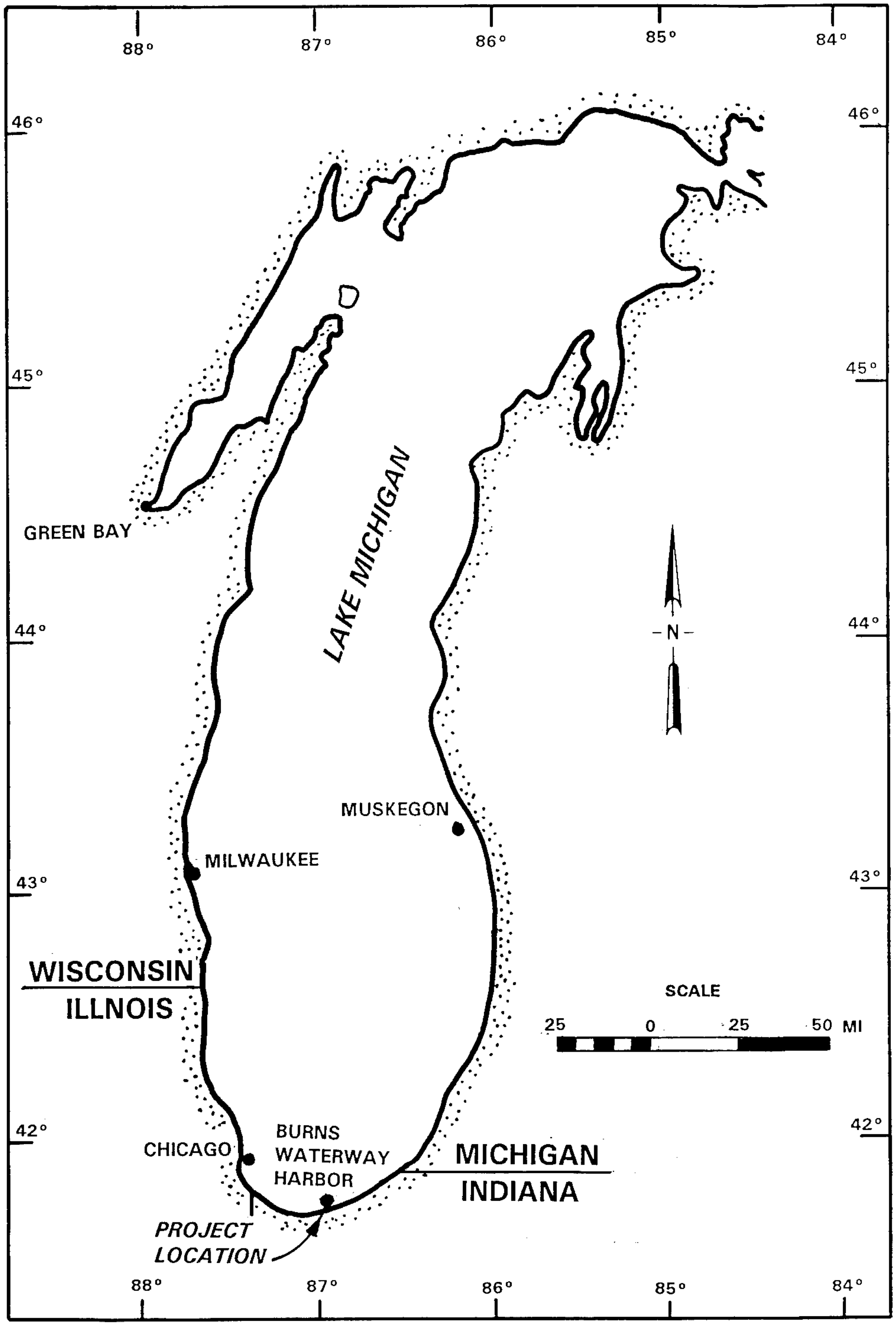

Figure 1. Project location

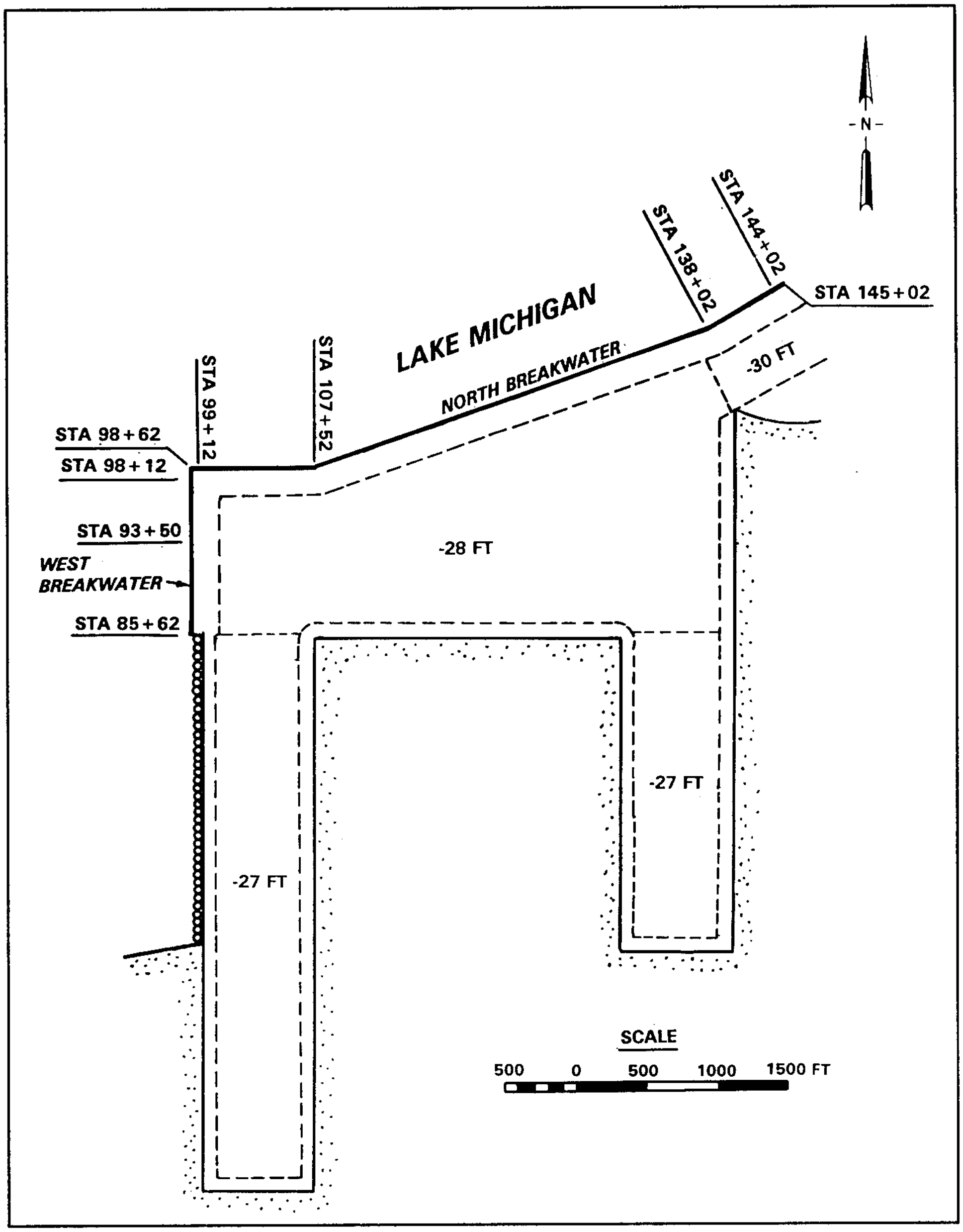

Figure 2. Layout of existing Burns Waterway Harbor structure

Purpose of the Model Study

At the request of the U.S. Army Engineer District, Chicago (NCC), a physical hydraulic model investigation was initiated by the U.S. Army Engineer Waterways Experiment Station (WES) to:

a. Evaluate the effectiveness of a proposed segmented reef structure, oriented lakeward of the existing breakwater, in reducing wave heights reaching the existing breakwater.

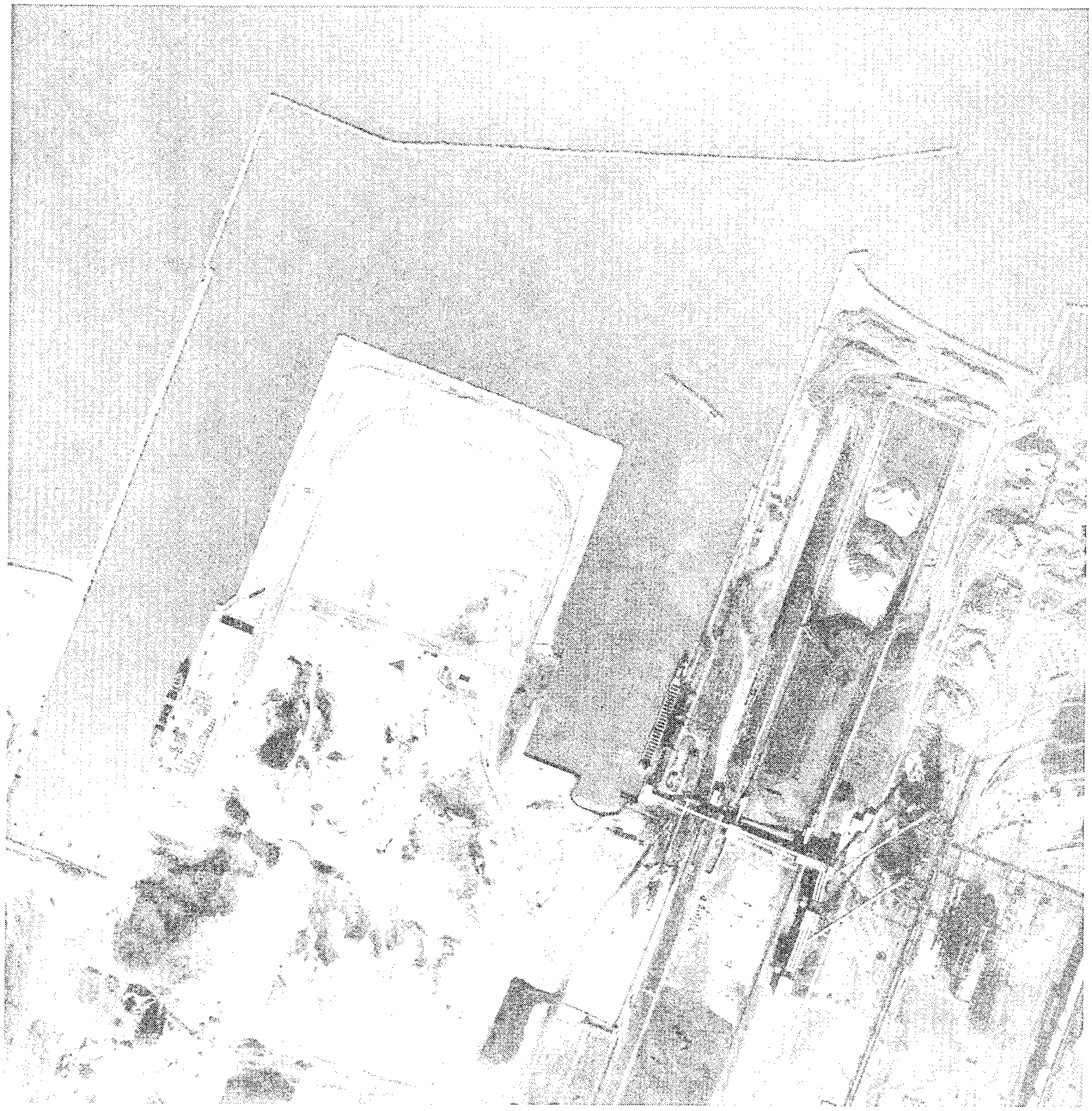

Figure 3. Aerial view of harbor

b. Optimize the crest width, length, and spacing of each segment of the reef structure to minimize transmitted wave energy.

c. Determine the optimum distance between the existing breakwater and the reef structure relative to waves impacting on the existing breakwater.

d. Evaluate the impact of the reef breakwaters on wave-induced currents lakeward of the existing breakwater.

Prior to this investigation, a two-dimensional model study was conducted to optimize the crest width, crest elevation, and armor stone size of the reef structure (Carver and Wright, in preparation).

Wave Height Criteria

For the purposes of the study, NCC specified that for an improvement plan to be acceptable, maximum significant wave heights should not exceed:

a. 15 ft in the lee of the reef breakwaters for 19 ft incident wave conditions.

b. 3 ft inside the harbor for 13 ft incident wave conditions.

c. 1 ft inside the harbor for 5 ft incident wave conditions.

2 The Model

Design of Model

The Burns Harbor model (Figure 4) was constructed to an undistorted scale of 1:75, model to prototype. Scale selection was based on the following factors:

a. Depth of water required in the model to prevent excessive bottom friction.

b. Absolute size of model waves.

c. Available shelter dimensions and area required for model construction.

d. Efficiency of model operation.

e. Available wave-generating and wave measuring equipment.

f. Model construction costs.

A geometrically undistorted model was necessary to ensure accurate reproduction of wave and current patterns. Following selection of the linear scale, the model was designed and operated in accordance with Froude's model law (Stevens, et al. 1942). The scale relations used for design and operation of the model were as follows:

Characteristic	Dimension[1]	Model to Prototype Scale Relations
Length	L	L_r = 1:75
Area	L^2	$A_r = L_r^2$ = 1:5, 625
Volume	L^3	$V_r = L_r^3$ = 1:421, 875
Time	T	$T_r = L_r^{1/2}$ = 1:8.66
Velocity	L/T	$V_r = L_r^{1/2}$ = 1:8.66

[1] Dimensions are in terms of length (L) and time (T).

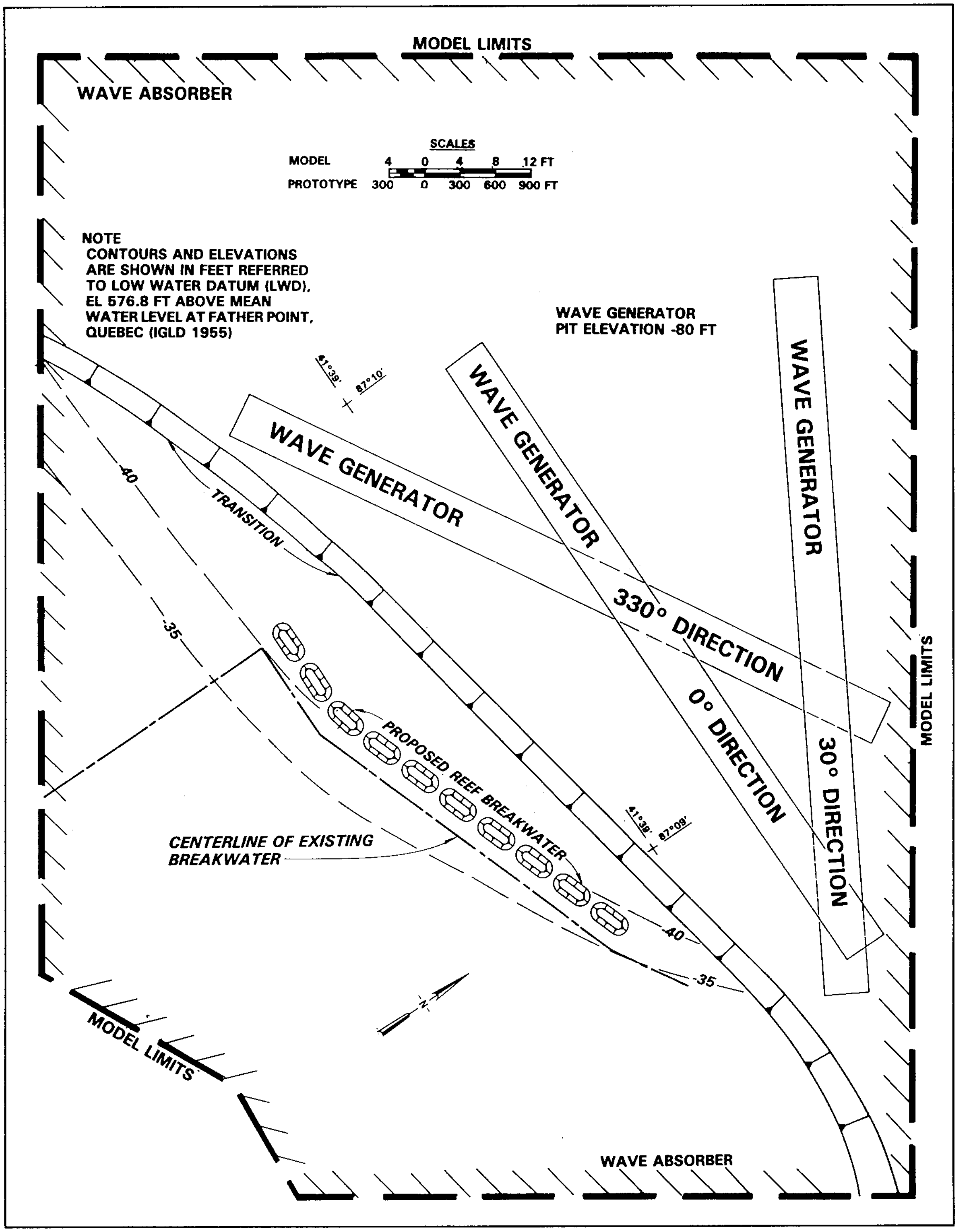

Figure 4. Model layout

Most of the existing breakwater at Burns Harbor, as well as the proposed reef breakwaters, are rubble-mound structures. Experience and experimental research have shown that considerable wave energy passes through the interstices of this type structure; thus, the transmission and absorption of wave energy became a matter of concern in design of the 1:75 scale model. In small-scale hydraulic models, rubble-mound structures reflect relatively more and absorb, or dissipate, relatively less wave energy than geometrically similar prototype structures (Le Méhauté 1965). Also, the transmission of wave energy through a rubble-mound structure is relatively less for the small scale model than for the prototype. Consequently, some adjustment in small-scale model rubble-mound structures is needed to ensure satisfactory reproduction of wave reflection and wave-transmission characteristics. From previous investigations (Dai and Jackson 1966, Brasfeild and Ball 1967) at WES, it was determined that a close approximation of the correct wave-energy transmission characteristics could be obtained by increasing the size of the rock used in the 1:75 scale model to approximately one and one-half times that required for geometric similarity. In constructing the rubble-mound structures in the Burns Harbor model, rock sizes were computed linearly by scale, then multiplied by 1.5 to determine the actual sizes to be used in the model.

The Model and Appurtenances

Due to funding constraints and high costs of construction, an existing model with gentle sloping contours closely resembling offshore bathymetry in the vicinity of Burns Harbor was used during testing. Adjustments to existing model contours and water levels were made to locate the proposed Burns Harbor reef breakwater in water depths ranging from 39 to 41 ft.

The model bathymetry extended to an offshore depth of -46 ft with a sloping transition to the wave generator pit el of -80 ft. The total area reproduced in the model was approximately 12,000 sq ft, representing about 3.7 square miles in the prototype. Vertical control for model construction was based on LWD, horizontal control was referenced to a local prototype grid system. A general view of the model is shown in Figure 5.

Model waves were generated by an 80-ft-long unidirectional spectral, electrohydraulic wave generator with a trapezoidal-shaped, vertical-motion plunger. The vertical motion of the plunger was controlled by a computer-generated command signal, and the movement of the plunger caused a displacement of water which generated the required test waves. Retractable casters mounted on the wave generator enabled it to be positioned to generate waves from required directions.

An Automated Data Acquisition and Control System, designed and constructed at WES (Figure 6), was used to generate and transmit control signals, monitor wave generator feedback, and secure and analyze wave data at selected locations in the model. Through the use of a microvax computer, the electrical output of capacitance-type wave gauges, which varied with the change in water-surface elevation with respect to time, was recorded on magnetic disks. These data were then analyzed to obtain the parametric wave data.

Figure 5. General view of model

A 2-ft (horizontal) solid layer of fiber wave absorber was placed around the inside perimeter of the model to dampen wave energy that might otherwise be reflected from the model walls. In addition, guide vanes were placed along the wave generator sides in the flat pit area to ensure proper formation of the wave train incident to the model contours.

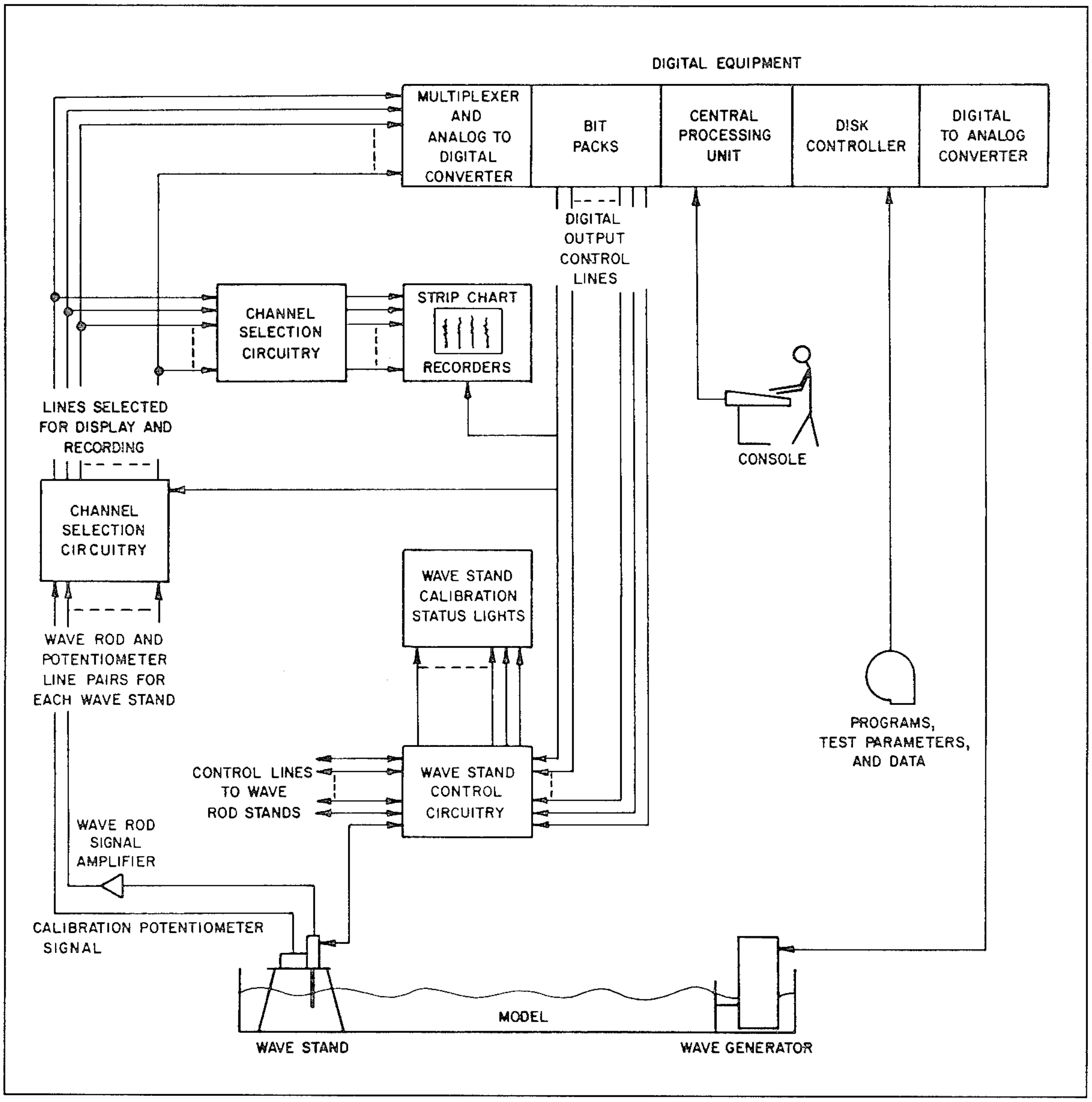

Figure 6. Automated Data Acquisition and Control System

3 Test Conditions and Procedures

Selection of Test Conditions

Still-water level

Still-water levels (SWL's) for harbor wave action models are selected so that various wave-induced phenomena that are dependent on water depths are accurately reproduced in the model. These phenomena include refraction of waves in the project area, overtopping of harbor structures by waves, reflection of wave energy from various structures, and transmission of wave energy through porous structures.

Water levels on the Great Lakes vary from year to year and month to month. Since 1860, continuous records of water levels on the Great Lakes have been recorded and maintained. Typical seasonal variations of the Lakes consist of high stages in the summer months and low stages in the winter months. For Lake Michigan, the higher levels usually occur in July and lower levels in February.

Seasonal and longer variations in the levels of the Great Lakes are caused by variations in precipitation and other factors that affect the actual quantities of water in the lakes. Wind, tides, and seiches are relatively short-period fluctuations caused by the tractive force of wind blowing over the water surface and by differential barometric pressures and are superimposed on the longer period variations in the lake level. Large short-period rises in local water levels are associated with the most severe storms, which generally occur in the winter when the lake level is usually low; thus the probability that a high lake level and a large wind tide or seiche will occur simultaneously is relatively small.

An SWL of 4.0 ft LWD was selected by NCC for use during model testing. This value represented an average SWL for the project area during major storm events.

Factors Influencing Selection of Test Wave Characteristics

In planning the testing program for a model investigation of harbor wave-action problems, it is necessary to select heights, periods, and directions for test waves that allow for realistic tests of the proposed improvement plans and an accurate evaluation of the various proposals.

Surface-wind waves are generated primarily by the interactions between tangential stresses of wind flowing over water, resonance between the water surface and atmospheric turbulence, and interactions between individual wave components. The height and period of the maximum significant wave that can be generated by a given storm depend on wind speed, length of time that wind of a given speed continues to blow, and distance over water (fetch) which the wind blows. Selection of test wave conditions entails evaluation of such factors as:

a. Fetch and decay distances (the latter being the distance over which waves travel after leaving the generating area) for various directions from which waves can approach the problem area.

b. Frequency of occurrence and duration of storm winds from the difference directions.

c. Alignment, size, and relative geographic position of the navigation entrance to the harbor.

d. Alignments, lengths, and locations of the various reflecting surfaces inside the harbor.

e. Refraction of waves caused by differentials in depth in the area lakeward of the harbor, which may create either a concentration or a diffusion of wave energy at the site.

Wave Refraction

When waves move into water of gradually decreasing depth, transformations take place in all wave characteristics except wave period (to the first order of approximation). The most important transformations with respect to the selection of test waves characteristics are the changes in wave height and direction of travel due to the phenomenon referred to as wave refraction. The change in wave height and direction may be determined by using the numerical Regional Coastal Processes Wave Transformation Model (RCPWAVE) developed by Ebersole (1985). When the refraction coefficient (K_r) is determined, it is multiplied by the shoaling coefficient (K_s) and gives a conversion factor of deepwater wave heights to shallow-water values. The shoaling coefficient, a function of wave length and water depth, can be obtained from the Shore Protection Manual (1984).

Due to the conceptual nature of the breakwater configuration and limited funds for the Burns Harbor project, a wave refraction analysis was not conducted. Instead, a wide range of wave conditions were tested. Changes in wave height and direction, as a result of refraction, should be covered in the bracket of wave conditions tested. Waves were generated in the -80 ft model pit. From this point, model contours refracted the wave trains to the structures. Critical directions of wave approach were determined by NCC to be 330, 0, and 30 deg.

Selection of Test Waves

Based on prototype wave data obtained at Burns Harbor (McGehee and Moritz, in preparation), NCC selected the following test wave characteristics to be used in the model investigation.

Selected Test Waves

Direction (deg)	Period (sec)	Height, (ft)
330	7.0	3, 5, 9, 12
	9.0	3, 5, 9, 12
	11.6	3, 5, 9, 12, 13, 15
0	7.0	3, 5, 9, 12
	9.0	3, 5, 9, 12, 13, 15, 18, 19.5
	11.6	3, 5, 9, 12, 13, 15, 18, 19.5
30	7.0	3, 5, 9, 12
	9.0	3, 5, 9, 12
	11.6	3, 5, 9, 12

Generally, accurate recorded prototype wave conditions in the area of concern are not available; however, repeated storm damage to the breakwater at Burns Harbor had resulted in a study of the project which included prototype wave measurements lakeward of the existing structures and inside the harbor. Major storm events during 1987 and 1988 were recorded (McGehee and Moritz, in preparation).

An analysis of the 1987 data revealed wave heights in excess of 19 ft with significant wave periods of 11.6 sec; and wave heights of 12 ft associated with wave periods of 7 and 9 sec.

Unidirectional wave spectra were generated for the selected test waves and used throughout the model investigation. Plots of a typical wave spectra are shown in Figure 7. The solid line represents the desired (target) spectra while the dashed line represents the spectra generated by the wave machine. A typical wave train is shown in Figure 8, which depicts water surface elevation (η) versus time. The selected test waves were significant wave heights, the average height of the highest one-third of the waves or H_s. In deepwater H_s is very similar to H_{mo} (energy based wave) where $H_{mo} = 4\ (E)^{1/2}$, and E equals total energy in the spectra which is obtained by integrating the energy density spectra over the frequency range.

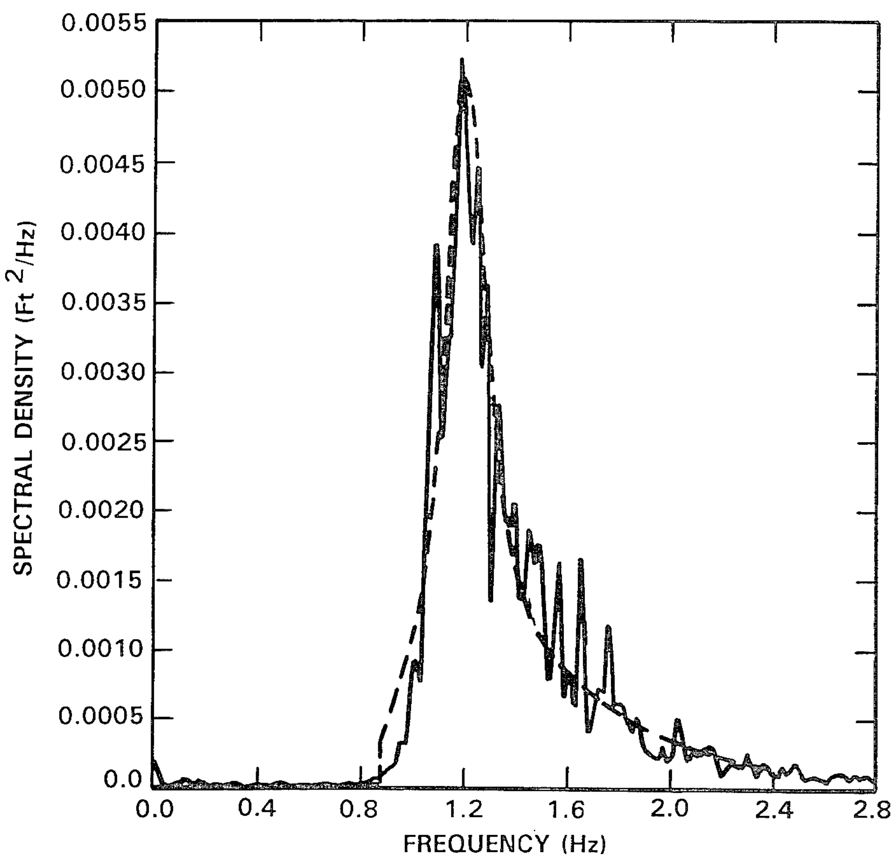

Figure 7. Typical energy density versus frequency plots (model terms) for a wave spectra; 9-sec, 12-ft waves

Analysis of Model Data

Relative merits of the various plans tested were evaluated by:

a. Comparison of wave heights at selected locations in the model.

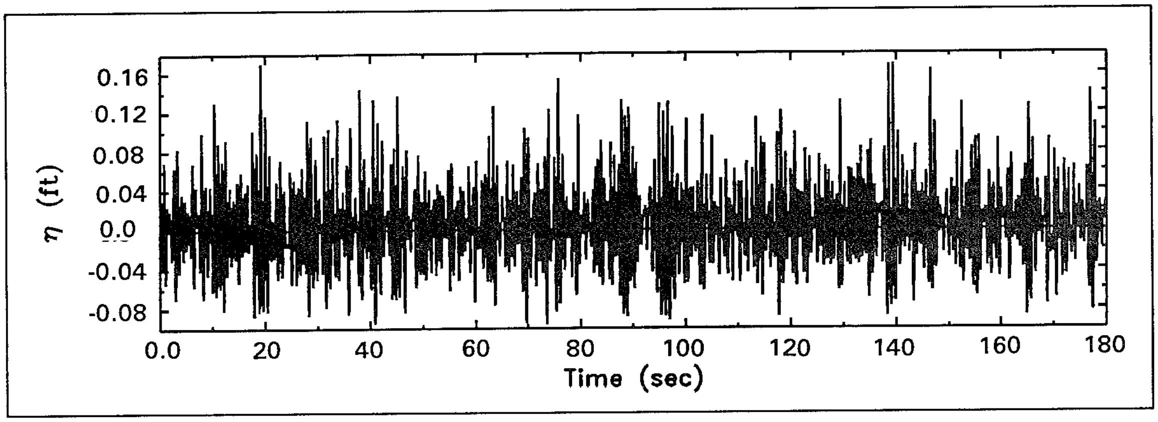

Figure 8. Typical wave train time series, 9-sec, 12-ft test waves

b. Comparison of wave-induced current patterns and magnitudes.

c. Visual observation and wave pattern photographs.

In the wave-height data analysis, the average height of the highest one-third of the waves (H_s), recorded at each gage location was selected. Current magnitudes were obtained by timing the progress of an injected dye tracer relative to a known distance on the model surface.

4 Test and Results

The Tests

Improvement plans

The originally proposed improvement plan consisted of a segmented reef structure located lakeward of and parallel to the existing north breakwater. Variations of the original improvement plan included changes in the length and width of the reef structures, gap widths between the segments, and the connecting of adjacent reef structures.

Preliminary tests were conducted to determine the most efficient location of the reef structure, (distance from the toe of existing breakwater to the toe of proposed breakwater). Distances of 75 ft, (the most efficient distance as defined by Carver and Wright (in preparation), 150 ft and 250 ft were tested for representative test wave conditions. To prevent contamination of wave data by reflected wave energy, the existing breakwater was not constructed in the model for the transmitted wave energy test. In addition, wave pattern photographs were obtained for representative test waves. After preliminary testing to optimize the reef breakwater configuration, wave patterns and current patterns and magnitudes were obtained with the existing breakwater installed. Brief descriptions of the various improvement plans are presented in the following subparagraphs; dimensional details are shown in Plates 1-6.

a. Plan 1 (Plate 1) consisted of the original improvement plan. Ten separate reef structures with crest elevations of -20 ft and crest widths of 75 ft with 1V:1.5H side slopes were placed in an area representative of the Lake Michigan contours lakeward of and parallel to the existing north breakwater. The reef structure consisted of 1 to 5-ton angular armor stone with a 12-ft thickness and 100 to 2,000-lb underlayer stone (6-ft-thick) placed on an approximate 5-ft layer of 1 to 100-lb bedding stone. Structures originated at a point that represented the north end of the west breakwater and extended eastward for a total length of 3,950 ft. Each segment was 250 ft long, measured from head to head, and 350 ft long, measured from toe to toe. Distances between the toes of the segmented structures were 50 ft.

b. Plan 2 (Plate 2) consisted of the elements of Plan 1 but each reef segment length was increased 25 ft on the east end resulting in 275-ft-long structures (measured head to head). Distances between the toes of the segmented structures were reduced to 25 ft.

c. Plan 3 (Plate 3) entailed the elements of Plan 2 except the openings between the second and third, and third and fourth segments (measured from west) were completely closed.

d. Plan 4 (Plate 4) included of the elements of Plan 3 except the opening between the first and second segment (measured from west) was completely closed.

e. Plan 5 (Plate 4) consisted of the elements of Plan 4 but the crest widths of the reef breakwaters were reduced from 75 to 70 ft.

f. Plan 6 (Plate 5) consisted of the elements of Plan 5 but the existing harbor breakwater was installed.

g. Plan 7 (Plate 6) entailed the existing breakwater of Plan 6 with the segmented reef structure removed. This plan represented existing conditions.

Wave height tests

Wave height tests were conducted for the various reef breakwater plans without the existing breakwater (Plans 1 through 5) for test waves for one or more of the selected test directions. Tests involving most of the plans were limited to the most critical incident wave direction (i.e., 0 deg). The optimum improvement plan was tested comprehensively for waves from all three incident wave directions. Wave gauge locations for the improvement plans are shown in Plates 1 through 4.

Wave patterns and current patterns and magnitude

Wave patterns and/or current patterns and magnitudes were obtained for the selected test plans. Wave pattern photographs were obtained for all improvement plans for representative incident waves from north. In addition, wave patterns for the optimum plan (Plan 5) were secured for representative incident waves from 330 and 30 deg. Current patterns and magnitudes were determined at selected locations by timing the progress of an injected dye tracer relative to a graduated scale placed on the model floor. These tests were conducted with the existing breakwater and optimum reef breakwater plan in place (Plan 6) and for the existing breakwater with the reef breakwater removed (Plan 7).

Test Results

In evaluating test results, the relative merits of the various improvement plans were based on an analysis of measured wave heights in the lee of the reef breakwater, current patterns and magnitudes, and visual observations. Model wave heights (significant wave height or H_s) were tabulated to show measured values at selected locations. Wave-induced current patterns and magnitudes were superimposed on photographs for the plan and wave condition tested. The north test direction, being the predominant angle of wave attack for storm waves, was used for all preliminary testing.

Test plans

Wave height tests for Plans 1 through 3 were conducted with 39 wave gauge locations. Gauges 1 through 13 were located 75 ft leeward of the shoreward toe of the proposed reef breakwater. Gauges 14 through 26 were 150 ft leeward of the toe of proposed reef breakwater, and gauges 27 through 39 were 250 ft leeward from the toe of the proposed structure. By comparing wave heights at various distances from the proposed reef structure, three dimensional wave effects could be effectively compared to determine the most suitable location of the reef breakwater (relative to the existing breakwater). The wave gauges were placed behind the center of each proposed reef breakwater segment and each gap between reef breakwater segments.

Results of wave height tests for Plan 1 are presented in Table 1 for test waves from 0 deg. Wave heights[1] ranged from 14.2 (gauge 9) to 16.4 ft (gauges 1 and 3) for 11.6 sec, 19.5-ft test waves at a distance 75 ft leeward of the shoreward toe of the reef. For the 150-ft distance, wave heights ranged from 14.1 ft (gauge 22) to 16.4 ft (gauge 14) for 11.6 sec, 19.5-ft test waves and the 250-ft distance location from the toe of the reef yielded wave heights ranging from 13.5 ft (gauge 35) to 16.4 ft (gauge 36). With the 75-, 150-, and 250-ft distances, wave heights exceeded the established 15-ft wave-height criteria at nine, nine, and eight wave gauge locations, respectively. Average wave heights in the lee of the Plan 1 reef breakwater were 15.4, 15.4, and 15.2 ft, respectively, for the 75-, 150-, and 250-ft distances. Typical wave patterns for Plan 1 are shown in Photos 1 through 6.

Wave heights obtained for Plan 2 are presented in Table 2 for test waves from 0 deg. For 11.6-sec, 19.5-ft incident waves, wave heights ranged from 14.2 (gauges 5 and 9) to 16.1 ft (gauges 1 and 3) at a distance 75 ft leeward of the shoreward toe of the reef; 13.9 (gauge 22) to 16.2 ft (gauge 14) at the 150-ft distance; and 13.1 (gauge 35) to 16.0 ft (gauge 27) at the 250-ft distance. With the 75-, 150-, and 250-ft distances, wave heights exceeded the established 15.0 ft wave height criterion at four, six, and six gauge locations,

[1] Refers to significant wave heights throughout report.

respectively. Average wave heights in the lee of the Plan 2 reef breakwater were 15.0, 15.0, and 14.7 ft, respectively, for the 75-, 150-, and 250-ft distances for the 11.6-sec, 19.5-ft incident wave conditions. Wave heights at the western gauge locations, where the reef structure was angled, exceeded the criterion by greater values than at the other gauge locations. The 75-ft distance resulted in wave heights within the criterion for gauges 5 through 13. Typical wave patterns for Plan 2 are shown in Photos 7 through 12.

Wave height data collected for Plan 3 for test waves from 0 deg are presented in Table 3. For 11.6-sec, 19.5-ft test waves, wave heights ranged from 13.9 (gauge 9) to 15.1 ft (gauge 10) at the distance 75 ft leeward of the shoreward toe of the reef, 13.3 (gauge 22) to 15.4 ft (gauge 23) for the distance 150 ft leeward of the shoreward reef toe, and 13.1 (gauge 35) to 15.7 ft (gauges 36 and 38) at the distance 250 ft leeward from the shoreward toe of the reef breakwater. With the 75-, 150-, and 250-ft distances, significant wave heights exceeded the established wave height criterion at one, two, and three gauge locations, respectively. Average wave heights in the lee of the Plan 3 breakwater were 14.6, 14.5, and 14.5 ft, respectively, for the 75-, 150-, and 250-ft distances for the 19.5-ft incident waves. Plan 3 test results indicated that by closing of the openings that were more normal to the predominant incoming 0-deg (north) waves, wave heights were reduced in the lee of that portion of the reef breakwater. Typical wave patterns for Plan 3 are shown in Photos 13 through 18.

A comparison of wave height data obtained for Plans 1 through 3 for the 75-, 150-, and 250-ft distances shoreward of the reef toe are presented graphically for 19.5-ft waves in Plates 7 through 9. At each distance, the data indicate that Plan 3 is the best of the plans relative to meeting the established wave height criterion. The data also reveal that the 75-ft distance leeward of the reef toe meets the criterion more often that the other distances. Also, the 75-ft distance would be located in more shallow water depths than the 150- and 250-ft distances, and would require less volume of stone. Therefore, considering wave protection provided and costs, the 75-ft distance was selected as optimal and used for additional testing.

An additional wave gauge (gauge 1A, Plate 3) was placed 75 ft leeward of the first and second segments of the structure for Plan 3. Wave height tests for 11.6-sec, 19.5-ft test waves indicated wave heights of 16.8 ft at this location (1.8 ft in excess of the criterion). By closing the opening (Plan 4), wave heights were reduced to 14.4 ft. A comparison of wave heights obtained at gauge 1A for Plans 3 and 4 for all incident wave conditions tested is shown in the following tabulation.

Test Waves from 0 deg		Plan 3	Plan 4
Period, sec	Height, ft	Wave Height, ft	Wave Height, ft
7.0	12.1	10.6	9.8
9.0	12.0	10.8	10.0
11.6	12.0	10.8	10.1
11.6	15.1	13.6	12.0
11.6	18.0	15.6	13.5
11.6	19.5	16.8	14.4

Wave height test results for Plan 4 at all gauge locations are presented in Table 4 for test waves from 0 deg. Wave heights ranged from 14.0 ft (gauge 9) to 15.1 ft (gauge 10) for 11.6-sec, 19.5-ft test waves. The established 15.0-ft wave height criterion was exceeded by only 0.1 ft at one gauge location. Average wave heights were 14.6 ft behind the structure. Typical wave patterns for Plan 4 are shown in Photos 19 through 24.

An analysis of stone volumes for the Plan 4 reef breakwater by NCC indicated that the plan's costs slightly exceeded calculated benefits. The 75-ft crest width was, therefore, reduced to 70 ft (Plan 5) in an effort to reduce costs. Wave heights were for Plans 4 and 5 for 11.6-sec, 19.5-ft test waves from 0 deg were plotted for comparison (Plate 10). For Plan 5, wave heights ranged from 14.0 (gauge 7) to 15.1 ft (gauges 3 and 10) with the established wave height criterion exceeded by 0.1 ft at two gauge locations. Average wave heights were 14.7 ft in the lee of the reef breakwater. Based on damage curves (structure damage versus incident wave height; Carver, Dubose, and Wright, 1993), 15.1-ft incident waves should result in damages of only about one quarter of one percent, which was considered acceptable by NCC.

Comprehensive wave height test results for Plan 5 are presented in Tables 5 through 7 for test waves from the 0-, 30-, and 330-deg directions, respectively. Wave transmission coefficients, available for the existing breakwater from two-dimensional model tests (Carver and Wright, in preparation), were applied to average wave heights obtained in the lee of the reef breakwater. This method was used to determine anticipated wave heights in the existing harbor for operational (5- and 13-ft incident waves) wave conditions. The analysis revealed that 7- and 9-sec, 5-ft incident waves from all three directions would result in wave heights in the existing harbor within the established 1.0-ft wave height criterion. However, calculations for the 11.6-sec, 5-ft waves resulted in wave heights of 1.2 ft in the existing harbor for test waves from 30 and 330 deg, and 1.3 ft for test waves from 0 deg. The recurrence of 11.6-sec, 5-ft waves at the site are not very common and slight exceedence of the criterion for these conditions was considered acceptable by NCC. For 11.6-sec, 13-ft incident waves from 0 deg, calculated wave heights in the existing harbor were within the established 3.0-ft wave height criterion. Calculations for test waves from

330 deg, however, revealed wave heights in the harbor of 3.1 ft, or 0.1 ft above the criterion. Calculations using maximum waves generated from 30 deg (12-ft waves) resulted in wave heights within the established criterion. Typical wave patterns obtained for Plan 5 for representative test waves from the various directions are shown in Photos 25 through 40.

Wave-induced current patterns and magnitudes secured for Plan 6 are shown in Photos 41 through 50. For test waves from 330 deg, currents generally moved from east to west for 7-sec, 5-ft waves, and from west to east for 9-sec, 9-ft and 11.6-sec, 15-ft waves. Current movement was from east to west for all test waves from the 0- and 30-deg directions. In general, velocities between the reef breakwater and the existing breakwater were slightly higher than those lakeward of the reef structure. Maximum velocities obtained were 0.6, 1.8, and 1.5 fps for the 330-, 0-, and 30-deg directions, respectively. Where current magnitudes are not shown in the photos, values were less than 1 fps. Typical wave patterns for Plan 6 also are shown in Photos 41 through 50.

Wave-induced current patterns and magnitudes obtained for Plan 7 are presented in Photos 51 through 60. For test waves from 330 deg, currents moved from east to west at some locations and from west to east at others. Test waves from 0 and 30 deg resulted, in general, in current movement from east to west. Maximum velocities obtained lakeward of the existing breakwater were 0.7, 2.1, and 0.7 fps for the 330-, 0-, and 30-deg directions, respectively. Typical wave patterns secured for Plan 7 are also shown in Photos 51 through 60.

Discussion of test results

The originally proposed reef breakwater plan (Plan 1) resulted in excessive wave conditions on the leeward side of the structure in several locations. For 11.6-sec, 19.5-ft incident waves from 0 deg, wave heights exceeded the established 15.0-ft wave height criterion at over half the gauge locations in the lee of the reef breakwaters, regardless of distance from the structure (75-, 150-, and 250-ft).

A 25-ft increase in the length of each reef segment (Plan 2) improved wave conditions in the lee of the structure, however, wave heights behind the curved portion of the reef breakwaters were in excess of the 15-ft wave height criterion. Closing of the westernmost three openings in the curved portion of the reef breakwaters, in conjunction with the 25-ft Plan 2 reef extensions (Plan 4), resulted in wave heights in the lee of the reef breakwater within the 15.0-ft criterion, with the exception of one gauge location which exceeded the criterion by 0.1 ft, at the 75-ft distance.

Of the three distances (75-, 150-, and 250-ft) tested, which represented spacing between the proposed shoreward toe of the reef breakwaters and the lakeward toe of the existing breakwater, the 75-ft distance was considered optimum. This distance provided the greatest wave protection and will require less stone to construct than the other distances tested.

By reducing the 75-ft-wide crest of the Plan 4 reef breakwater configuration to 70 ft in width (Plan 5), wave heights in the lee of the structure will exceed the 15.0-ft criterion by only 0.1 ft at two gauge locations for 11.6-sec, 19.5-ft incident wave conditions from 0 deg. Average wave heights in the lee of the structure also will increase by only 0.1 ft for these conditions. Since anticipated structure damages for 15.1-ft waves are considered to be acceptable by NCC and reduced stone volumes will reduce construction costs significantly, the 70-ft-wide Plan 5 reef breakwater configuration was considered optimum for 11.6-sec, 19.5-ft incident wave conditions from 0 deg. Wave heights expected in the existing harbor (calculated by application of wave transmission coefficients obtained from two-dimensional model tests for the existing breakwater; Carver and Wright, in preparation) for 13-ft incident waves will result in the 3.0-ft wave height criterion being exceeded by 0.1 ft for one-wave direction (330 deg). For 5-ft incident wave conditions with 7- and 9-sec periods, wave heights expected in the existing harbor will meet the 1.0-ft wave height criterion from all three test directions. However, for 5-ft incident waves with a 11.6-sec period, expected wave heights in the existing harbor will exceed the criterion by 0.2 to 0.3 ft, depending upon direction of wave approach. Since 7- and 9-sec, 5-ft waves commonly occur, and 11.6-sec, 5-ft waves occur infrequently at the site, NCC considered the test plan (Plan 5) acceptable. It appeared not to be economically justifiable to construct a plan that would reduce wave heights by 0.1 to 0.3 ft in the existing harbor for 13- and 5-ft incident waves, respectively, considering the frequency of occurrence of the conditions that exceeded the criteria.

Examination of wave-induced current patterns and magnitudes indicated similar conditions for existing conditions and the optimum reef breakwater plan lakeward of the existing breakwater. Maximum velocities were 2.1 fps for existing conditions and 1.8 fps for the reef breakwater plan. The installation of the reef structure should, therefore, have no adverse impact (scour, sedimentation, etc.) due to current effects.

5 Conclusions

Based on results of the coastal hydraulic model investigation reported herein, it is concluded that:

a. The originally proposed reef breakwater plan (Plan 1) will result in excessive wave conditions (in excess of the established 15.0-ft wave height criterion) for 11.6-sec, 19.5-ft incident waves from 0 deg on the leeward side of the proposed reef breakwaters, regardless of its distance from the existing structure.

b. The shoreward toe of the reef breakwater should be located 75-ft lakeward of the existing breakwater's lakeward toe. This distance provides greater wave protection, with less stone volumes, than the other distances tested.

c. Of the reef breakwater configurations tested with the 75-ft crest widths, Plan 4 (275-ft-long reef segments with three westernmost openings closed) was acceptable considering wave heights obtained in the lee of the structure for 11.6-sec, 19.5-ft incident waves from 0 deg.

d. The 75-ft-wide crest of the Plan 4 reef breakwater configuration can be reduced to 70 ft in width (Plan 5) and still provide acceptable wave protection in the lee of the structure for 11.6-sec, 19.5-ft incident wave conditions from 0 deg.

e. The Plan 5 reef configuration (275-ft-long reef segments with three westernmost openings closed and 70-ft crest widths) will result in acceptable wave heights in the existing harbor for 7- to 11.6-sec, 5-ft and 11.6-sec, 13-ft incident wave conditions.

f. Considering wave protection provided in the lee of the reef breakwater and in the existing harbor for various incident wave conditions versus volume of construction materials required, the Plan 4 reef breakwater configuration was selected as optimum, based on the plans tested.

g. The optimum reef breakwater configuration, in conjunction with the existing breakwater (Plan 6), will have no adverse impacts on wave-induced current patterns and/or magnitudes lakeward of the existing structure.

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Table 1
Wave Heights for Plan 1 for Test Waves from 0 Degrees, SWL = +4.0 ft

		Test Wave					
Period (sec)		7.0	9.0	11.6	11.6	11.6	11.6
Height (ft)		12.0	12.0	12.0	15.0	18.0	19.5
	Gauge	Wave Height, ft, at Indicated Gauge Location					
	1	11.7	11.4	10.9	14.9	15.8	16.4
	2	11.1	11.3	12.3	14.3	15.4	16.0
	3	10.3	10.1	10.6	12.3	14.9	16.4
	4	10.4	10.3	10.7	12.8	14.5	15.6
	5	9.9	9.7	10.3	11.7	13.9	14.5
	6	10.6	10.6	11.1	13.5	14.9	15.4
	7	10.0	9.7	10.4	12.1	13.9	14.6
	8	10.5	10.6	11.0	13.0	14.5	15.2
	9	10.3	9.9	10.3	12.4	13.5	14.2
	10	10.9	10.6	11.5	13.3	15.0	15.5
	11	10.1	10.0	10.5	12.6	14.3	15.3
	12	10.1	10.2	10.6	12.6	14.1	15.0
	13	10.0	9.8	10.6	13.0	14.9	15.5
	14	11.4	11.0	11.6	15.4	15.9	16.4

(Sheet 1 of 3)

Table 1 (Continued)

		Test Wave					
Period (sec)		7.0	9.0	11.6	11.6	11.6	11.6
Height (ft)		12.0	12.0	12.0	15.0	18.0	19.5
	Gauge	Wave Height, ft, at Indicated Gauge Location					
	15	11.6	12.0	12.0	13.9	15.2	15.7
	16	10.7	10.7	10.6	12.2	14.6	15.9
	17	10.4	10.0	10.9	12.8	14.5	15.8
	18	10.2	10.2	10.1	11.6	13.9	14.4
	19	10.6	10.0	10.9	13.3	15.0	15.8
	20	10.4	10.7	10.0	12.2	13.6	14.7
	21	10.3	10.3	11.0	13.1	14.6	15.3
	22	10.8	10.9	10.7	12.4	13.4	14.1
	23	10.9	10.5	11.4	13.6	15.3	16.1
	24	10.6	10.7	10.7	12.5	14.0	15.0
	25	9.9	10.0	10.3	12.4	14.4	15.3
	26	10.7	10.6	10.8	13.2	14.7	15.4
	27	11.6	11.2	12.1	15.5	15.6	16.2
	28	11.7	11.2	11.3	13.3	14.6	15.4
	29	10.3	10.8	10.7	12.1	14.4	15.3

(Sheet 2 of 3)

Table 1 (Concluded)

		Test Wave					
Period (sec)		7.0	9.0	11.6	11.6	11.6	11.6
Height (ft)		12.0	12.0	12.0	15.0	18.0	19.5
	Gauge	Wave Height, ft, at Indicated Gauge Location					
	30	11.0	9.9	11.0	13.1	14.9	16.3
	31	10.3	10.3	10.0	11.3	13.4	14.4
	32	10.6	10.0	10.9	13.5	15.3	15.9
	33	10.6	10.4	9.8	11.6	13.4	14.4
	34	10.7	10.4	11.3	13.1	14.4	15.9
	35	10.8	10.7	10.3	11.8	12.9	13.5
	36	11.1	10.5	11.8	14.1	15.7	16.4
	37	10.8	10.8	10.1	11.4	13.0	14.0
	38	9.7	9.4	10.3	12.9	14.9	16.1
	39	11.3	11.2	10.7	12.3	13.4	14.2

(Sheet 3 of 3)

Table 2
Wave Heights for Plan 2 for Test Waves from 0 Degrees, SWL = +4.0 ft

		Test Wave					
Period (sec)		7.0	9.0	11.6	11.6	11.6	11.6
Height (ft)		12.0	12.0	12.0	15.0	18.0	19.5
	Gauge	Wave Height, ft, at Indicated Gauge Location					
	1	11.9	11.8	11.1	14.8	15.8	16.1
	2	10.8	10.8	12.0	14.0	15.3	15.7
	3	10.2	9.8	10.2	12.1	14.4	16.1
	4	9.7	9.9	10.7	12.5	14.0	15.2
	5	10.1	9.5	10.1	11.8	13.9	14.2
	6	10.0	10.2	11.0	13.2	14.5	14.9
	7	10.7	9.7	10.0	11.9	13.6	14.5
	8	10.4	10.3	10.9	12.7	14.0	14.7
	9	10.2	9.8	10.3	12.4	13.4	14.2
	10	10.5	10.2	11.3	13.1	14.3	14.9
	11	9.8	9.6	10.1	12.0	13.8	14.7
	12	9.8	10.0	10.4	12.5	13.7	14.6
	13	9.9	9.7	10.2	12.8	14.3	15.0
	14	11.4	10.9	11.3	15.1	15.1	16.2

(Sheet 1 of 3)

Table 2 (Continued)

		Test Wave					
Period (sec)		7.0	9.0	11.6	11.6	11.6	11.6
Height (ft)		12.0	12.0	12.0	15.0	18.0	19.5
	Gauge	Wave Height, ft, at Indicated Gauge Location					
	15	11.1	11.4	11.9	14.0	15.2	15.9
	16	10.0	10.1	10.4	12.1	14.6	14.5
	17	10.4	10.1	10.7	12.7	14.4	15.2
	18	10.3	9.9	10.1	11.8	14.4	14.5
	19	10.3	10.2	11.0	13.0	14.6	15.3
	20	10.2	9.9	9.8	12.0	13.6	14.6
	21	10.2	10.3	10.9	12.9	14.0	14.8
	22	10.6	10.3	10.5	12.1	13.3	13.9
	23	10.5	10.5	11.4	13.3	15.1	15.7
	24	10.6	10.3	10.3	11.8	13.3	14.3
	25	9.5	9.9	10.2	12.3	14.2	15.3
	26	10.4	10.1	10.5	12.7	14.2	14.7
	27	11.0	10.9	12.0	14.8	14.9	16.0
	28	11.4	10.9	11.2	12.9	14.7	15.0
	29	10.1	10.5	10.1	11.7	14.1	15.2

(Sheet 2 of 3)

Table 2 (Concluded)

		Test Wave					
Period (sec)		7.0	9.0	11.6	11.6	11.6	11.6
Height (ft)		12.0	12.0	12.0	15.0	18.0	19.5
	Gauge	Wave Height, ft, at Indicated Gauge Location					
	30	10.8	9.9	10.7	12.8	14.3	15.2
	31	9.9	9.9	9.8	11.2	13.5	14.6
	32	10.6	10.0	10.9	13.1	14.6	15.5
	33	10.3	10.2	9.6	11.3	13.2	14.0
	34	10.6	10.0	10.7	12.7	14.0	15.0
	35	10.0	10.3	10.1	11.5	12.5	13.1
	36	11.0	10.6	11.4	13.5	15.3	15.7
	37	10.1	9.8	9.6	10.9	12.5	13.5
	38	9.8	9.8	10.2	12.7	14.4	15.5
	39	10.4	10.3	10.4	11.6	13.0	13.4

(Sheet 3 of 3)

Table 3
Wave Heights for Plan 3 for Test Waves from 0 Degrees, SWL = +4.0 ft

		Test Wave					
Period (sec)		7.0	9.0	11.6	11.6	11.6	11.6
Height (ft)		12.0	12.0	12.0	15.0	18.0	19.5
	Gauge	**Wave Height, ft, at Indicated Gauge Location**					
	1	10.5	10.8	10.8	13.3	14.3	14.9
	2	10.7	10.5	10.9	13.4	14.5	14.8
	3	9.8	9.4	10.4	12.4	13.8	14.9
	4	10.5	10.3	10.8	12.7	13.9	14.6
	5	9.8	9.5	10.1	12.1	14.1	14.4
	6	10.1	10.0	10.9	13.1	14.3	14.8
	7	9.8	9.6	10.0	12.1	13.3	14.6
	8	10.2	10.2	10.7	12.7	13.8	14.4
	9	10.4	9.9	10.2	12.2	13.1	13.9
	10	10.5	10.3	11.4	13.3	14.5	15.1
	11	9.8	9.7	10.1	12.0	13.4	14.3
	12	9.9	10.0	10.5	12.6	13.5	14.6

(Sheet 1 of 3)

Table 3 (Continued)

		Test Wave					
Period (sec)		7.0	9.0	11.6	11.6	11.6	11.6
Height (ft)		12.0	12.0	12.0	15.0	18.0	19.5
	Gauge	Wave Height, ft, at Indicated Gauge Location					
	13	10.1	9.6	10.5	12.8	14.4	14.9
	14	10.4	10.6	10.8	13.1	14.4	14.9
	15	10.3	10.5	10.6	12.4	14.0	14.8
	16	10.3	10.1	10.4	12.1	14.2	15.1
	17	10.4	10.3	10.3	12.3	13.7	14.3
	18	9.8	9.5	9.7	11.3	13.3	14.1
	19	10.7	10.4	10.7	12.6	14.3	14.7
	20	9.9	10.0	9.6	11.5	13.3	14.3
	21	10.1	10.2	10.6	12.4	13.6	14.5
	22	10.3	10.2	10.1	11.7	12.8	13.3
	23	10.9	10.7	11.1	13.0	14.8	15.4
	24	10.3	9.8	9.9	11.5	12.8	14.1
	25	9.6	10.1	10.1	12.0	13.8	14.7
	26	10.3	10.2	10.2	12.5	13.8	14.4
	27	10.6	10.1	10.8	12.7	13.9	14.5

(Sheet 2 of 3)

Table 3 (Concluded)

		Test Wave					
Period (sec)		7.0	9.0	11.6	11.6	11.6	11.6
Height (ft)		12.0	12.0	12.0	15.0	18.0	19.5
	Gauge	Wave Height, ft, at Indicated Gauge Location					
	28	10.2	10.1	10.5	12.4	13.7	14.6
	29	10.0	10.2	10.3	12.1	14.3	14.8
	30	10.7	9.9	10.3	12.4	13.8	14.6
	31	9.7	9.7	9.9	11.1	13.6	14.2
	32	10.7	10.1	10.8	13.1	14.7	15.4
	33	10.2	10.2	9.5	11.3	13.2	14.3
	34	10.3	10.1	10.7	12.7	14.0	14.9
	35	9.8	9.9	10.0	11.4	12.5	13.1
	36	11.1	10.7	11.3	13.4	15.2	15.7
	37	9.8	9.6	9.4	10.8	12.4	13.6
	38	9.8	9.6	10.2	12.5	14.5	15.7
	39	10.4	10.1	10.1	11.8	12.9	13.2

(Sheet 3 of 3)

Table 4
Wave Heights for Plan 4 for Test Waves from 0 Degrees, SWL = +4.0 ft

		Test Wave													
Period (sec)		7.0	7.0	7.0	9.0	9.0	9.0	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6
Height (ft)		5.0	9.0	12.0	5.0	9.0	12.0	3.0	5.0	9.0	12.0	13.0	15.1	18.0	19.5
	Gauge	Wave Height, ft at Indicated Gauge Location													
	1A	4.6	8.0	9.8	4.8	8.0	10.0	2.8	4.4	7.9	10.1	10.4	12.0	13.5	14.4
	1	4.8	8.3	10.2	4.9	8.1	10.5	2.8	4.7	8.4	11.0	11.4	13.7	14.0	14.6
	2	4.7	8.2	10.2	4.7	7.9	10.3	2.8	4.5	8.3	10.8	11.4	13.3	14.8	14.9
	3	4.5	7.7	9.8	4.4	7.6	9.5	2.7	4.4	8.3	10.5	10.8	12.4	14.1	14.8
	4	4.9	8.5	10.6	5.1	8.6	10.4	2.9	4.6	8.6	10.8	11.1	12.7	13.9	14.6
	5	4.0	7.3	10.0	4.0	7.1	9.4	2.5	4.0	7.7	10.3	10.5	12.3	14.7	14.4
	6	4.9	8.1	10.4	4.9	8.4	10.4	2.9	4.8	8.8	11.1	11.5	13.2	14.3	14.9
	7	4.1	7.5	10.0	4.1	7.3	9.7	2.5	4.2	7.8	10.0	10.5	12.3	13.5	14.4
	8	4.6	8.0	10.5	4.8	8.3	10.4	2.8	4.6	8.6	10.9	11.2	12.6	13.9	14.3
	9	4.1	7.5	10.3	4.1	7.3	9.7	2.6	4.2	8.1	10.4	10.8	12.3	13.4	14.0
	10	5.0	8.6	10.8	5.3	8.8	10.5	3.0	5.0	9.1	11.5	11.8	13.5	14.6	15.1
	11	4.0	7.2	9.9	4.0	6.9	9.6	2.6	4.2	7.6	10.1	10.5	12.0	13.4	14.1
	12	4.8	8.2	9.9	4.9	8.2	10.1	2.9	4.7	8.5	10.6	10.9	12.5	13.7	14.6
	13	3.9	7.1	10.1	4.0	7.1	9.7	2.5	4.1	8.1	10.5	10.9	12.8	14.2	14.6

Table 5
Wave Heights for Plan 5 for Test Waves from 0 Degrees, SWL = +4.0 ft

		Test Wave															
Period (sec)		7.0	7.0	7.0	7.0	9.0	9.0	9.0	9.0	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6
Height (ft)		3.0	5.0	9.0	12.0	3.0	5.0	9.0	12.0	3.0	5.0	9.0	12.0	13.0	15.0	18.0	19.5
	Gauge	Wave Height, ft, at Indicated Gauge Location															
	1A	2.9	4.8	8.1	9.9	3.0	5.0	8.1	10.1	2.8	4.7	8.3	10.4	11.0	12.7	14.5	14.9
	1	3.0	5.0	8.1	10.2	3.0	5.0	8.3	10.2	2.8	4.8	8.4	10.8	11.6	13.2	14.4	14.7
	2	2.8	4.8	7.9	10.1	2.8	4.5	8.1	10.2	2.8	4.7	8.3	10.7	11.4	12.8	14.8	14.9
	3	2.5	4.2	7.6	9.6	2.5	4.2	7.6	9.4	2.5	4.4	8.1	10.2	10.8	12.4	14.3	15.1
	4	2.9	4.4	8.0	10.2	3.0	4.9	8.2	10.1	2.7	4.6	8.3	10.4	11.0	12.4	13.9	14.6
	5	2.6	4.0	7.4	10.0	2.5	4.2	7.3	9.4	2.6	4.2	8.0	10.6	11.3	12.9	14.2	14.3
	6	2.7	4.6	7.9	9.8	2.7	4.7	7.9	9.8	2.7	4.4	8.4	10.3	11.2	12.7	14.0	14.5
	7	2.3	4.1	6.9	9.5	2.3	4.0	6.9	9.2	2.4	3.9	7.6	9.7	10.2	11.9	13.2	14.0
	8	2.7	4.5	7.9	10.2	2.7	4.6	8.0	10.1	2.7	4.5	8.3	10.7	11.5	12.8	14.3	14.7
	9	2.5	4.1	7.3	9.6	2.4	4.1	7.3	9.3	2.6	4.2	7.9	9.9	11.0	12.2	13.6	14.5
	10	3.0	4.9	8.1	10.1	3.0	4.9	8.3	10.1	2.9	4.8	8.7	10.8	11.5	12.9	14.4	15.1
	11	2.2	3.7	6.9	9.6	2.2	3.7	6.7	9.5	2.4	4.0	7.5	9.9	10.6	12.1	13.7	14.4
	12	2.8	4.6	7.8	9.8	2.8	4.5	8.0	10.1	2.7	4.4	8.2	10.4	11.1	12.8	14.1	14.9
	13	2.4	3.9	6.8	9.6	2.3	4.0	6.8	9.3	2.4	4.1	7.6	10.1	10.9	12.5	14.1	14.7

Table 6
Wave Heights for Plan 5 for Test Waves from 30 Degrees, SWL = +4.0 ft

		Test Wave											
Period (sec)		7.0	7.0	7.0	7.0	9.0	9.0	9.0	9.0	11.6	11.6	11.6	11.6
Height (ft)		3.0	5.0	9.0	12.0	3.0	5.0	9.0	12.0	3.0	5.0	9.0	12.0
	Gauge	Wave Height, ft, at Indicated Gauge Location											
	1A	2.5	4.2	7.2	9.4	2.5	4.0	7.5	9.3	2.4	4.2	7.8	9.9
	1	2.4	4.1	6.7	9.3	2.4	4.2	7.3	9.3	2.4	4.2	7.6	9.9
	2	2.4	4.1	7.3	9.6	2.5	4.2	7.3	9.8	2.5	4.2	7.6	10.3
	3	2.6	4.1	7.2	9.1	2.5	4.4	7.5	9.3	2.5	4.2	7.9	10.1
	4	2.5	4.0	7.5	9.6	2.4	4.3	7.3	9.7	2.4	4.1	7.6	9.8
	5	3.0	4.5	8.3	10.2	2.8	5.0	8.2	10.4	2.7	4.4	8.1	10.4
	6	2.0	3.4	6.7	8.7	2.1	3.7	6.5	8.5	2.1	3.5	6.7	8.8
	7	2.7	4.3	7.6	10.0	2.7	4.5	7.6	10.2	2.6	4.2	8.1	10.2
	8	2.4	3.8	6.9	9.7	2.4	3.9	7.2	9.8	2.3	3.8	7.4	9.9
	9	2.8	4.7	8.0	10.3	2.7	4.6	8.0	10.5	2.7	4.3	8.4	10.8
	10	2.3	3.8	6.7	9.1	2.1	3.7	6.6	9.1	2.2	3.7	7.1	9.3
	11	2.8	4.6	8.0	10.4	2.6	4.5	7.8	10.4	2.7	4.3	7.6	10.1
	12	2.4	4.1	7.3	9.7	2.4	4.0	7.5	9.5	2.4	3.8	7.0	9.2
	13	2.7	4.5	7.7	9.8	2.9	4.6	7.8	9.6	2.7	4.5	7.7	9.9

Table 7
Wave Heights for Plan 5 for Test Waves from 330 Degrees, SWL = +4.0 ft

		Test Wave													
Period (sec)		7.0	7.0	7.0	7.0	9.0	9.0	9.0	9.0	11.6	11.6	11.6	11.6	11.6	11.6
Height (ft)		3.0	5.0	9.0	12.0	3.0	5.0	9.0	12.0	3.0	5.0	9.0	12.0	13.0	15.0
	Gauge	Wave Height, ft, at Indicated Gauge Location													
	1A	2.7	4.7	8.1	10.3	2.7	4.8	8.1	10.0	2.7	4.6	8.8	11.3	11.9	13.7
	1	2.7	4.5	8.0	9.9	2.6	4.8	7.9	10.0	2.5	4.5	8.2	10.1	10.7	11.9
	2	2.9	4.6	7.9	9.8	2.9	4.9	8.2	10.1	2.8	4.6	8.3	10.5	10.9	12.4
	3	2.7	4.5	7.9	9.9	2.7	4.6	7.9	9.6	2.6	4.3	8.0	10.4	10.9	12.5
	4	2.6	4.3	7.6	9.6	2.6	4.5	7.6	9.5	2.6	4.3	8.0	10.4	11.1	12.6
	5	2.2	3.6	6.8	9.1	2.2	3.9	7.0	9.4	2.2	3.8	6.9	9.1	9.8	11.3
	6	2.8	4.6	8.2	10.2	2.7	4.6	8.0	10.2	2.7	4.4	8.6	11.1	11.9	13.6
	7	2.2	3.7	7.0	9.6	2.2	3.9	7.1	9.7	2.1	3.7	7.2	9.7	10.1	11.8
	8	2.9	4.8	8.3	10.3	2.9	4.9	8.3	10.4	2.8	4.6	8.8	11.4	12.0	13.9
	9	2.1	3.5	6.7	9.2	2.2	3.8	6.9	9.6	2.1	3.6	6.9	9.5	9.8	11.4
	10	2.7	4.5	8.0	10.4	2.7	4.6	8.0	10.3	2.6	4.4	8.6	11.1	11.9	13.3
	11	2.6	4.2	7.5	9.7	2.5	4.4	7.6	9.8	2.5	4.2	7.5	9.8	10.5	12.0
	12	2.7	4.4	7.8	10.2	2.6	4.4	8.0	9.9	2.6	4.3	8.3	10.7	11.6	13.4
	13	2.2	3.8	6.7	9.2	2.3	3.9	7.1	9.4	2.2	3.8	6.8	9.0	9.5	11.1

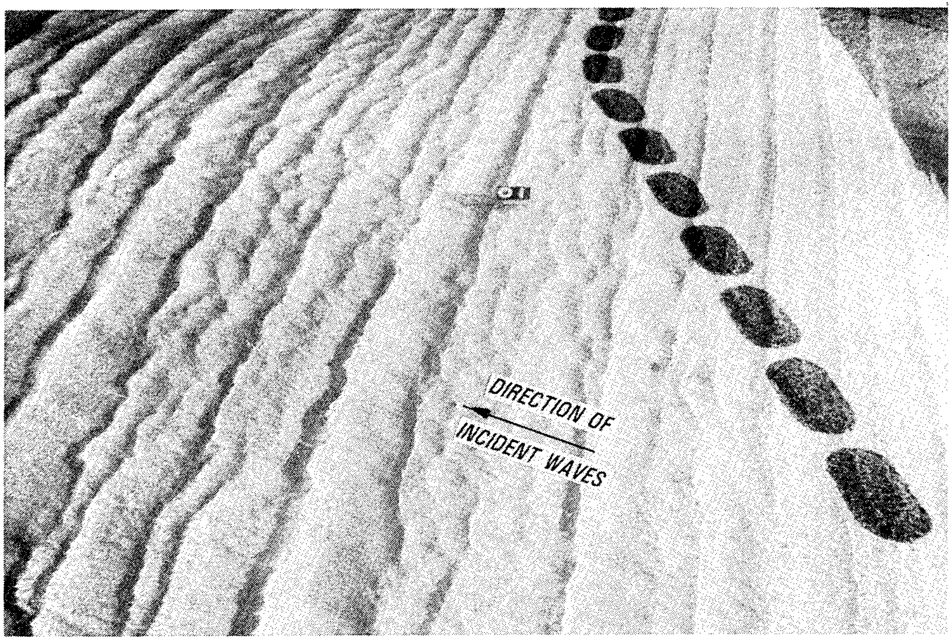


Photo 1. Typical wave patterns for Plan 1; 7-sec, 12-ft waves from 0 deg

Photo 2. Typical wave patterns for Plan 1; 9-sec, 12-ft waves from 0 deg

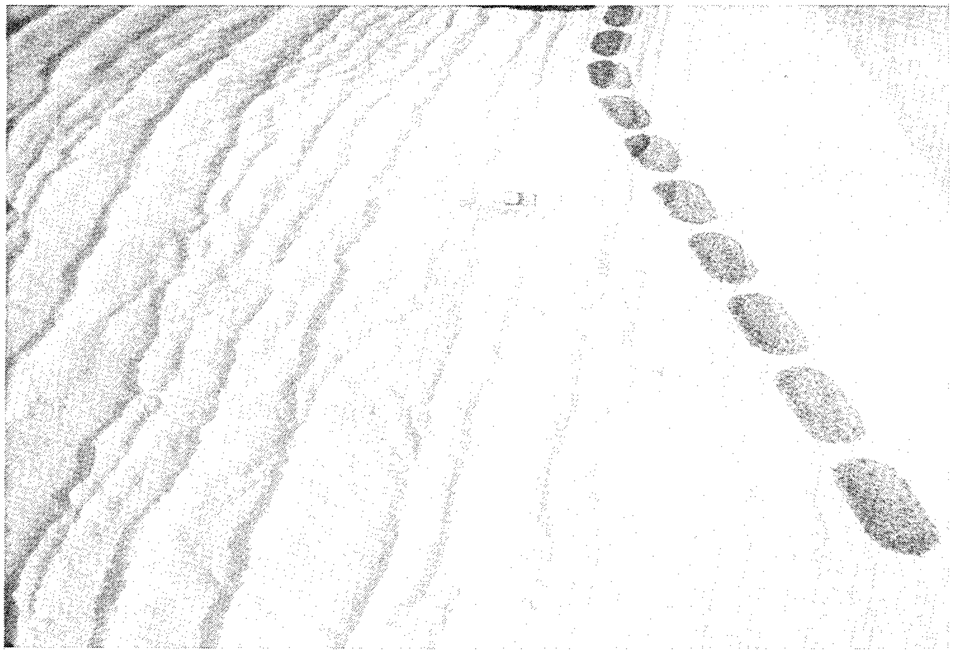


Photo 3. Typical wave patterns for Plan 1; 11.6-sec, 12-ft waves from 0 deg

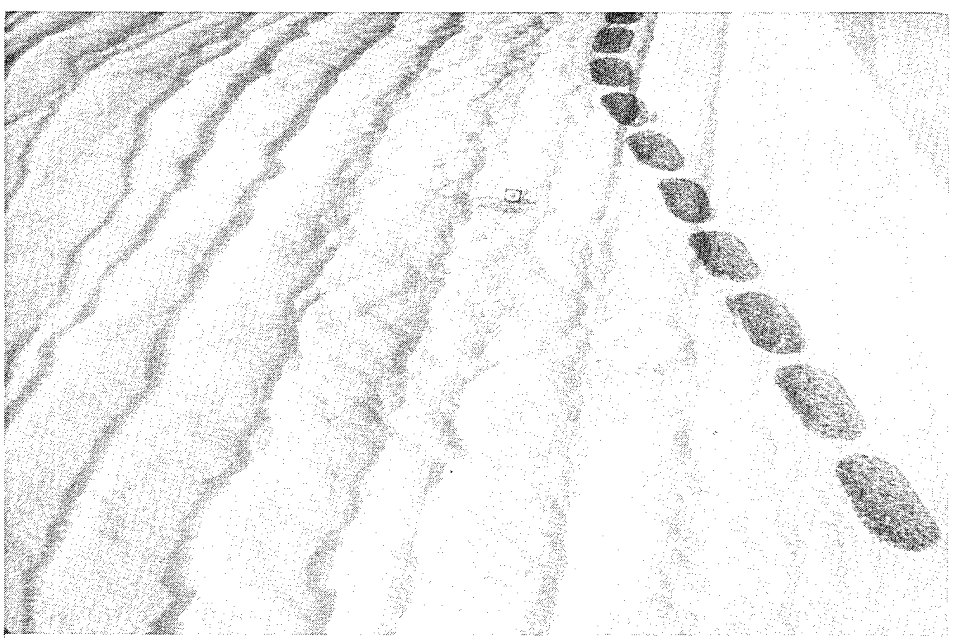


Photo 4. Typical wave patterns for Plan 1; 11.6-sec, 15-ft waves from 0 deg

Photo 5. Typical wave patterns for Plan 1; 11.6-sec, 18-ft waves from 0 deg

Photo 6. Typical wave patterns for Plan 1; 11.6-sec, 19.5-ft waves from 0 deg

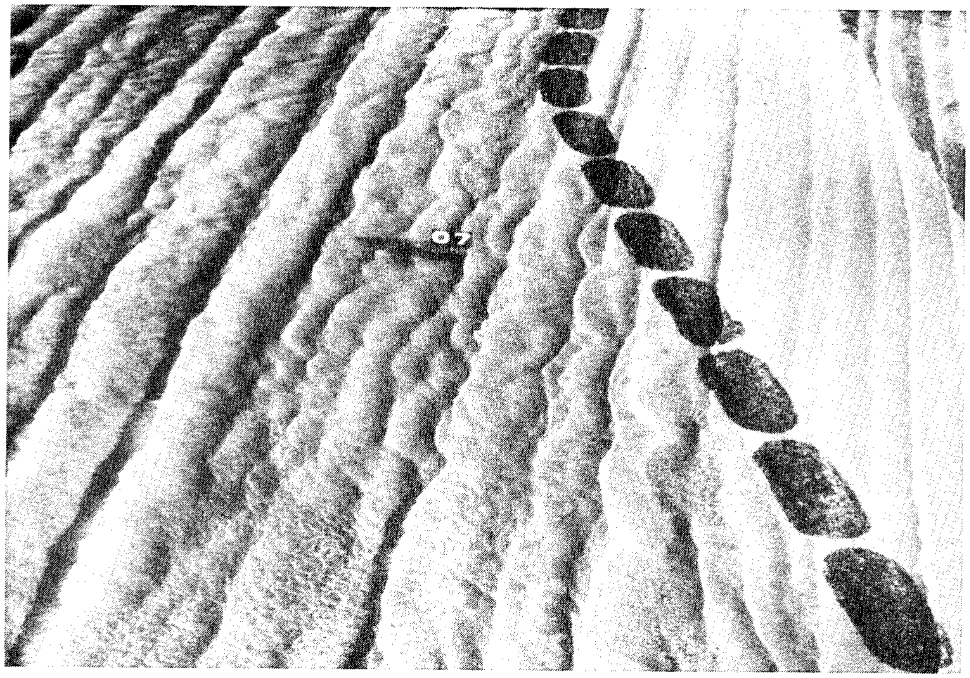


Photo 7. Typical wave patterns for Plan 2; 7-sec, 12-ft waves from 0 deg

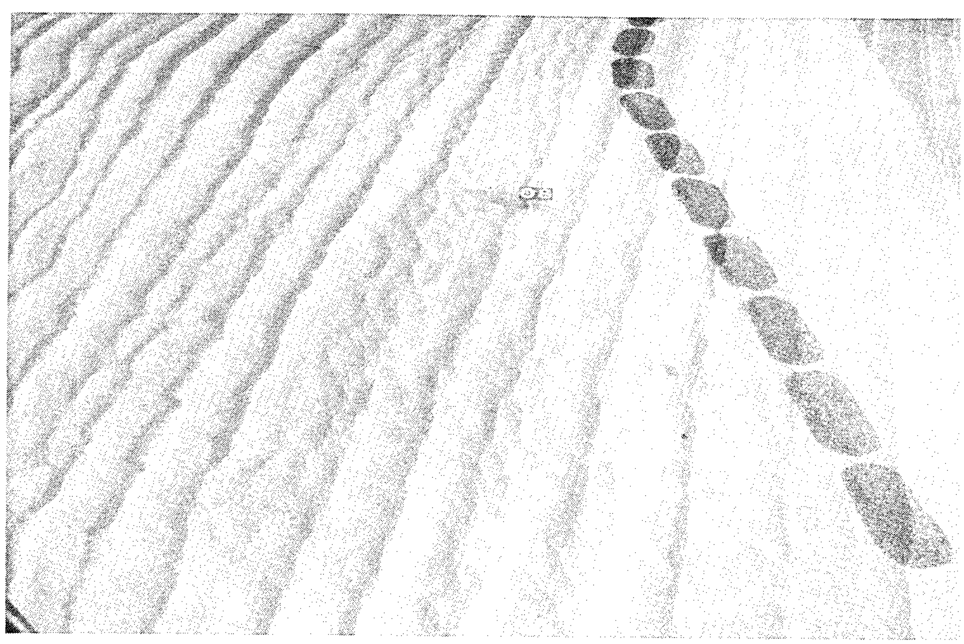


Photo 8. Typical wave patterns for Plan 2; 9-sec, 12-ft waves from 0 deg

Photo 9. Typical wave patterns for Plan 2; 11.6-sec, 12-ft waves from 0 deg

Photo 10. Typical wave patterns for Plan 2; 11.6-sec, 15-ft waves from 0 deg

Photo 11. Typical wave patterns for Plan 2; 11.6-sec, 18-ft waves from 0 deg

Photo 12. Typical wave patterns for Plan 2; 11.6-sec, 19.5-ft waves from 0 deg

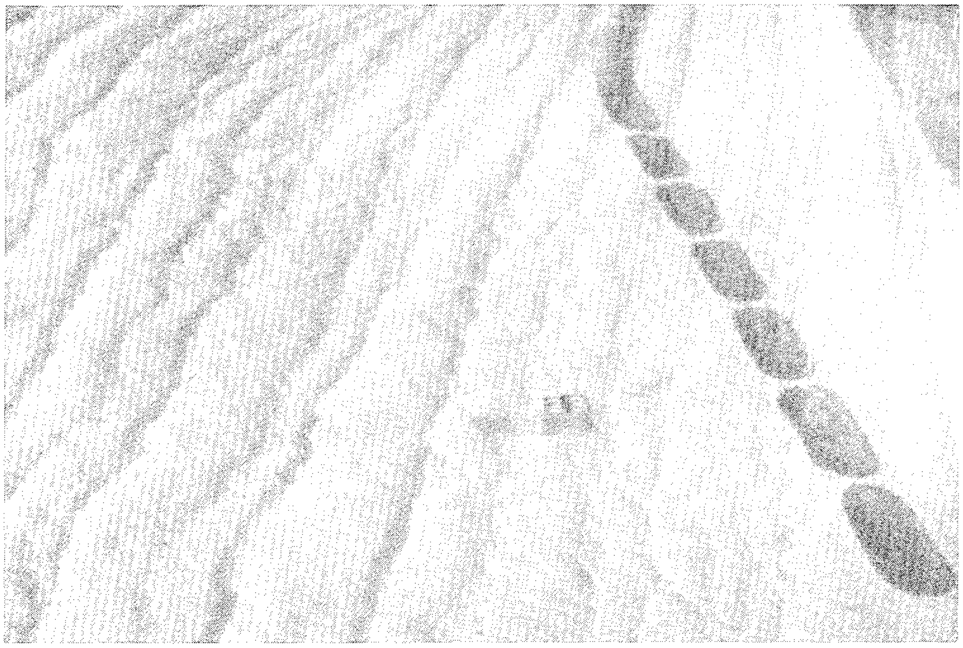


Photo 17. Typical wave patterns for Plan 3; 11.6-sec, 18-ft waves from 0 deg

Photo 18. Typical wave patterns for Plan 3; 11.6-sec, 19.5-ft waves from 0 deg

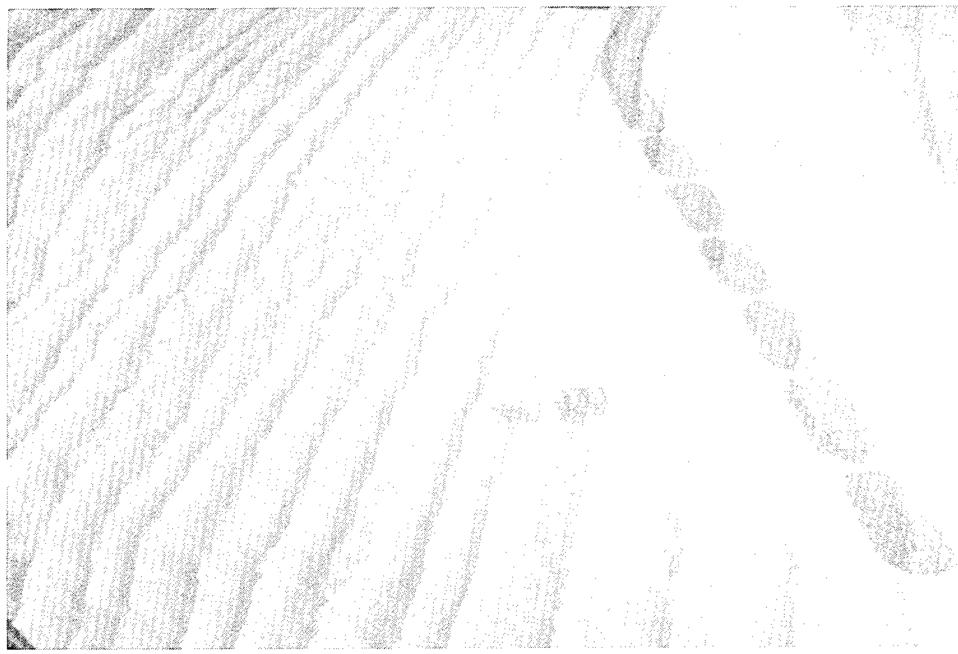


Photo 19. Typical wave patterns for Plan 4; 7-sec, 12-ft waves from 0 deg

Photo 20. Typical wave patterns for Plan 4; 9-sec, 12-ft waves from 0 deg

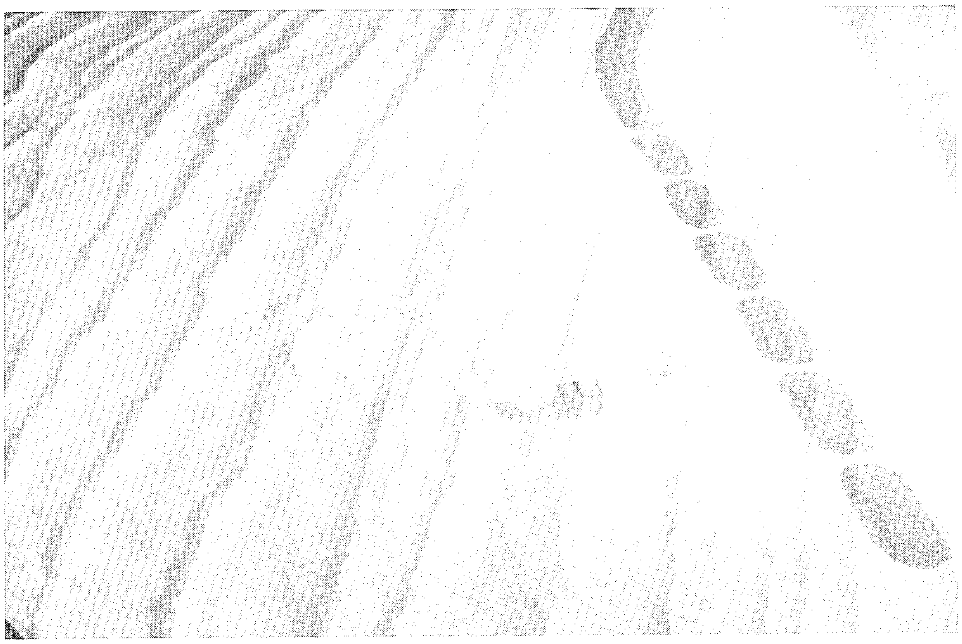


Photo 21. Typical wave patterns for Plan 4; 11.6-sec, 12-ft waves from 0 deg

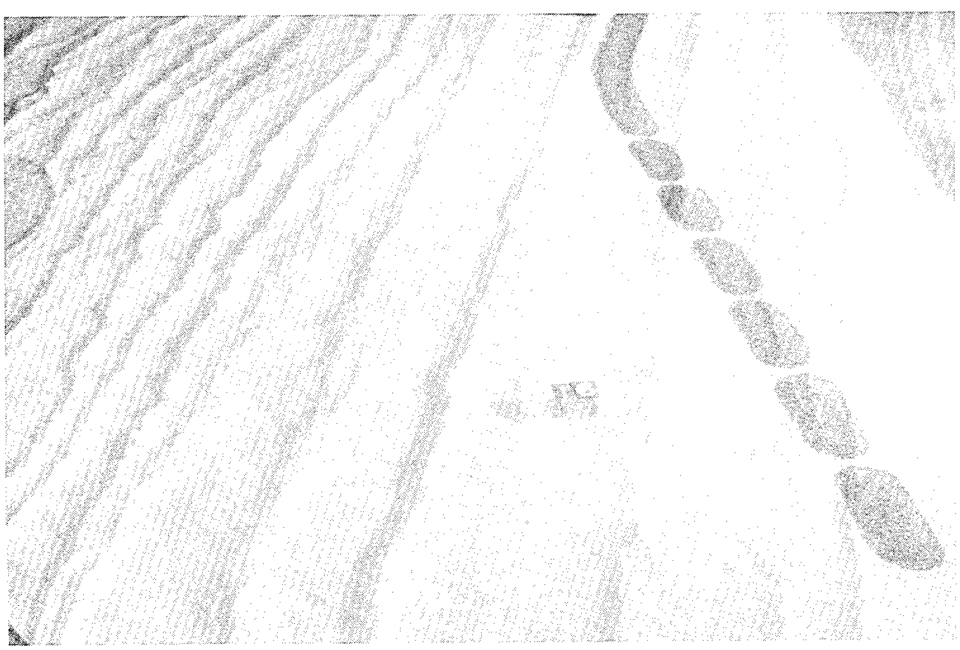


Photo 22. Typical wave patterns for Plan 4; 11.6-sec, 15-ft waves from 0 deg

Photo 23. Typical wave patterns for Plan 4; 11.6-sec, 18-ft waves from 0 deg

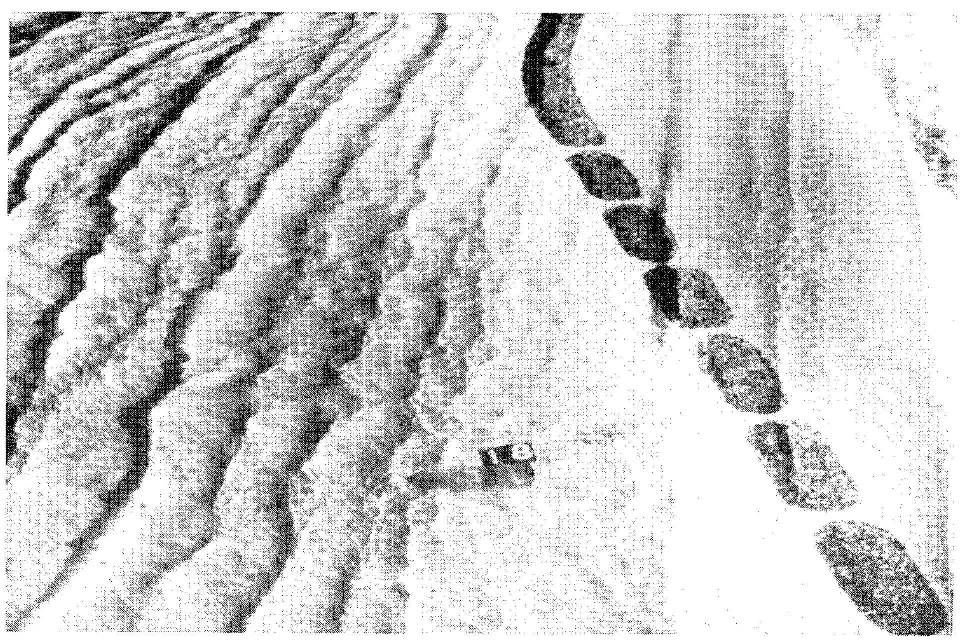


Photo 24. Typical wave patterns for Plan 4; 11.6-sec, 19.5-ft waves from 0 deg

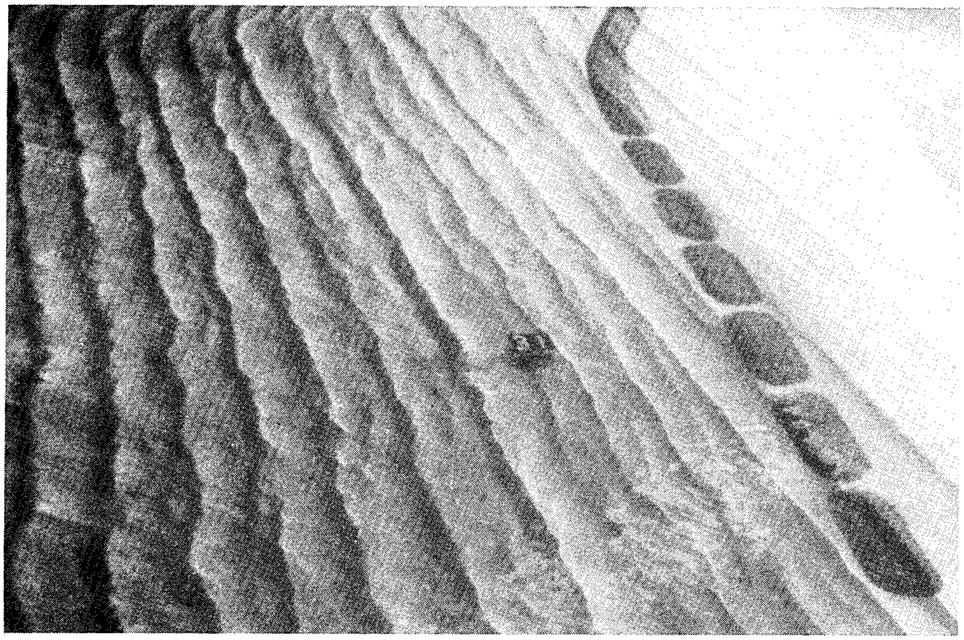


Photo 25. Typical wave patterns for Plan 5; 7-sec, 12-ft waves from 330 deg

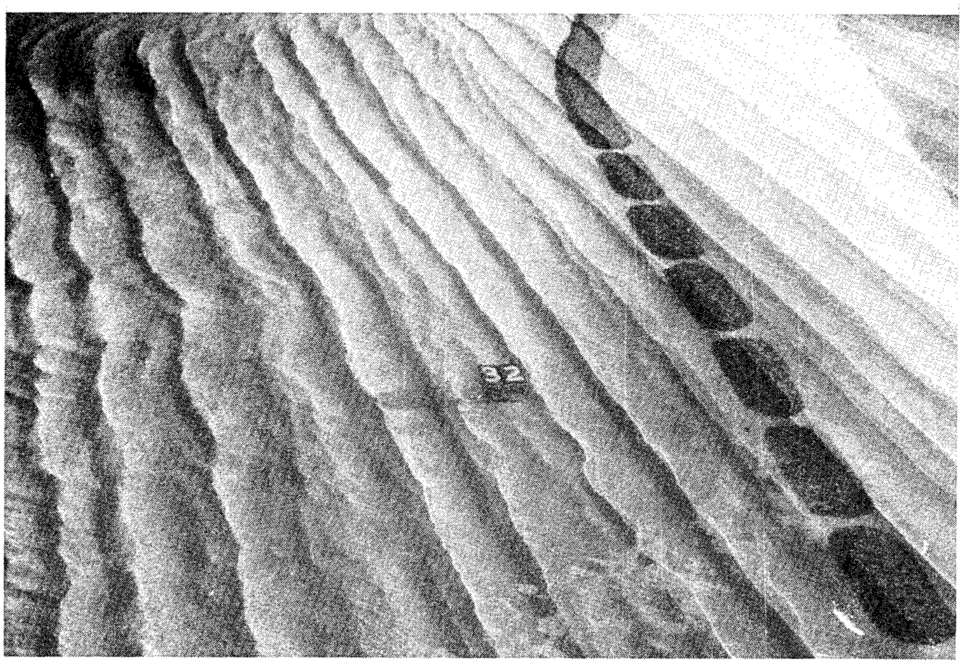


Photo 26. Typical wave patterns for Plan 5; 9-sec, 12-ft waves from 330 deg

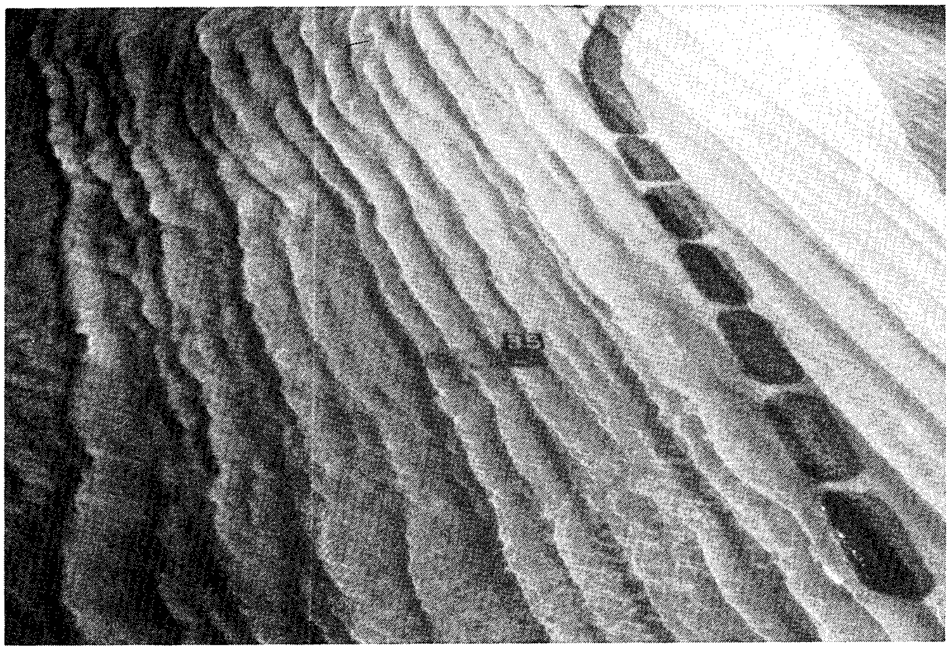


Photo 29. Typical wave patterns for Plan 5; 11.6-sec, 13-ft waves from 330 deg

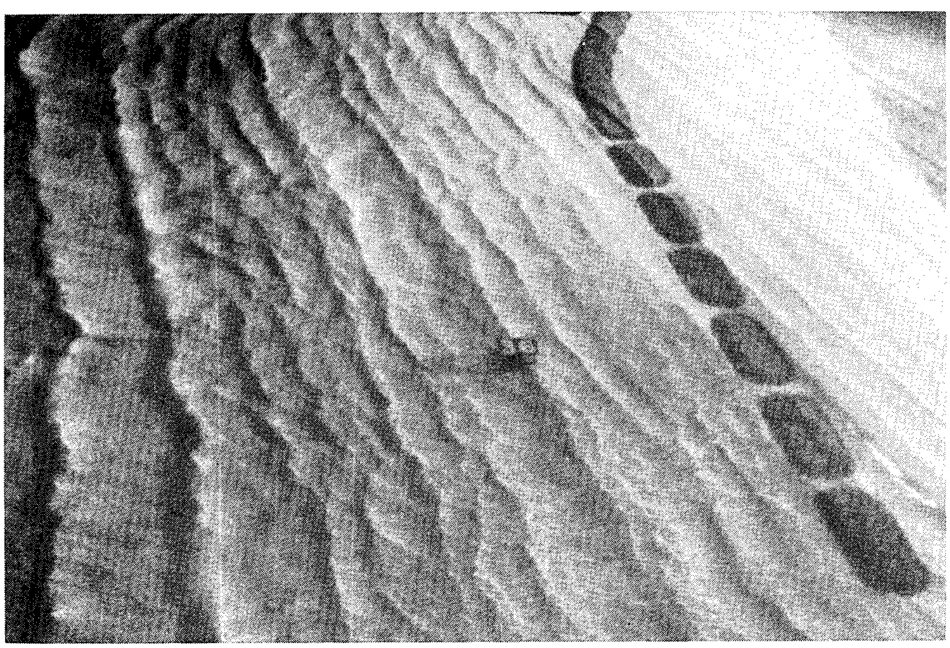


Photo 30. Typical wave patterns for Plan 5; 11.6-sec, 15-ft waves from 330 deg

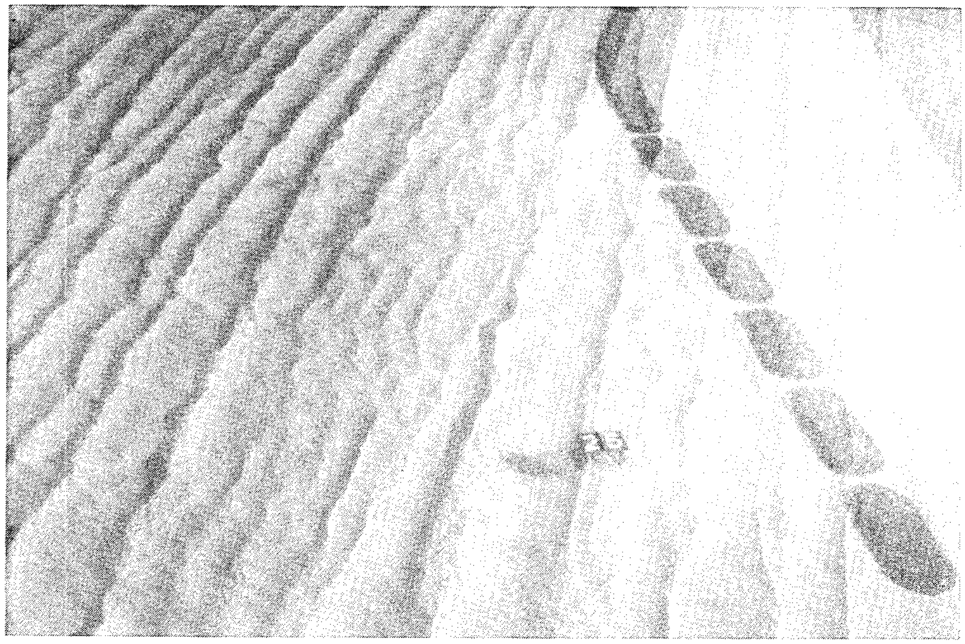


Photo 31. Typical wave patterns for Plan 5; 7-sec, 12-ft waves from 0 deg

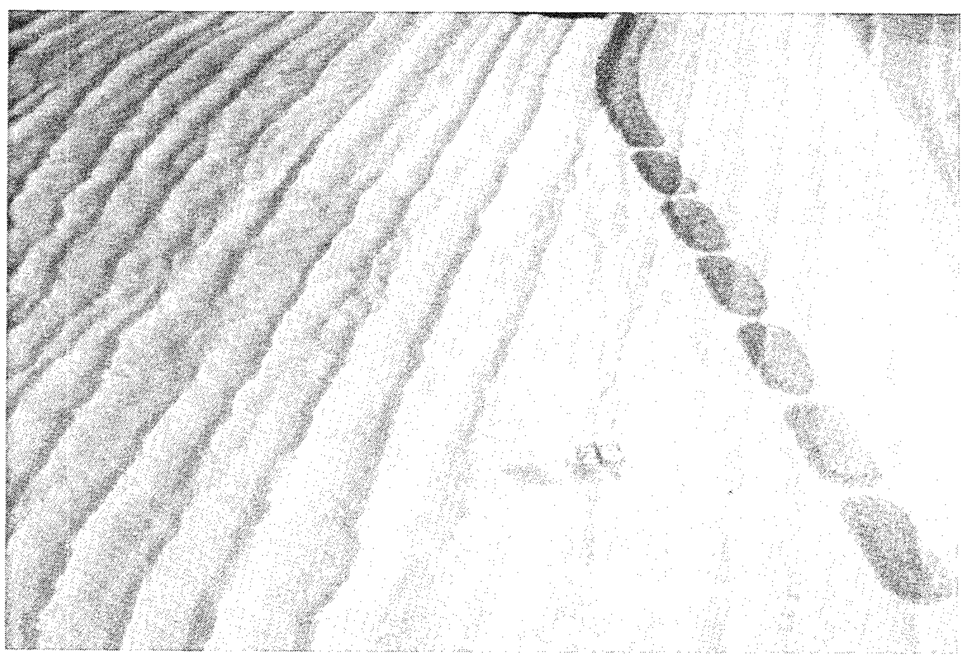


Photo 32. Typical wave patterns for Plan 5; 9-sec, 12-ft waves from 0 deg

Photo 33. Typical wave patterns for Plan 5; 11.6-sec, 12-ft waves from 0 deg

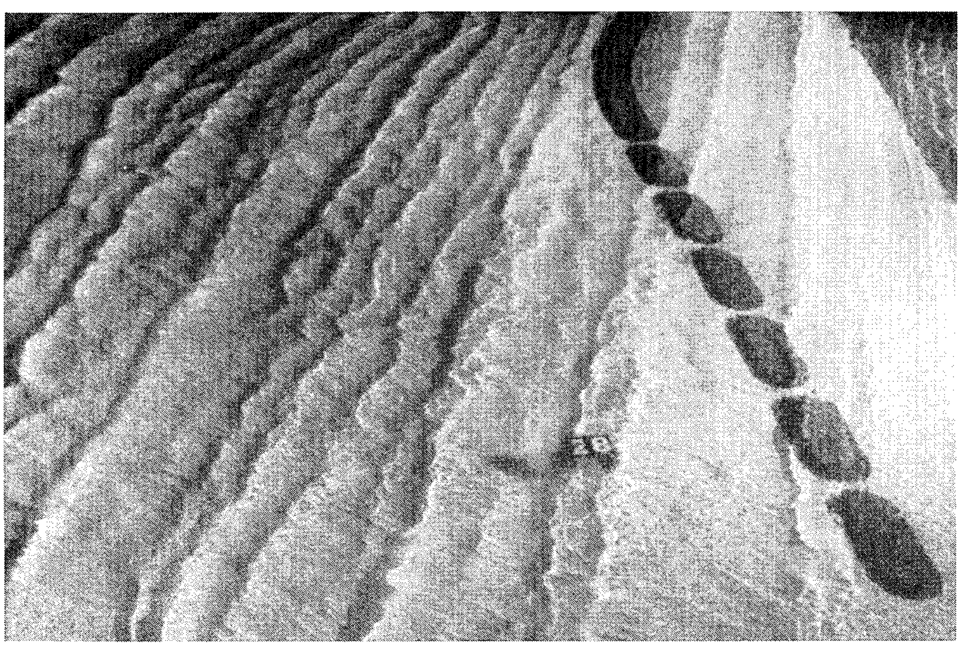


Photo 34. Typical wave patterns for Plan 5; 11.6-sec, 15-ft waves from 0 deg

Photo 35. Typical wave patterns for Plan 5; 11.6-sec, 18-ft waves from 0 deg

Photo 36. Typical wave patterns for Plan 5; 11.6-sec, 19.5-ft waves from 0 deg

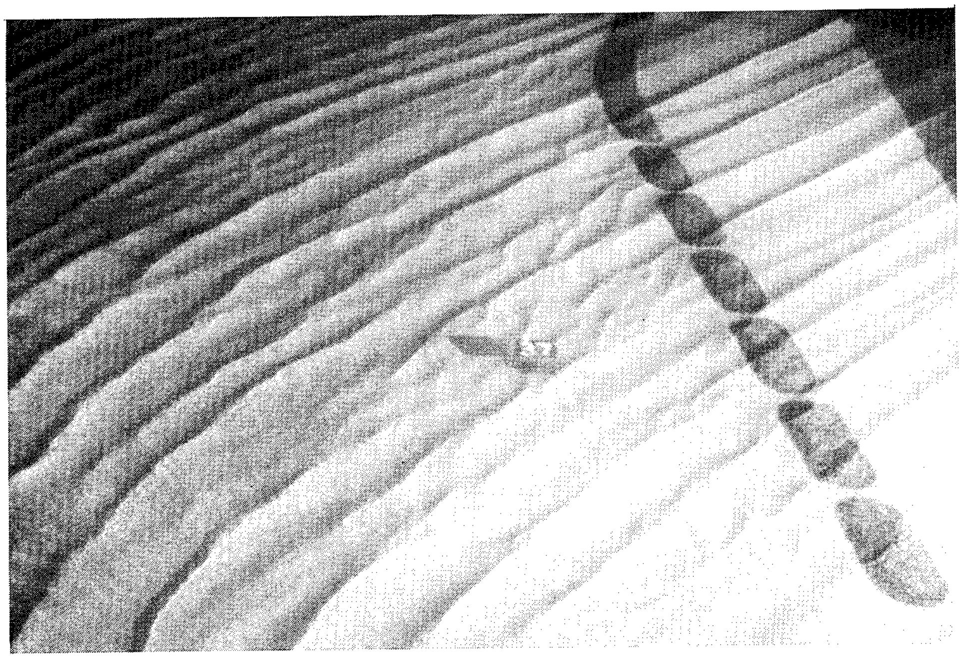


Photo 37. Typical wave patterns for Plan 5; 7-sec, 12-ft waves from 30 deg

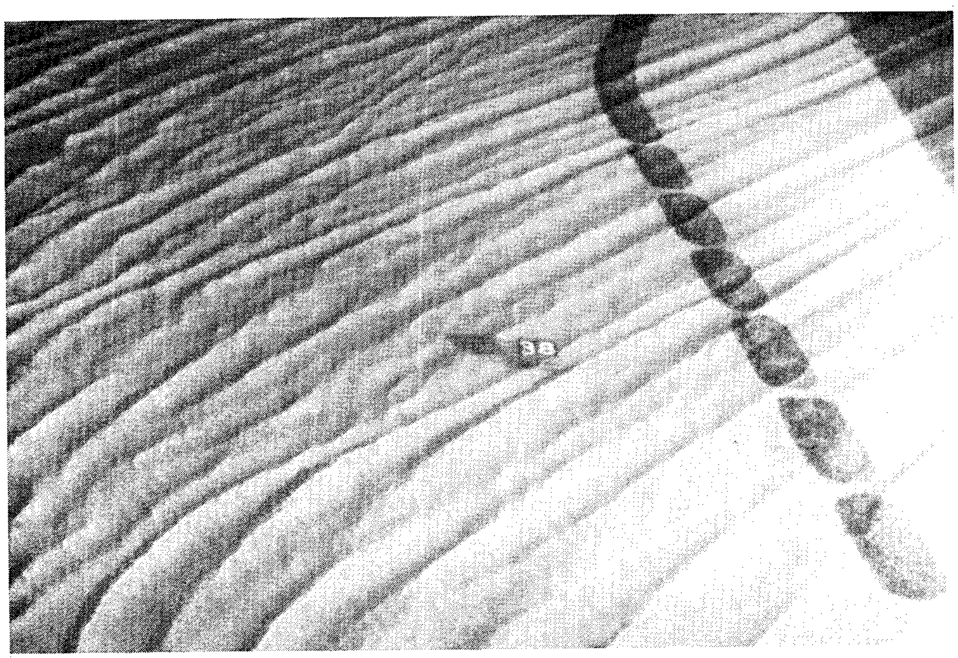


Photo 38. Typical wave patterns for Plan 5; 9-sec, 12-ft waves from 30 deg

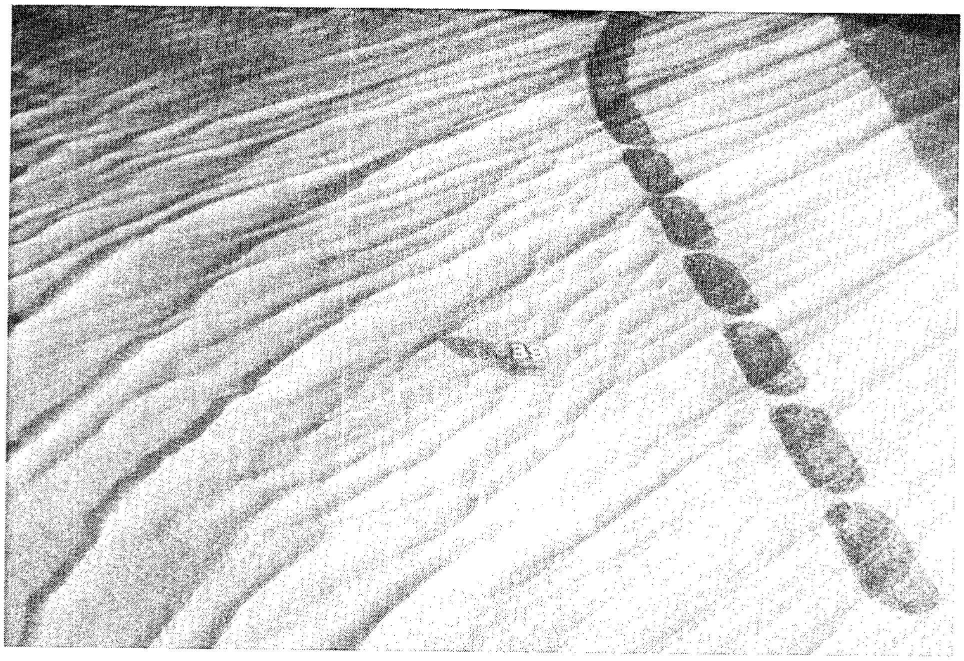


Photo 39. Typical wave patterns for Plan 5; 11.6-sec, 9-ft waves from 30 deg

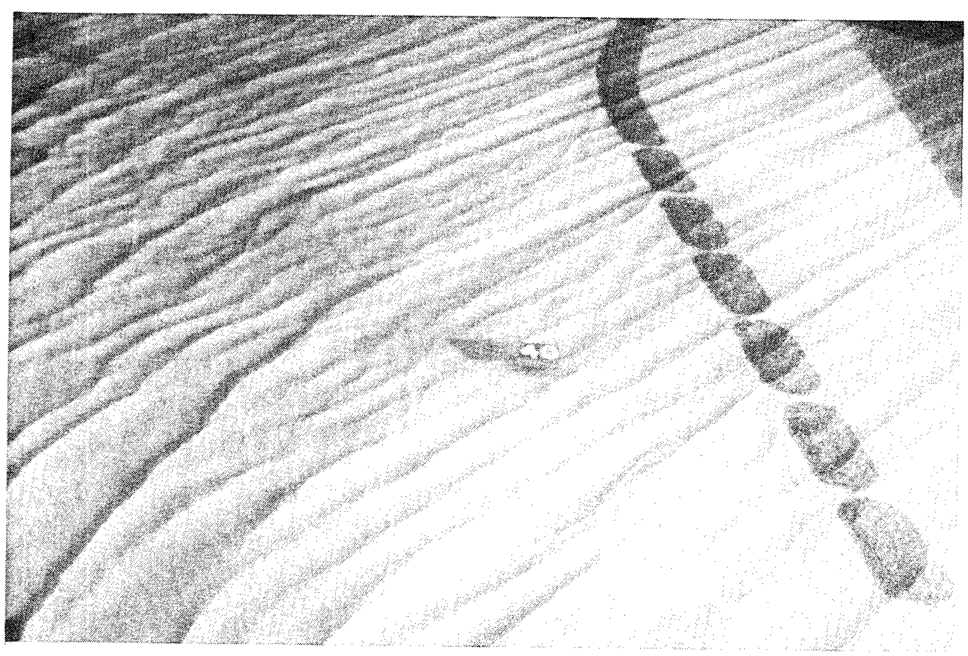


Photo 40. Typical wave patterns for Plan 5; 11.6-sec, 12-ft waves from 30 deg

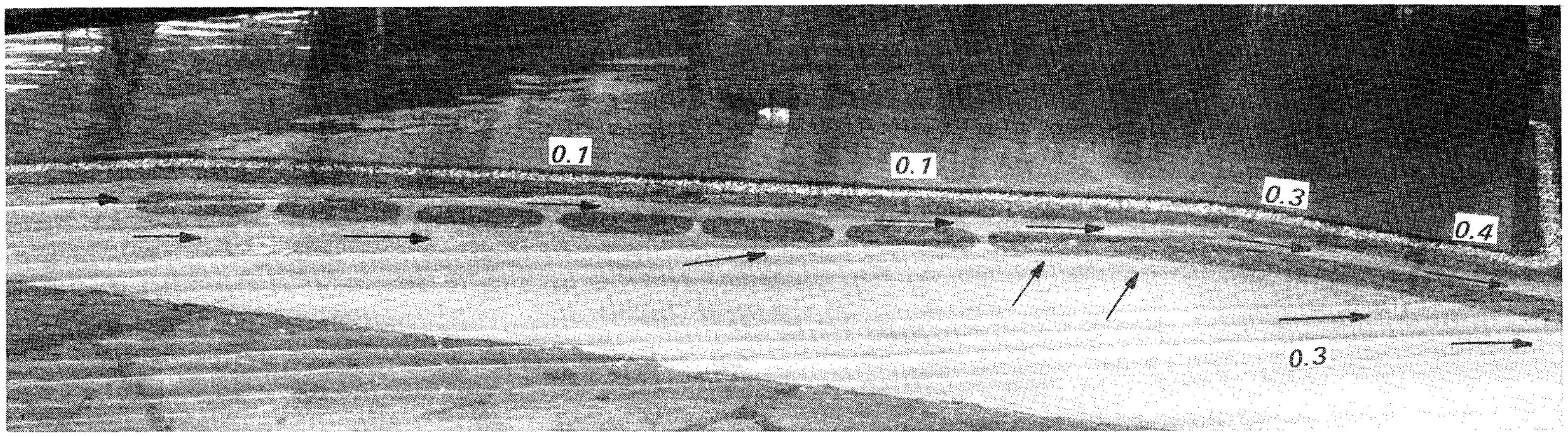


Photo 41. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 6; 7-sec, 5-ft waves from 330 deg

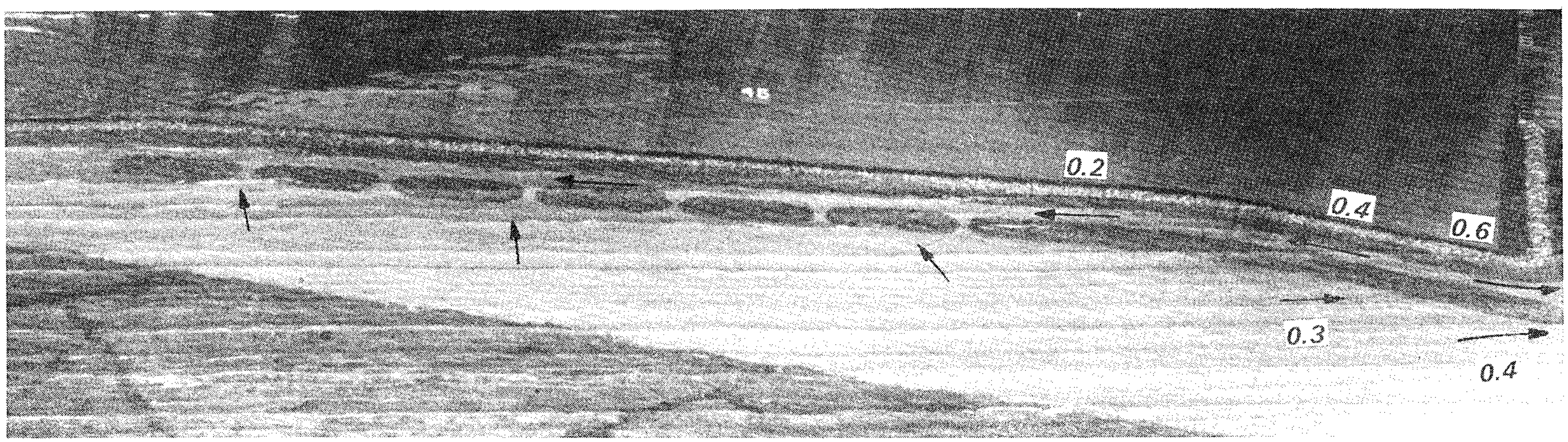


Photo 42. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 6; 9-sec, 9-ft waves from 330 deg

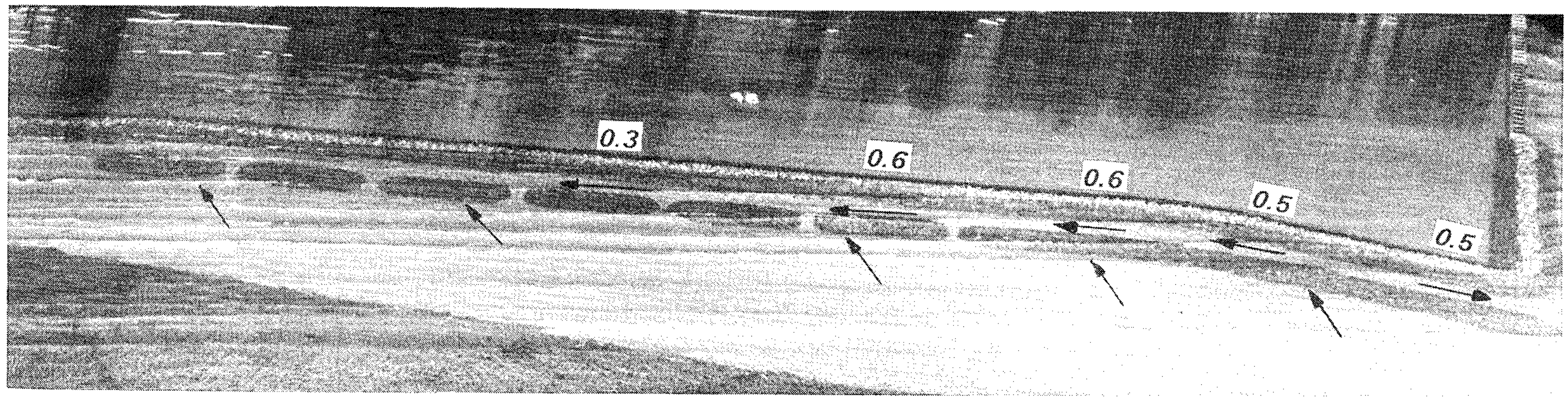


Photo 43. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 6; 11.6-sec, 15-ft waves from 330 deg

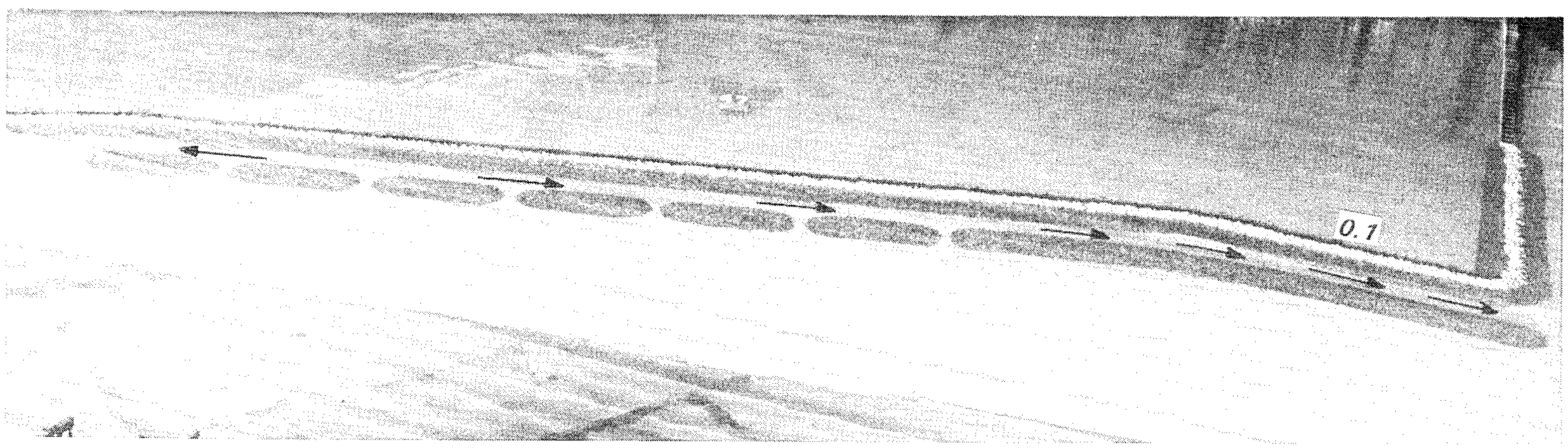


Photo 44. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 6; 7-sec, 5-ft waves from 0 deg

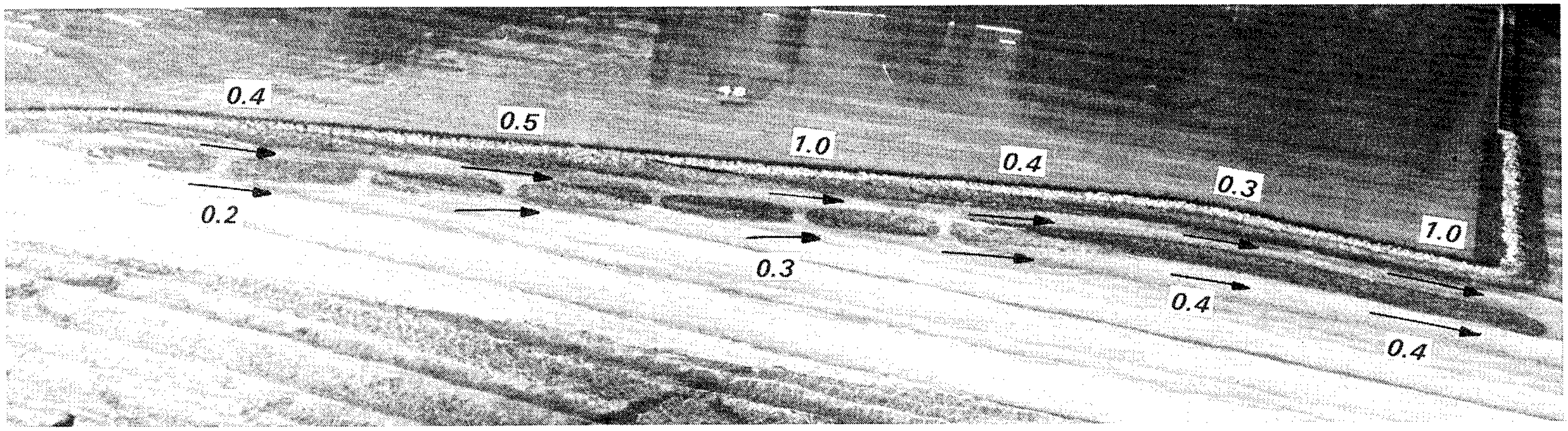


Photo 45. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 6; 9-sec, 12-ft waves from 0 deg

Photo 46. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 6; 11.6-sec, 13-ft waves from 0 deg

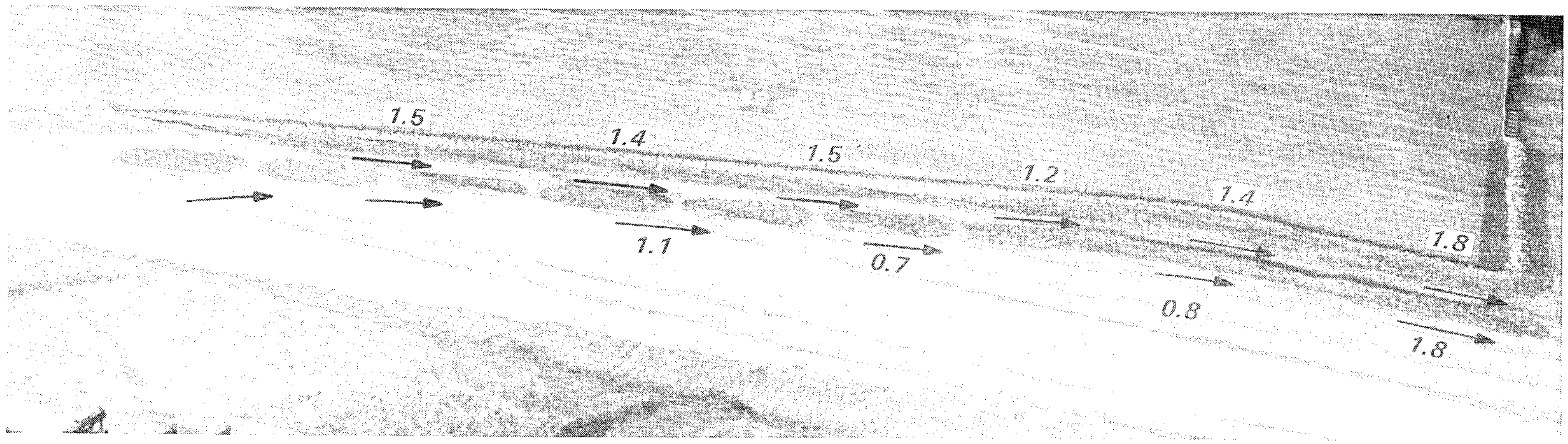


Photo 47. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 6; 11.6-sec, 19.5-ft waves from 0 deg

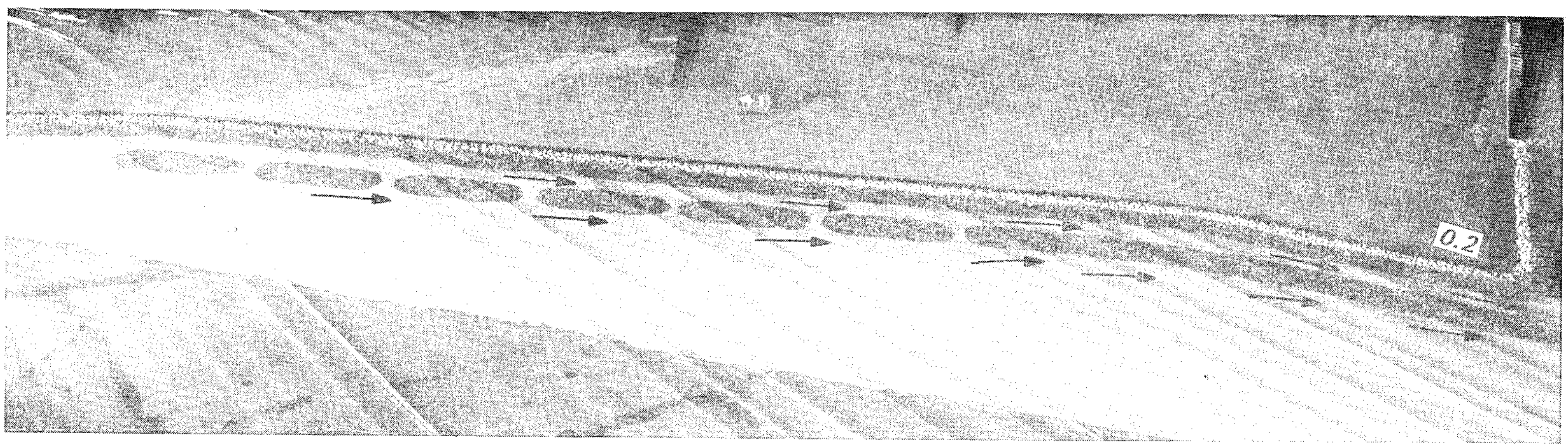


Photo 48. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 6; 7-sec, 5-ft waves from 30 deg

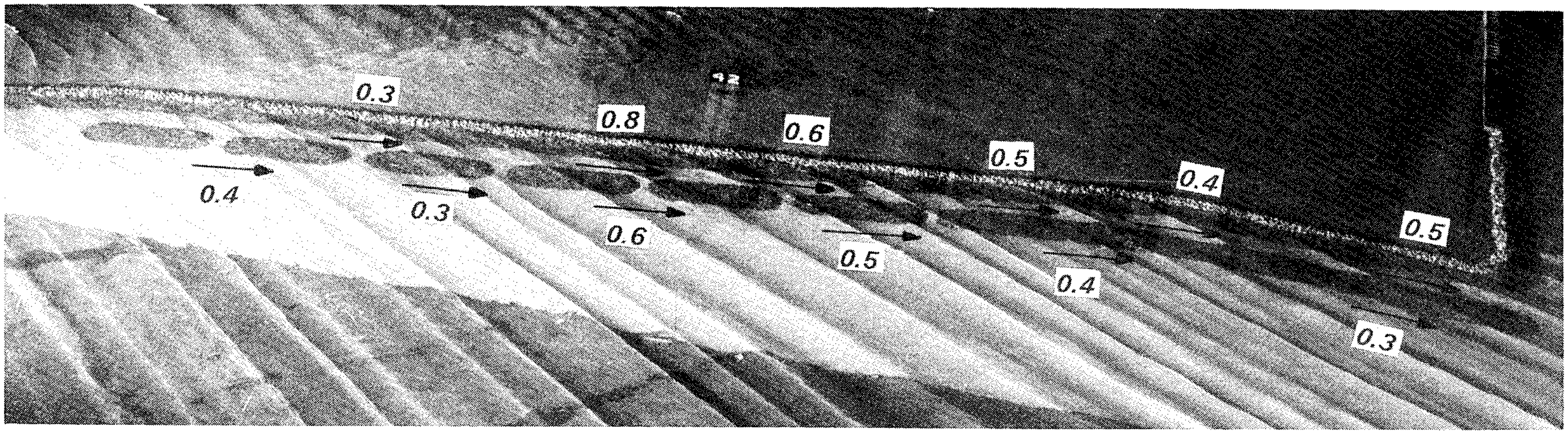


Photo 49. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 6; 9-sec, 9-ft waves from 30 deg

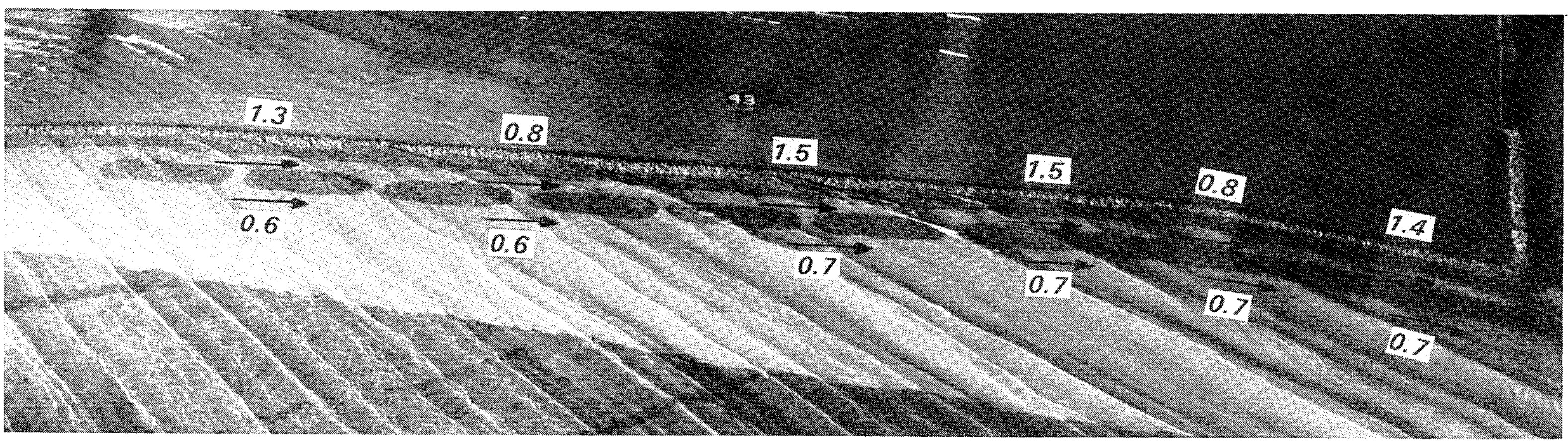


Photo 50. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 6; 11.6-sec, 12-ft waves from 30 deg

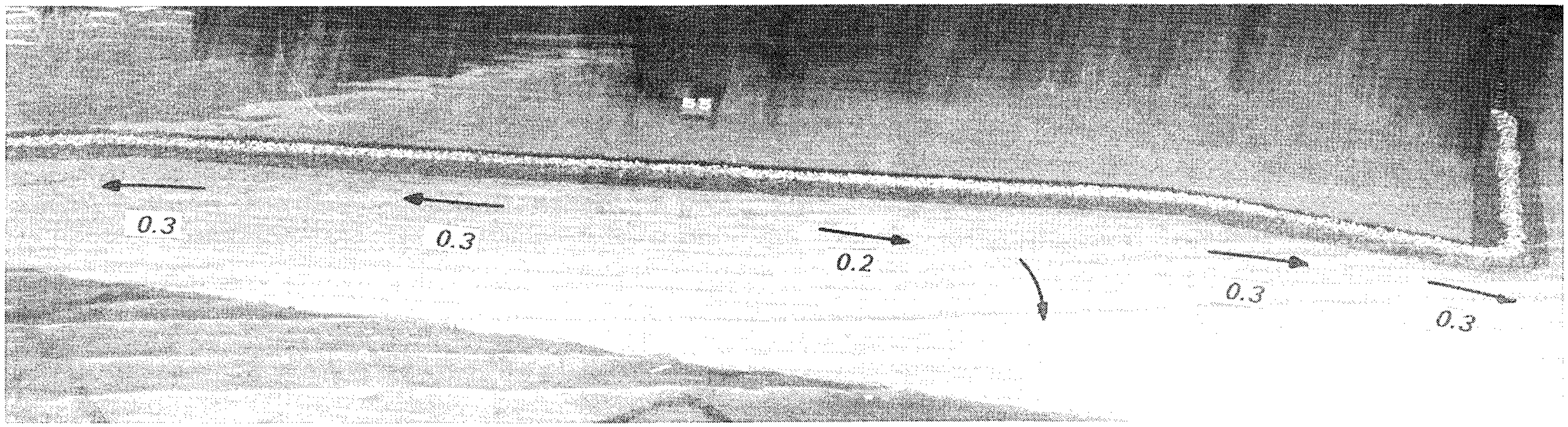


Photo 51. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 7; 7-sec, 5-ft waves from 330 deg

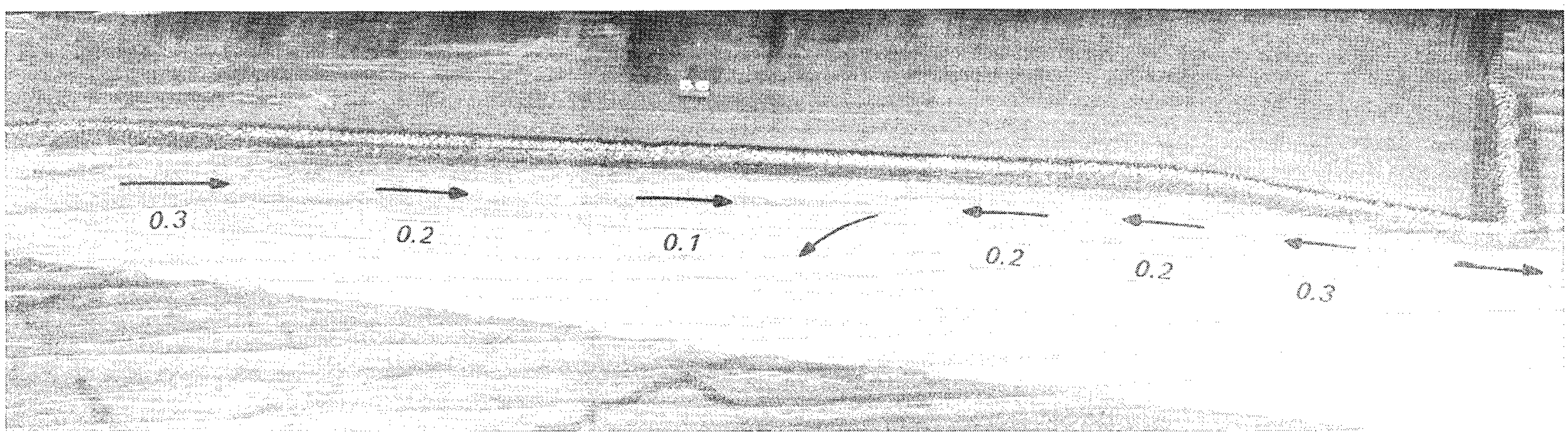


Photo 52. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 7; 9-sec, 9-ft waves from 330 deg

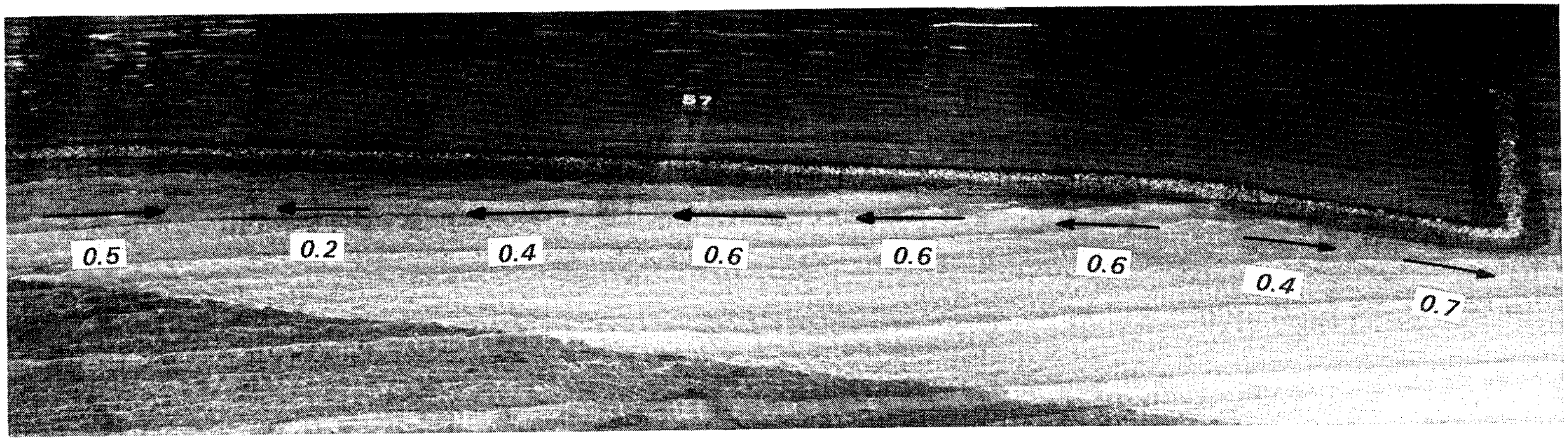


Photo 53. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 7; 11.6-sec, 15-ft waves from 330 deg

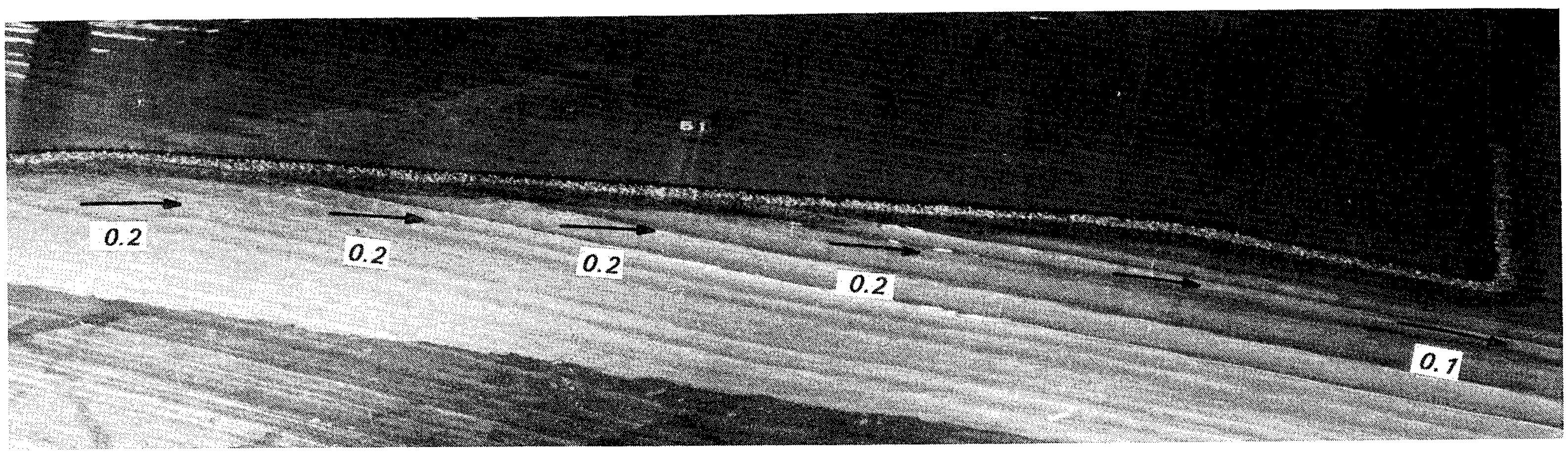


Photo 54. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 7; 7-sec, 5-ft waves from 0 deg

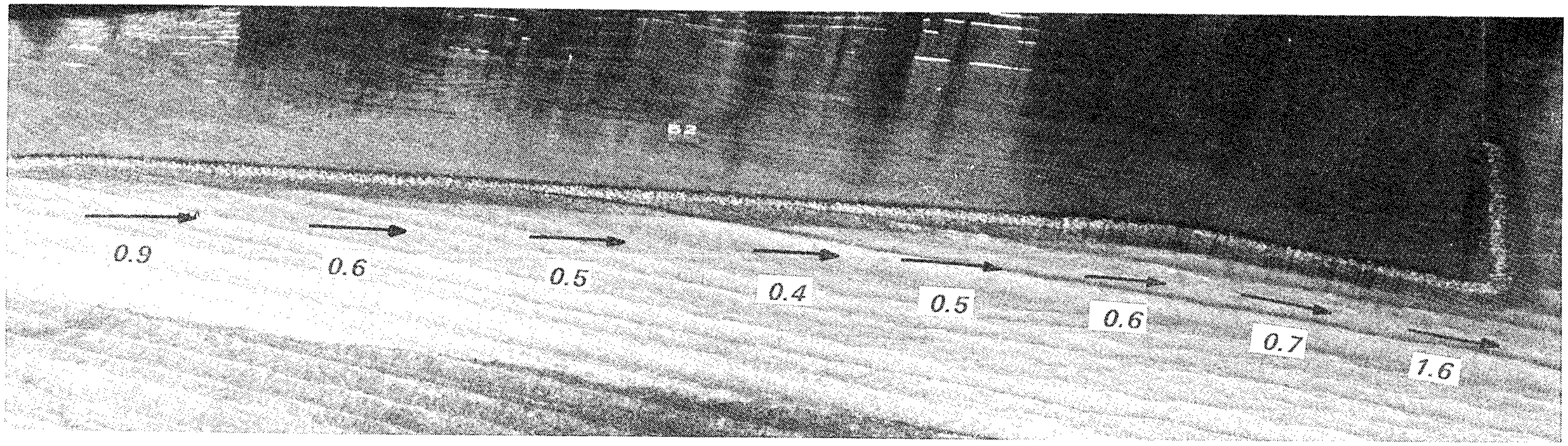


Photo 55. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 7; 9-sec, 12-ft waves from 0 deg

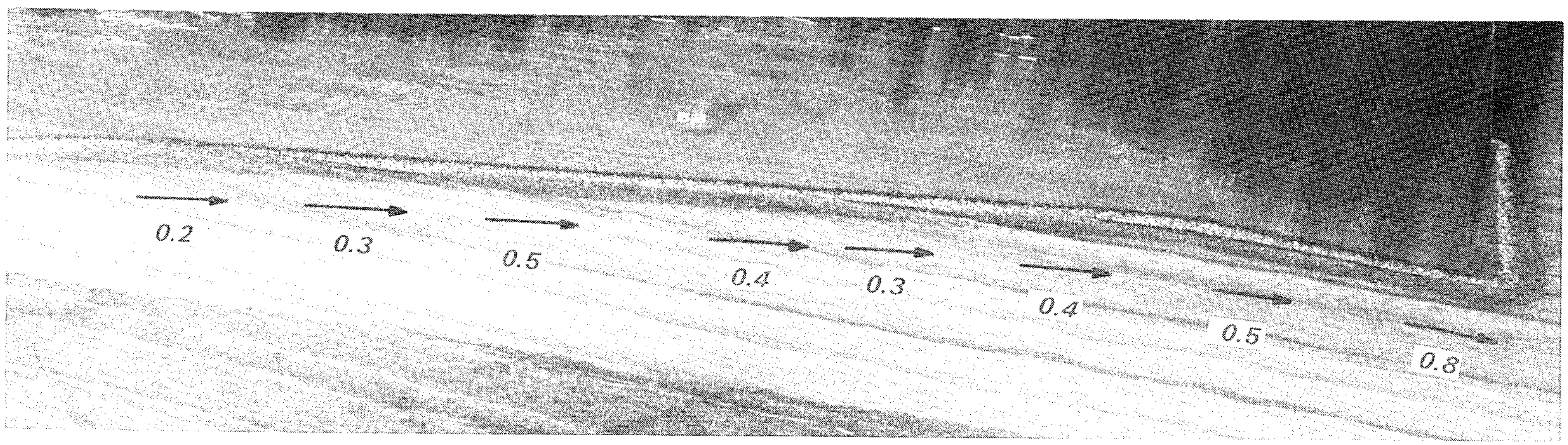


Photo 56. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 7; 11.6-sec, 13-ft waves from 0 deg

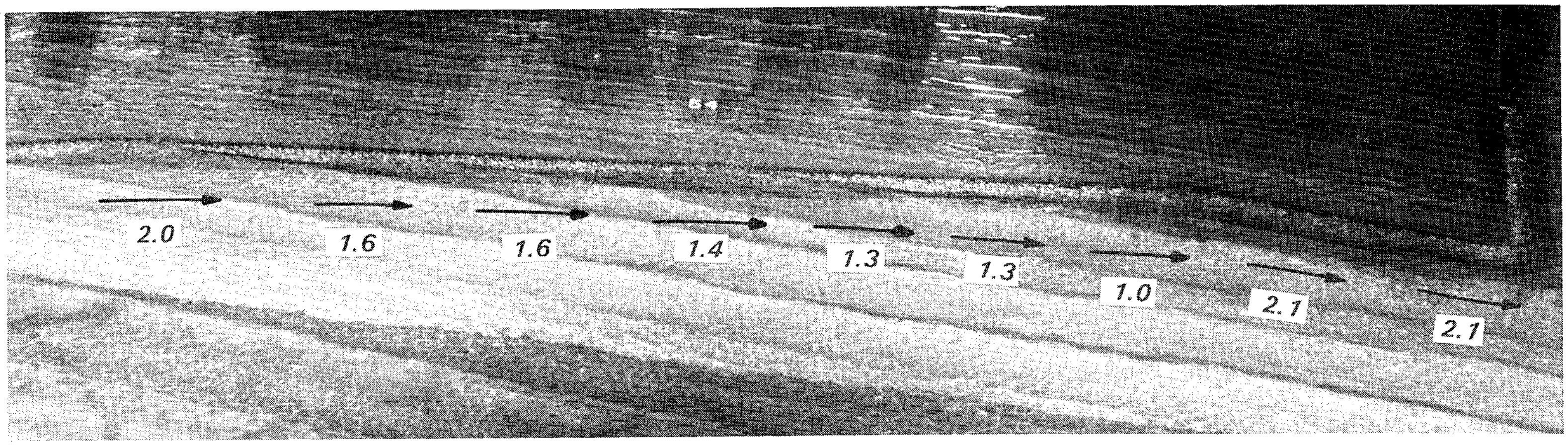


Photo 57. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 7; 11.6-sec, 19.5-ft waves from 0 deg

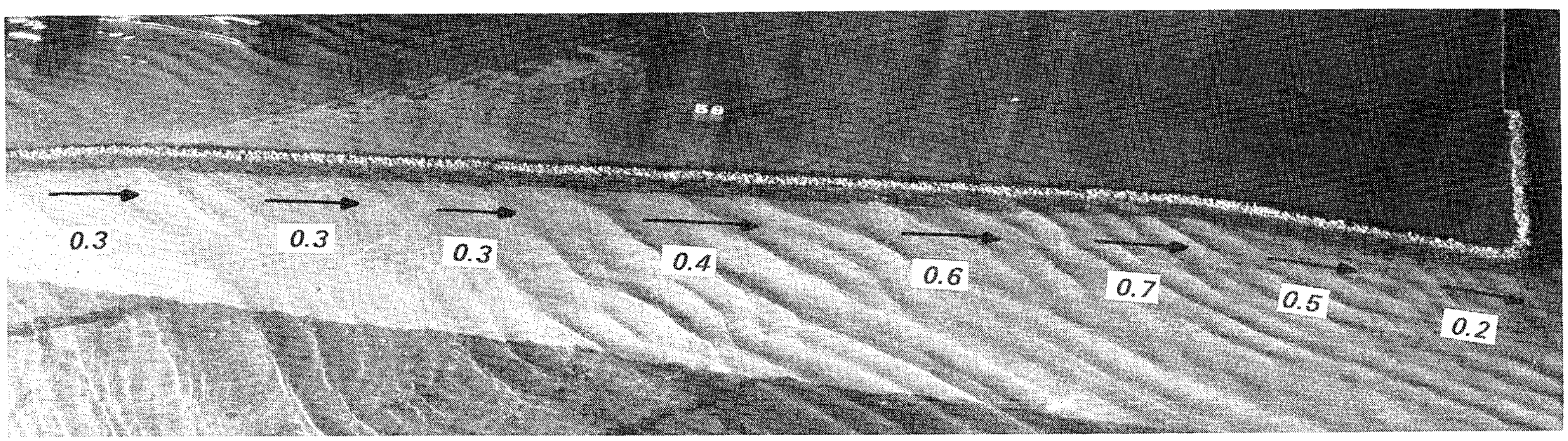


Photo 58. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 7; 7-sec, 5-ft waves from 30 deg

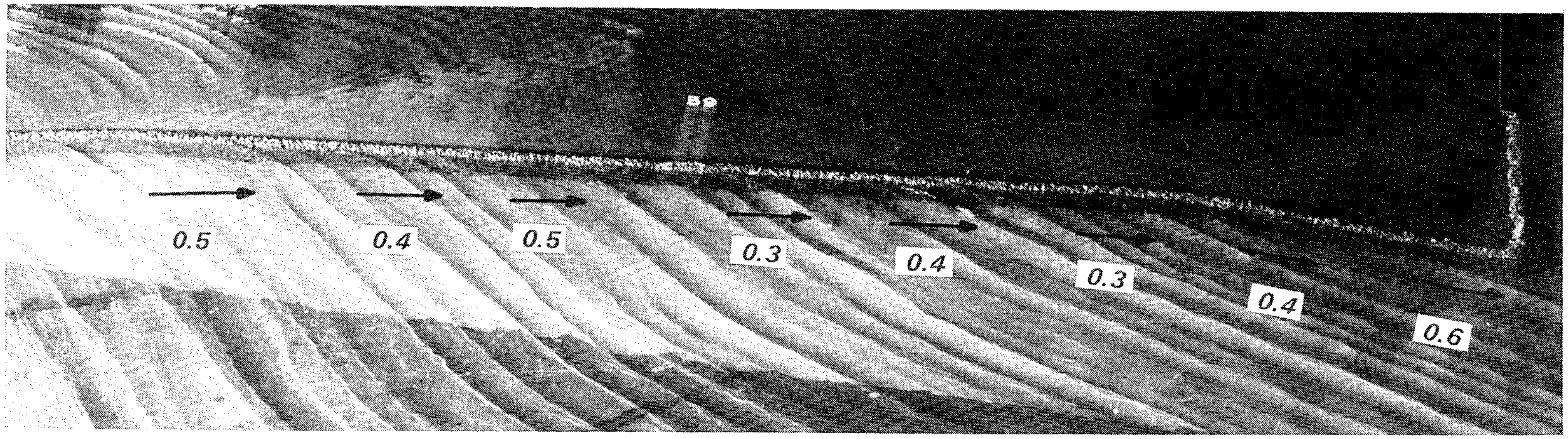


Photo 59. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 7; 9-sec, 9-ft waves from 30 deg

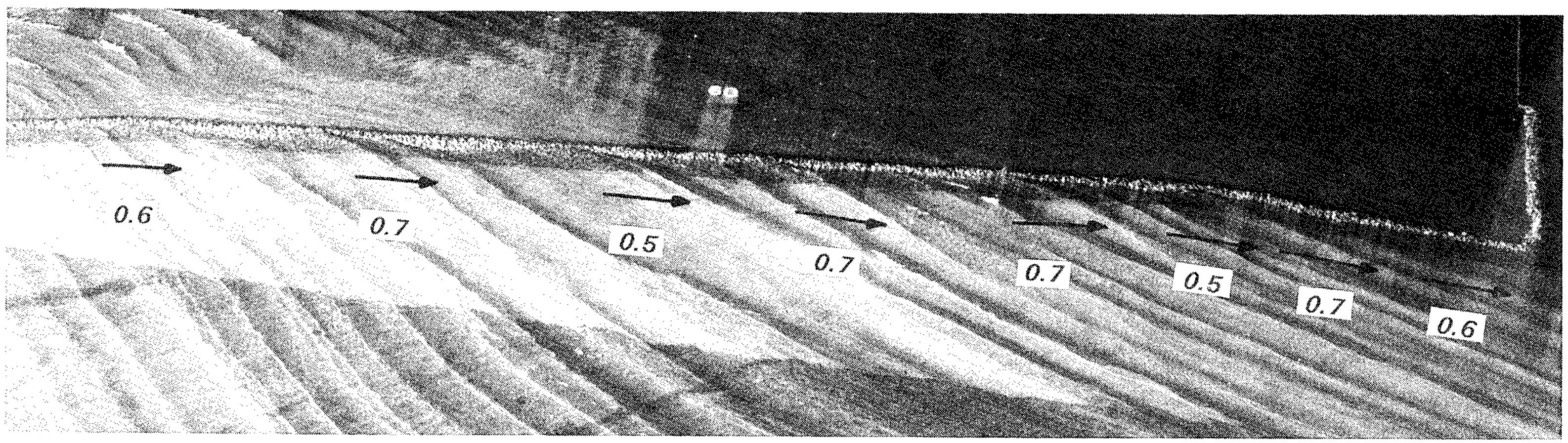
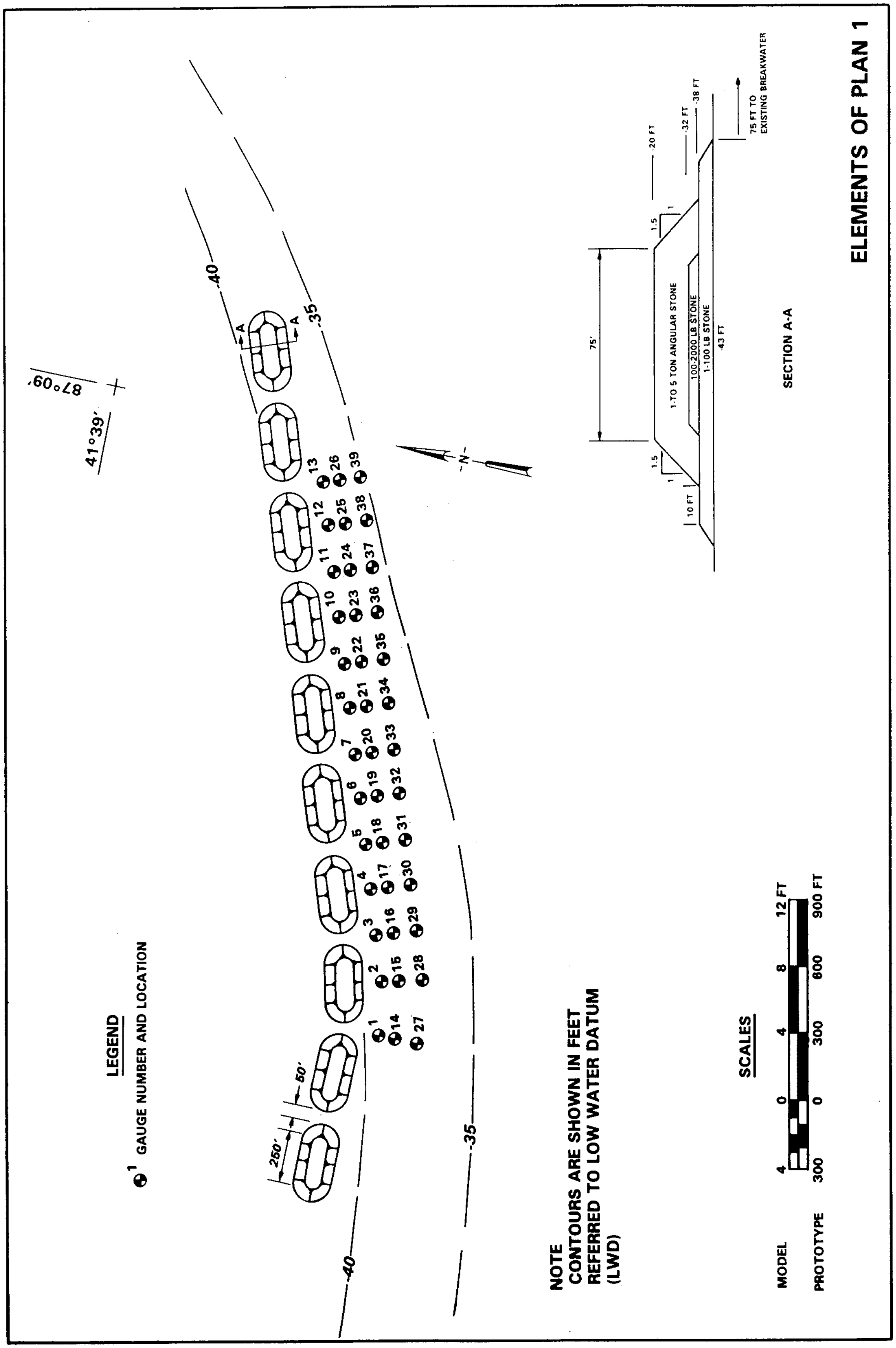
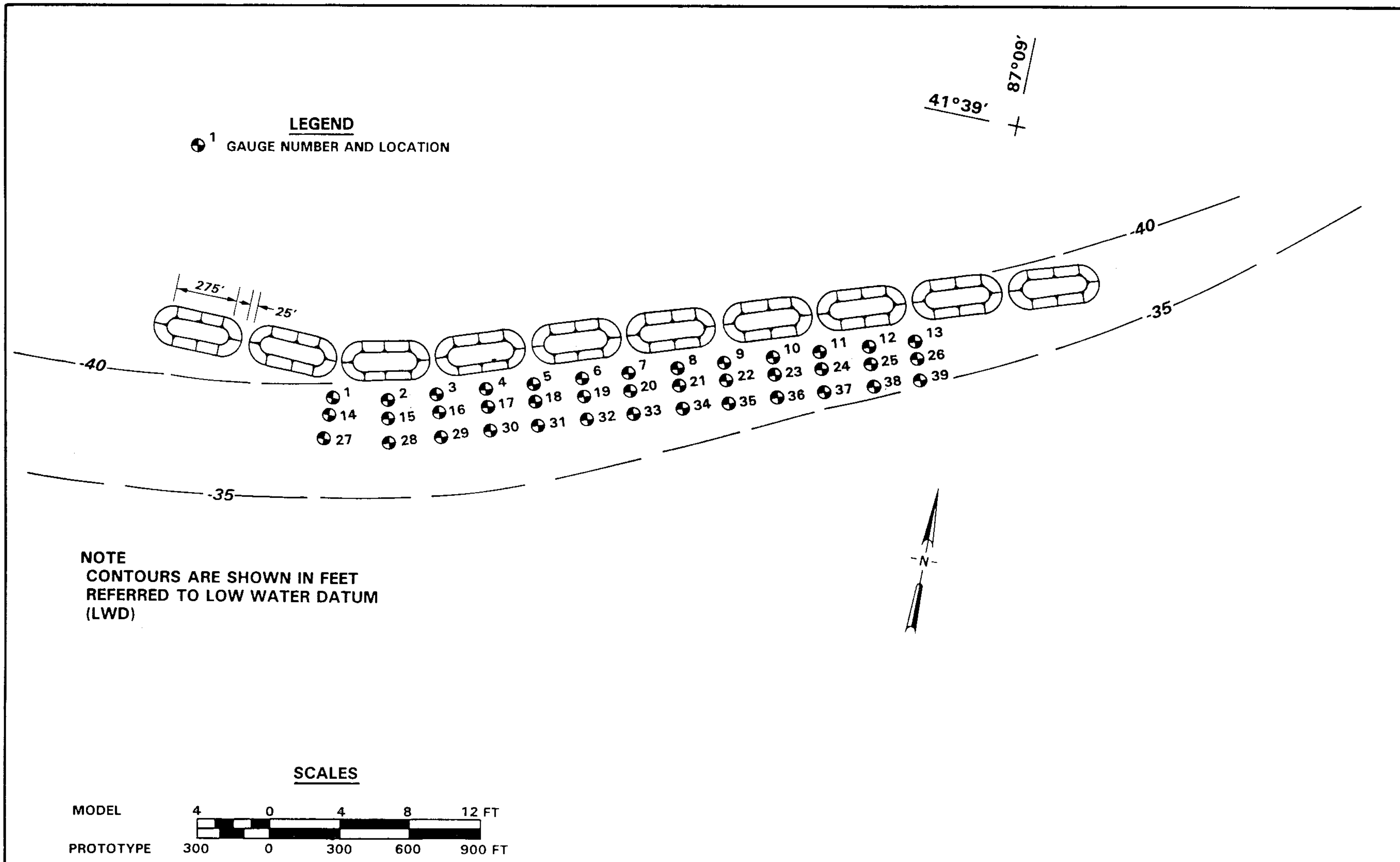


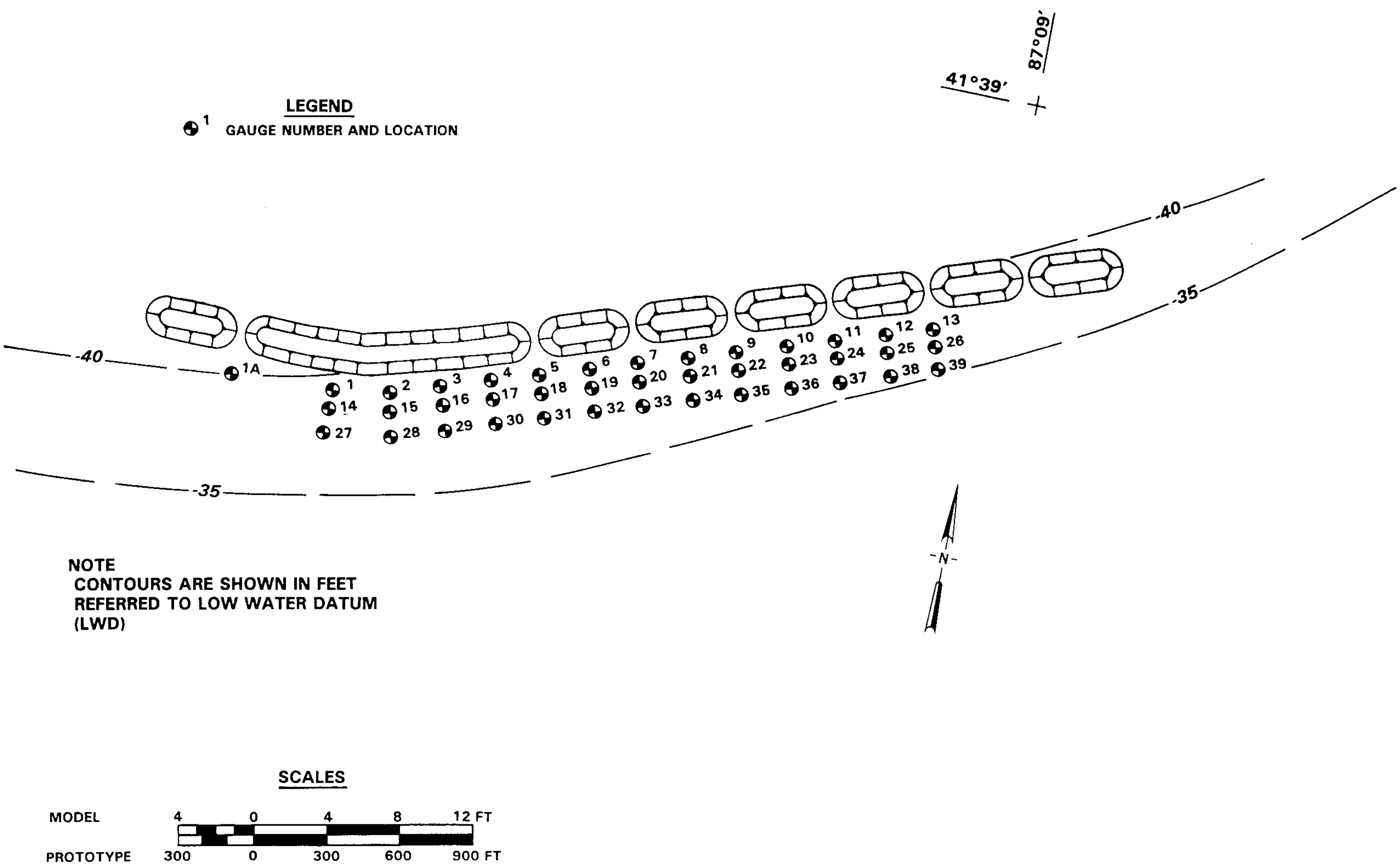
Photo 60. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 7; 11.6-sec, 12-ft waves from 30 deg



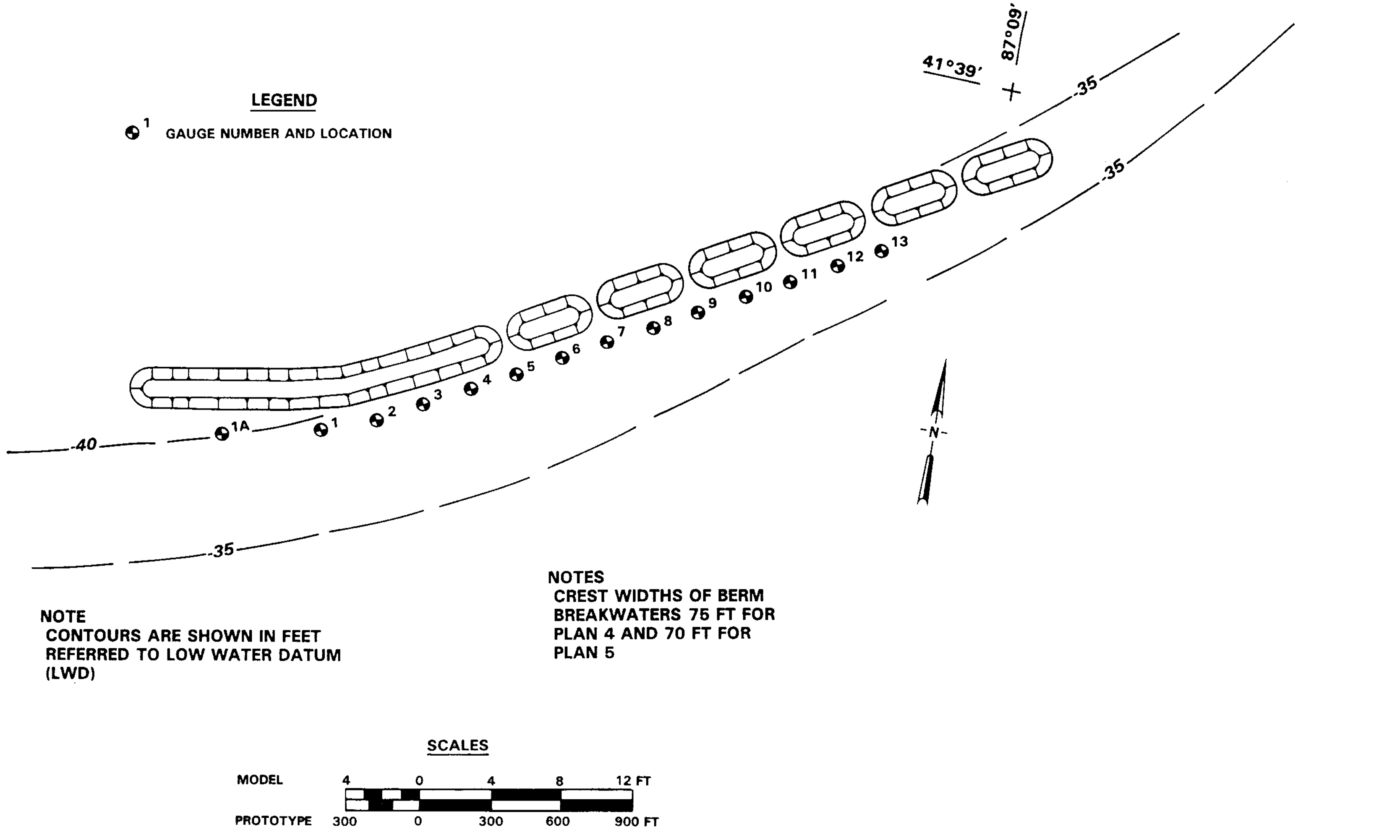
ELEMENTS OF PLAN 1



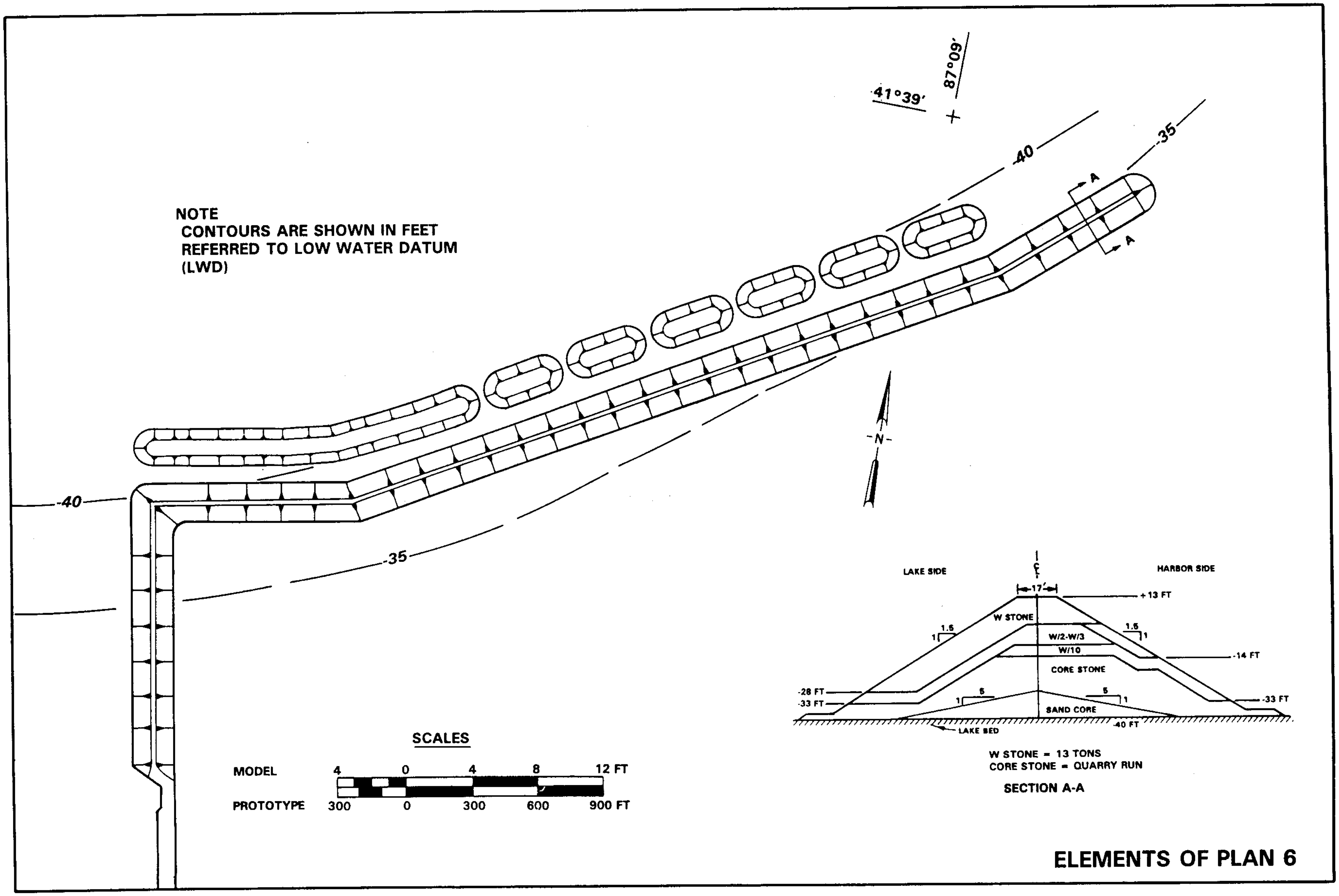
ELEMENTS OF PLAN 2



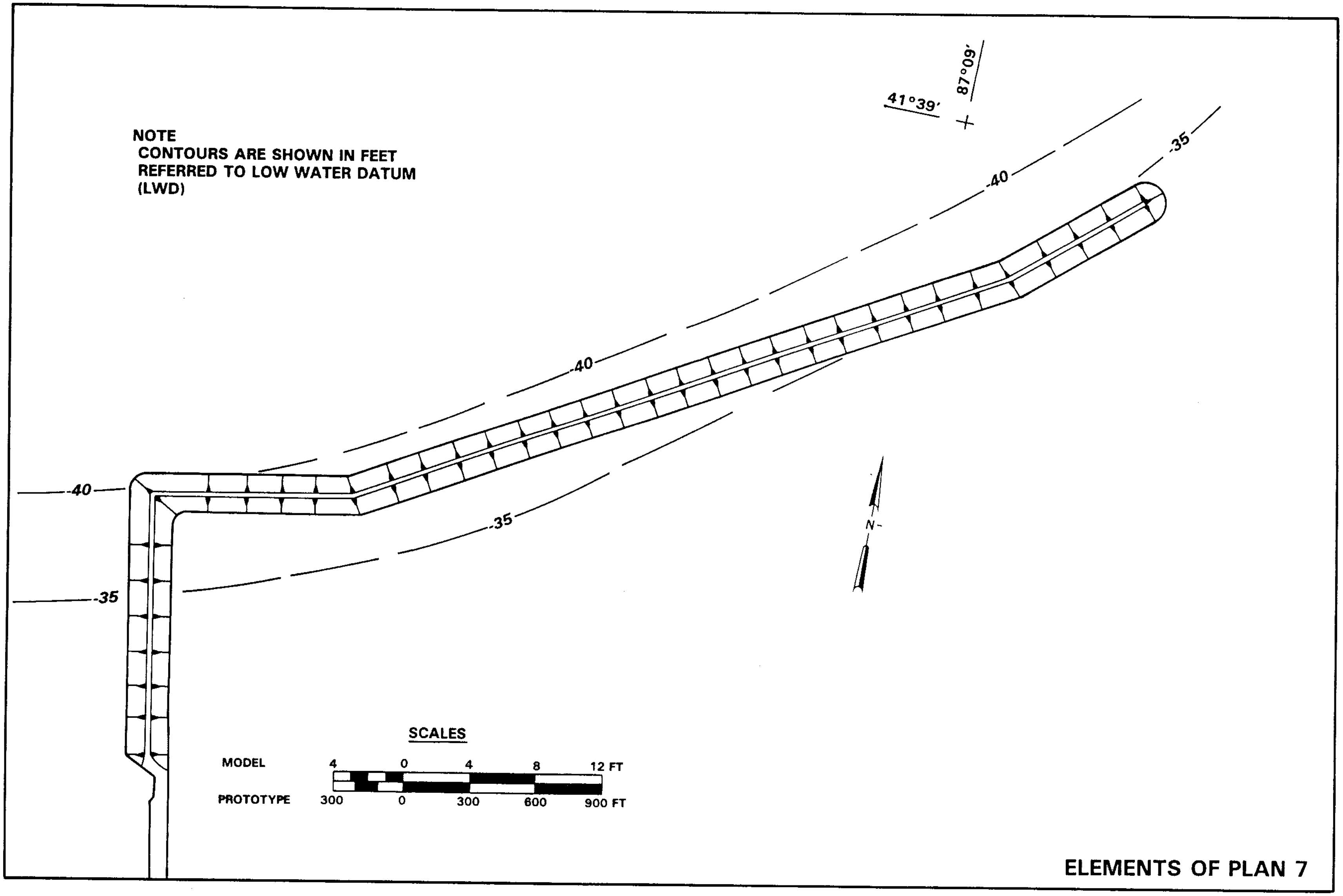
ELEMENTS OF PLAN 3



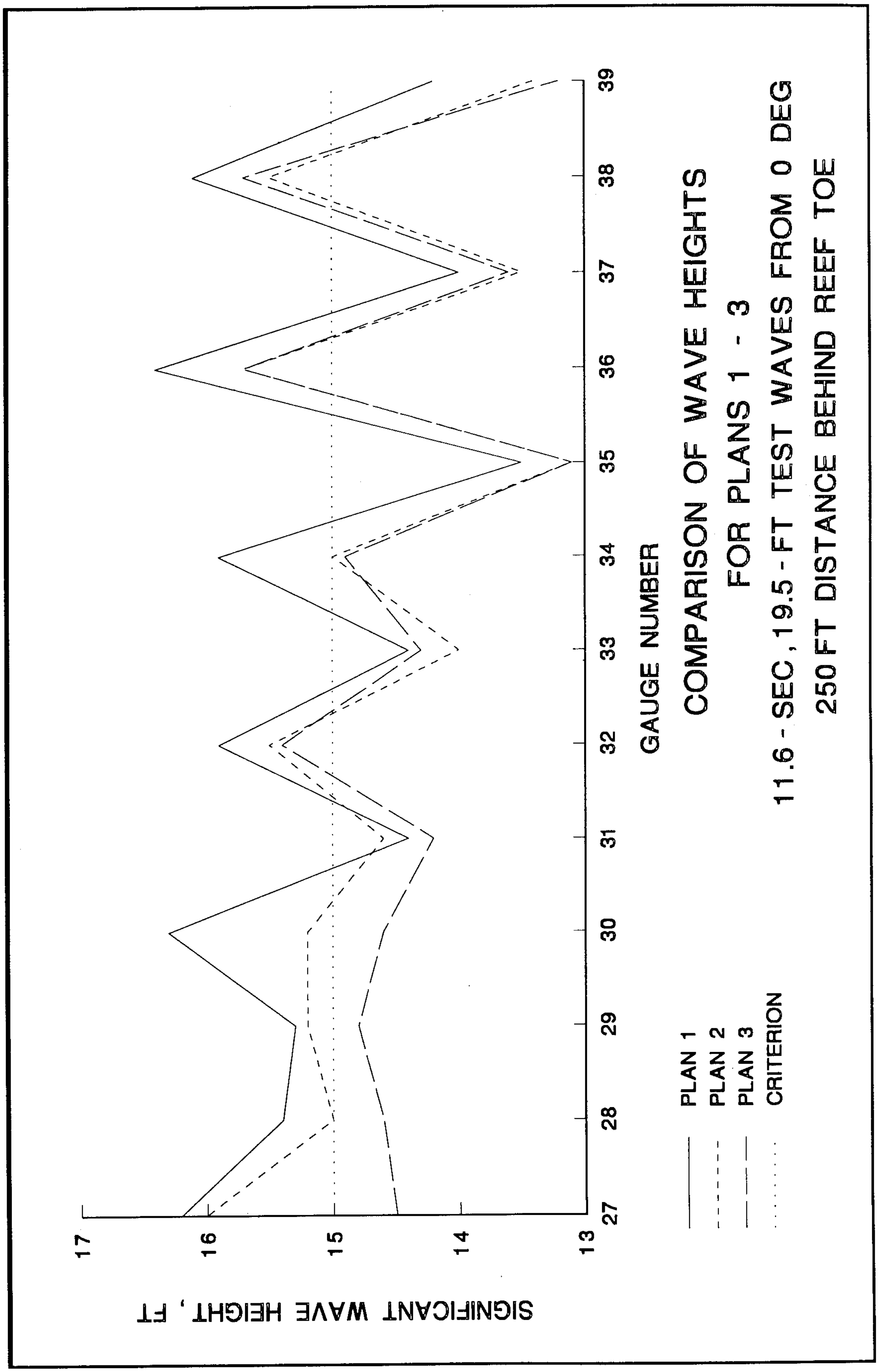
ELEMENTS OF PLANS 4 AND 5



ELEMENTS OF PLAN 6



ELEMENTS OF PLAN 7


SIGNIFICANT WAVE HEIGHT, FT
13
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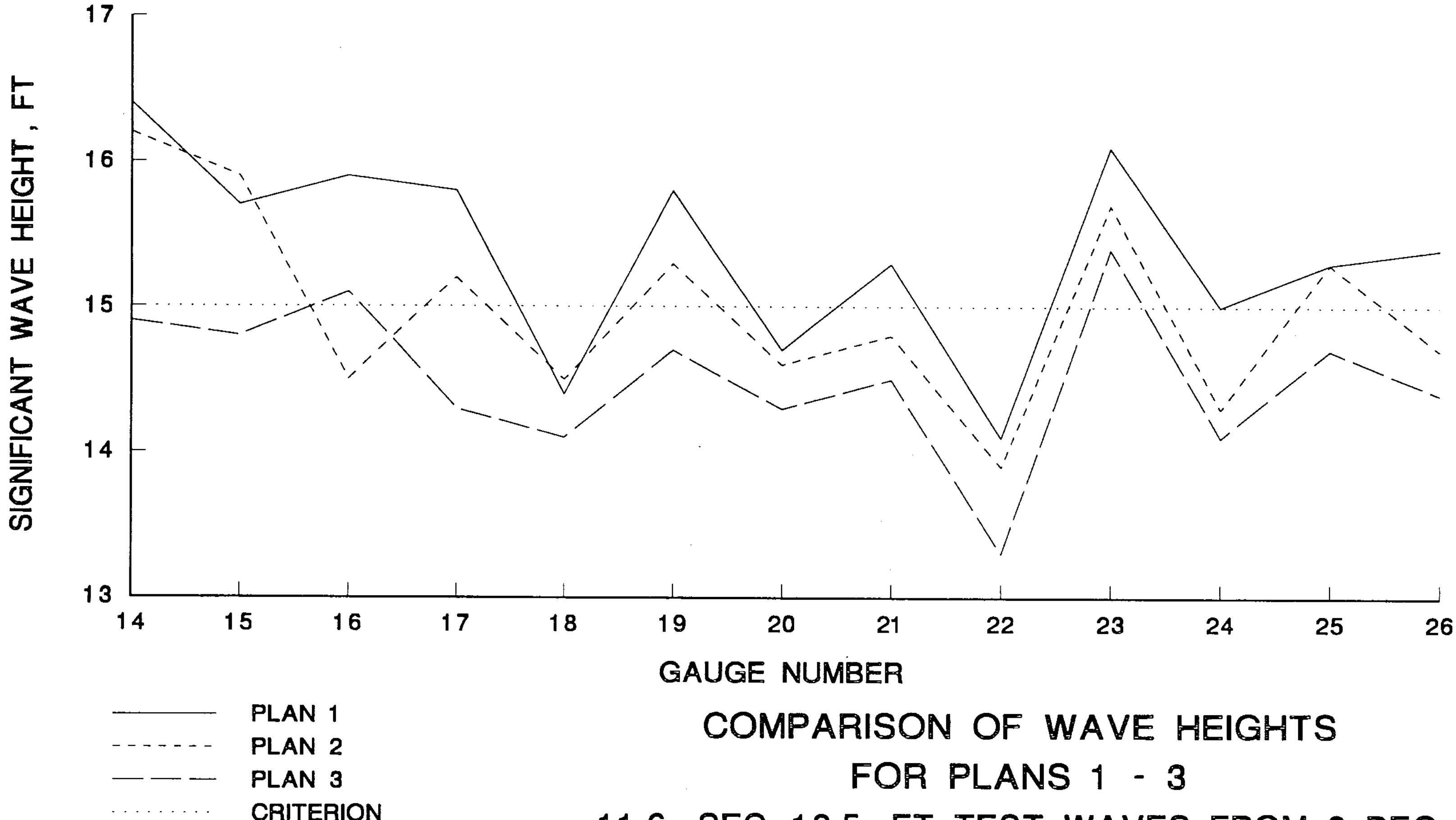
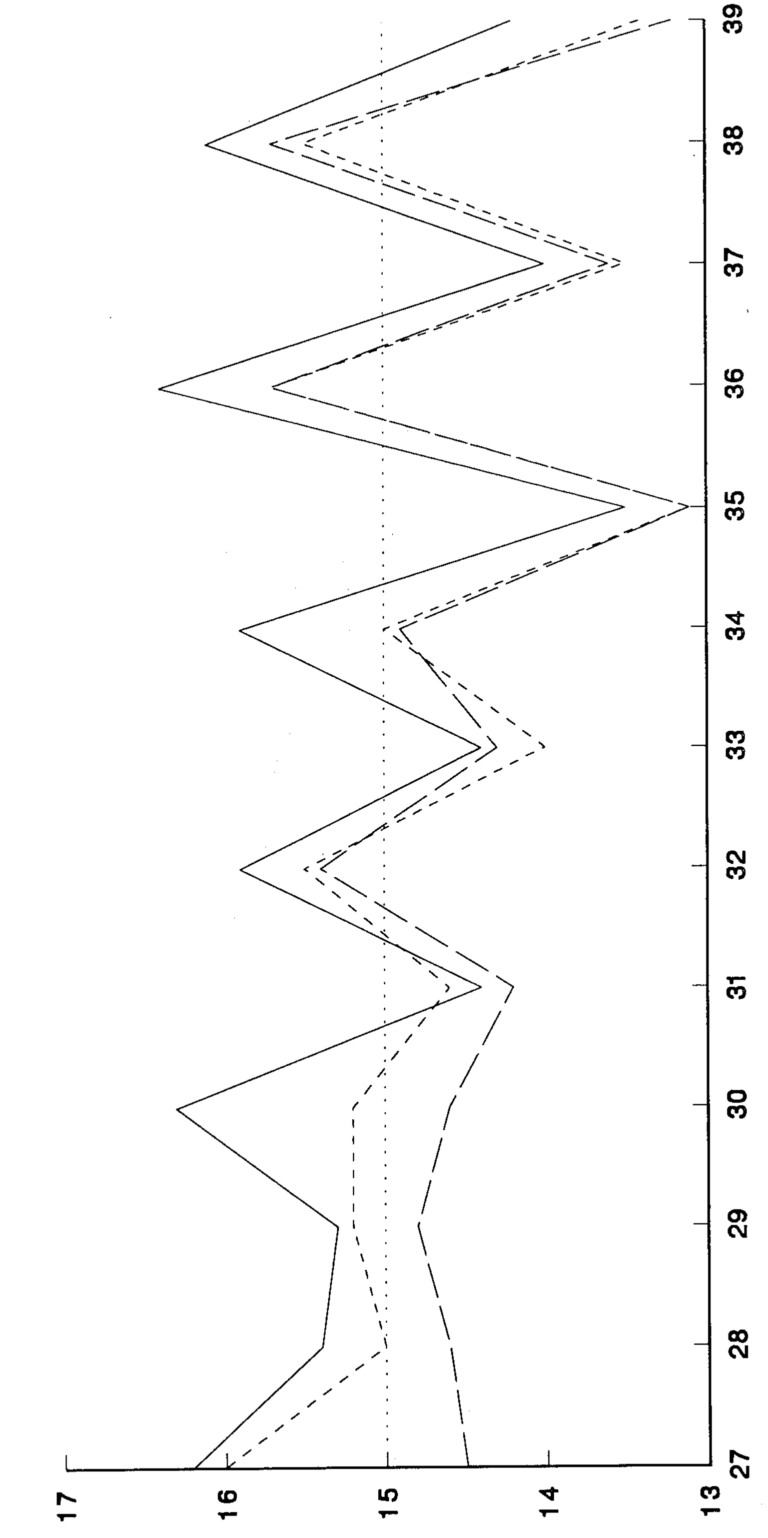
GAUGE NUMBER
PLAN 1
PLAN 2
PLAN 3
CRITERION
COMPARISON OF WAVE HEIGHTS
FOR PLANS 1 - 3
11.6 - SEC, 19.5 - FT TEST WAVES FROM 0 DEG
250 FT DISTANCE BEHIND REEF TOE

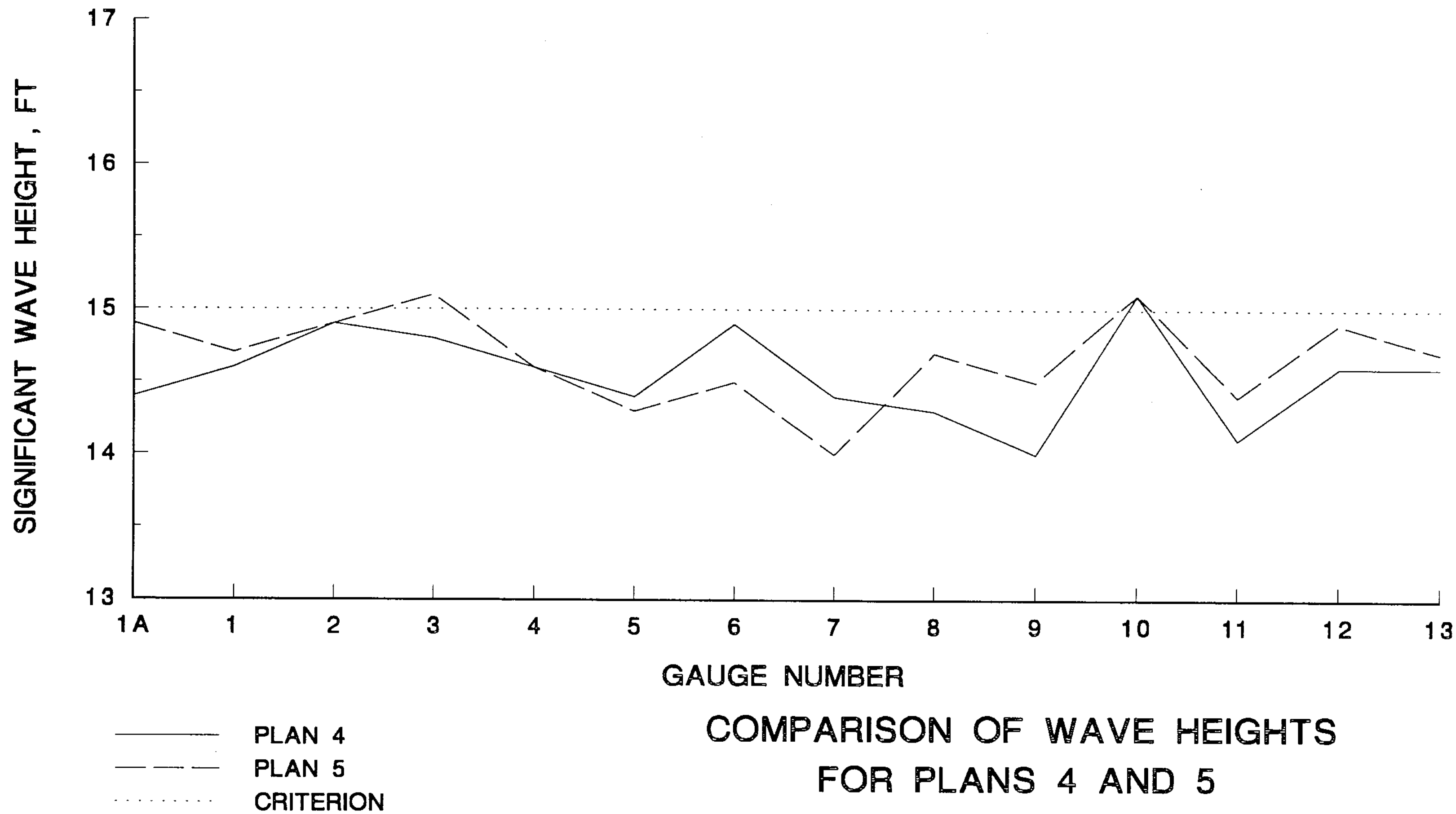


COMPARISON OF WAVE HEIGHTS
FOR PLANS 1 - 3
11.6 - SEC, 19.5 - FT TEST WAVES FROM 0 DEG
150 FT DISTANCE BEHIND REEF TOE



COMPARISON OF WAVE HEIGHTS
FOR PLANS 1 - 3

11.6 - SEC, 19.5 - FT TEST WAVES FROM 0 DEG
250 FT DISTANCE BEHIND REEF TOE



COMPARISON OF WAVE HEIGHTS
FOR PLANS 4 AND 5
11.6 - SEC, 19.5 - FT TEST WAVES FROM 0 DEG
75 FT DISTANCE BEHIND REEF TOE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 1995	Final report

4. TITLE AND SUBTITLE

Reef Breakwater Design for Burns Waterway Harbor, Indiana

5. FUNDING NUMBERS

6. AUTHOR(S)

Hugh F. Acuff, Robert R. Bottin, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

Technical Report
CERC-95-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Engineer District, Chicago
Chicago, IL 14207

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

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

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A 1:75-scale undistorted hydraulic model was used to evaluate the effectiveness of a proposed segmented reef structure, oriented lakeward of the existing Burns Waterway Harbor breakwater, in reducing wave heights reaching the existing breakwaters. The model reproduced bathymetry which extended to an offshore depth of -46 ft in Lake Michigan, and the proposed reef breakwater was located in water depths ranging from -39 to -41 ft. The total area reproduced in the model was approximately 12,000 sq ft, representing about 3.7 square miles in the prototype. An 80-ft-long electrohydraulic, spectral wave generator and an Automated Data Acquisition and Control System were utilized in model operation. It was concluded from the model investigation that (a) the originally proposed reef breakwater plan (Plan 1) will result in excessive wave conditions (in excess of the established 15.0-ft wave height criterion) for 11.6-sec, 19.5-ft incident waves from 0 deg on the leeward side of the proposed reef breakwaters, regardless of its distance from the existing structure, (b) the shoreward toe of the reef breakwater should be located 75-ft lakeward of the existing breakwater's lakeward toe (This distance provides greater wave protection, with less stone volumes, than the other distances tested), (c) of the reef breakwater configurations tested with the 75-ft crest widths, Plan 4 (275-ft-long reef segments with three

(Continued)

14. SUBJECT TERMS		15. NUMBER OF PAGES
Burns Waterway Harbor, Indiana	Transmitted wave energy	89
Hydraulic models	Wave-induced currents	16. PRICE CODE
Reef breakwaters	Wave protection	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

13. Abstract (Concluded).

westernmost openings closed) was acceptableconsidering wave heights obtained in the lee of the structure for 11.6-sec, 19.5-ft incident waves from 0 deg, (d) the 75-ft-wide crest of the Plan 4 reef breakwater configuration can be reduced to 70 ft in width (Plan 5) and still provide acceptable wave protection in the lee of the structure for 11.6-sec, 19.5-ft incident wave conditions from 0 deg, (e) the Plan 5 reef configuration (275-ft-long reef segments with three westernmost openings closed and 70-ft crest widths) will result in acceptable wave heights in the existing harbor for 7- to 11.6-sec, 5-ft and 11.6-sec, 13-ft incident wave conditions, (f) considering wave protection provided in the lee of the reef breakwater and in the existing harbor for various incident wave conditions versus volume of construction materials required, the Plan 4 reef breakwater configuration was selected as optimum, based on the plans tested, and (g) the optimum reef breakwater configuration, in conjunction with the existing breakwater (Plan 6), will have no adverse impacts on wave-induced current patterns and/or magnitudes lakeward of the existing structure.

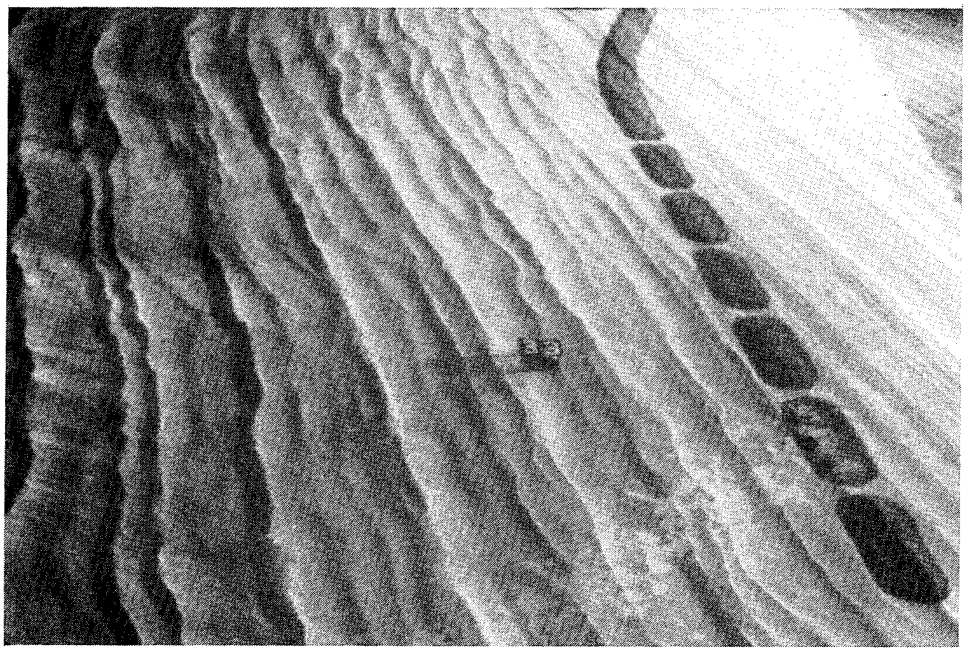


Photo 27. Typical wave patterns for Plan 5; 11.6-sec, 9-ft waves from 330 deg

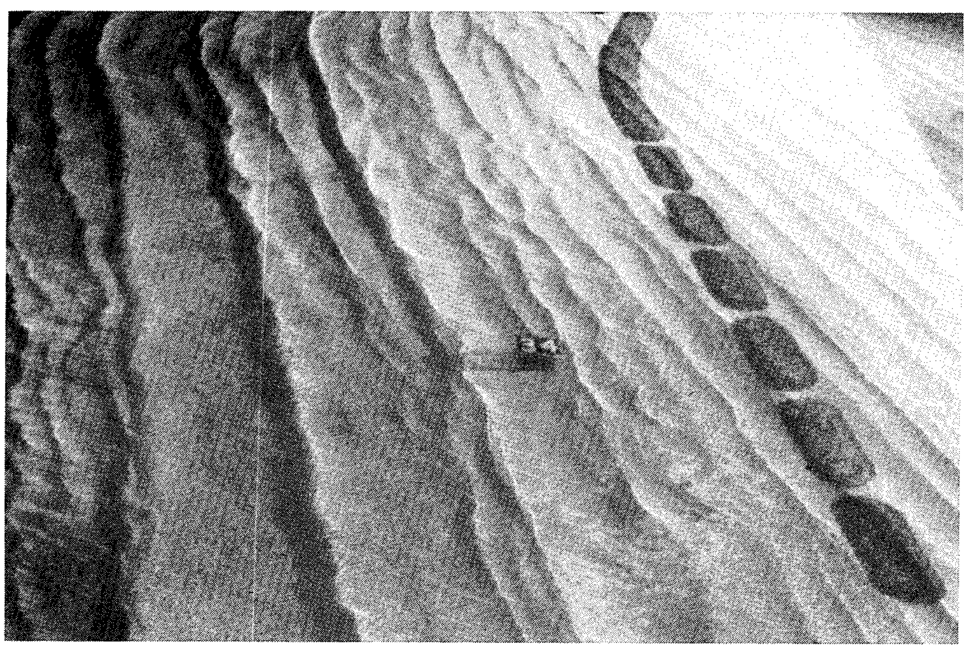


Photo 28. Typical wave patterns for Plan 5; 11.6-sec, 12-ft waves from 330 deg