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WAVE ACTION AND BREAKWATER LOCATION HARBOR OF REFUGE FOR LIGHT-DRAFT VESSELS BARCELONA, NEW YORK

Hydraulic Model Investigation

TECHNICAL REPORT NO. 2-523

September 1959

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

PREFACE

The model investigation described in this report was proposed by the District Engineer, U. S. Army Engineer District, Buffalo, in a letter to the U. S. Army Engineer Waterways Experiment Station, dated 30 March 1956. Authority to perform the investigation was granted by the Chief of Engineers on 21 June 1956. Construction of the model was completed in May 1957, and tests were conducted during the period June 1957 to February 1958.

Liaison was maintained during the course of the investigation by progress reports and conferences. The following representatives of the Buffalo District and North Central Division attended conferences at the Waterways Experiment Station: Colonel L. W. Olmstead, CE, District Engineer; Lt. Col. D. B. Williams, Executive Officer; Mr. S. B. Hunt, Chief, Engineering Division; Mr. J. G. Weinrub, Assistant Chief, Engineering Division; Mr. T. V. Joyce, Chief, Planning and Reports Branch; and Mr. R. D. Repp, Chief, Technical Liaison Branch, all of the U. S. Army Engineer District, Buffalo; Mr. C. F. MacNish, Assistant Chief, Engineering Division; Mr. F. R. Lundsten, Chief, Construction Branch; and Mr. R. E. Emmenegger, engineer, Hydraulics Division, all of the U. S. Army Engineer Division, North Central. Also, Mr. E. Allen, supervisor, Westfield, New York; Mr. H. Monroe, member of Barcelona Harbor Committee, Westfield, New York; Mr. E. Gross, reporter, Buffalo Evening News, Buffalo, New York; and Mr. F. O'Connell, reporter, Courier-Express, Buffalo, New York, attended a conference at the Waterways Experiment Station.

The investigation was conducted in the Wave Action Section, Hydrodynamics Branch, Hydraulics Division, of the Waterways Experiment Station

under the direction of Mr. E. P. Fortson, Jr., Chief of the Hydraulics Division, and Mr. F. R. Brown, Chief of the Hydrodynamics Branch. The tests were conducted by Messrs. R. A. Jackson and J. M. Crow, Jr., under the supervision of Mr. R. Y. Hudson, Chief of the Wave Action Section. This report was prepared by Messrs. R. A. Jackson, R. Y. Hudson, and J. G. Housley.

Directors of the Waterways Experiment Station during the course of the investigation and preparation of this report were Col. A. P. Rollins, Jr., CE, and Col. Edmund H. Lang, CE. Technical director was Mr. J. B. Tiffany.

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SUMMARY

A hydraulic model investigation of the proposed small-boat harbor of refuge at Barcelona, New York, was conducted to determine whether the proposed breakwaters were adequate to protect the enclosed mooring basin from storm waves, and if they were not, to determine the necessary modifications that would provide sufficient protection at minimum cost. The study was performed on a 1:68-scale model constructed of concrete and equipped with wave-generating and wave-height measuring devices. It was concluded from the results of the model tests that a simple arrowhead-type breakwater system, similar to the plan originally proposed, will provide adequate protection from storm waves for small craft properly anchored in the designated mooring area. Also it was found that, because of the characteristic shape of the arrowhead-type breakwater system, only moderate reduction in wave heights would be effected in the entrance channel for waves from most of the storm-wave directions. It would be advisable, therefore, for small craft to enter the harbor as quickly as possible after receipt of storm warnings, before wave action in the vicinity of Barcelona becomes appreciable. It is recommended that: (a) the width of the original design navigation opening be reduced from 200 to 150 ft; (b) the angle in the original design west breakwater be eliminated; and (c) the length of the original design east breakwater be reduced by removing 200 ft from its shoreward end.

WAVE ACTION AND BREAKWATER LOCATION

HARBOR OF REFUGE FOR LIGHT-DRAFT VESSELS

BARCELONA, NEW YORK

Hydraulic Model Investigation

PART I: INTRODUCTION

1. The site of the proposed harbor at Barcelona, New York, on the south shore of Lake Erie about 30 miles east of Erie, Pennsylvania, and about 59 miles west of Buffalo, New York (fig. 1), is exposed to wind waves generated by storms from all directions from about west-southwest clockwise to northeast. These limiting directions are determined by the shape of Lake Erie and the location of the harbor site with respect to the lake shores. At the present time, there is a small shallow-water mooring area at Barcelona which is protected from westerly storm waves by a short peninsula aligned in a north-south direction. However, a dredged harbor with protecting breakwaters is desired to provide protection for recreational, light-draft fishing, and other commercial vessels from waves from all storm directions.

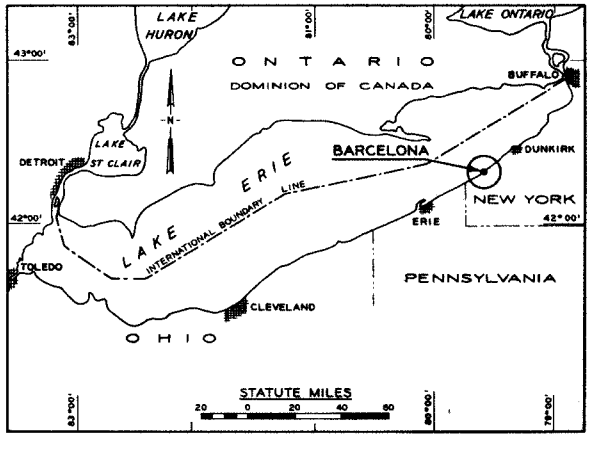

Fig. 1. Location map

2. The purpose of the model study was to determine whether the proposed arrowhead-type breakwater system would provide adequate protection for small craft anchored in the enclosed mooring area from wave action during storms on Lake Erie, and if it would not, to develop a plan which would provide sufficient protection. If the proposed breakwaters proved capable of providing the desired protection from storm-wave action, it was desired that the optimum arrangement of the basic elements of the proposed plan be determined as well as any possible economies in construction.

PART II: THE MODEL

Design of Model

3. The Barcelona harbor model was constructed to a linear scale of 1:68, model to prototype. Selection of this scale was based on consideration of such factors as: (a) the depth of water required in the model to prevent excessive bottom friction effects; (b) the absolute size of the model waves; (c) the available shelter and model-basin area; (d) the efficiency of model operation; (e) the characteristics of available wave-generating and wave-measuring apparatus; and (f) the cost of model construction. A geometrically undistorted model was necessary to insure accurate reproduction of wave patterns. After the linear scale had been selected, based on the above-listed considerations, the model was designed and operated in accordance with Froude's model law. Based on Froude's law, the linear scale (L_r) of 1:68, and a specific-weight scale (γ_r) of 1:1, the following model-prototype relations were derived:

Characteristics	Dimensions*	Model-Prototype Scales
Length	L	$L_r = 1:68$
Area	L^2	$A_r = L_r^2 = 1:4624$
Volume	L^3	$V_r = L_r^3 = 1:314,432$
Time	T	$T_r = L_r^{1/2} = 1:8.25$
Velocity	L/T	$V_r = L_r^{1/2} = 1:8.25$
Unit pressure	F/L^2	$P_r = L_r \gamma_r = 1:68$
Force	F	$F_r = L_r^3 \gamma_r = 1:314,432$

* In terms of force, length, and time.

Description of Model

4. The model was constructed of concrete, and reproduced to scale the proposed prototype harbor and the contours of the lake bottom adjacent to the harbor. A sufficient area was reproduced (1700 sq ft in the model,

equivalent to 0.28 sq mile in the prototype) upshore, downshore, and lakeward to permit generation of waves and wave-front patterns from the different wind directions selected for testing. Model limits are shown in fig. 2.

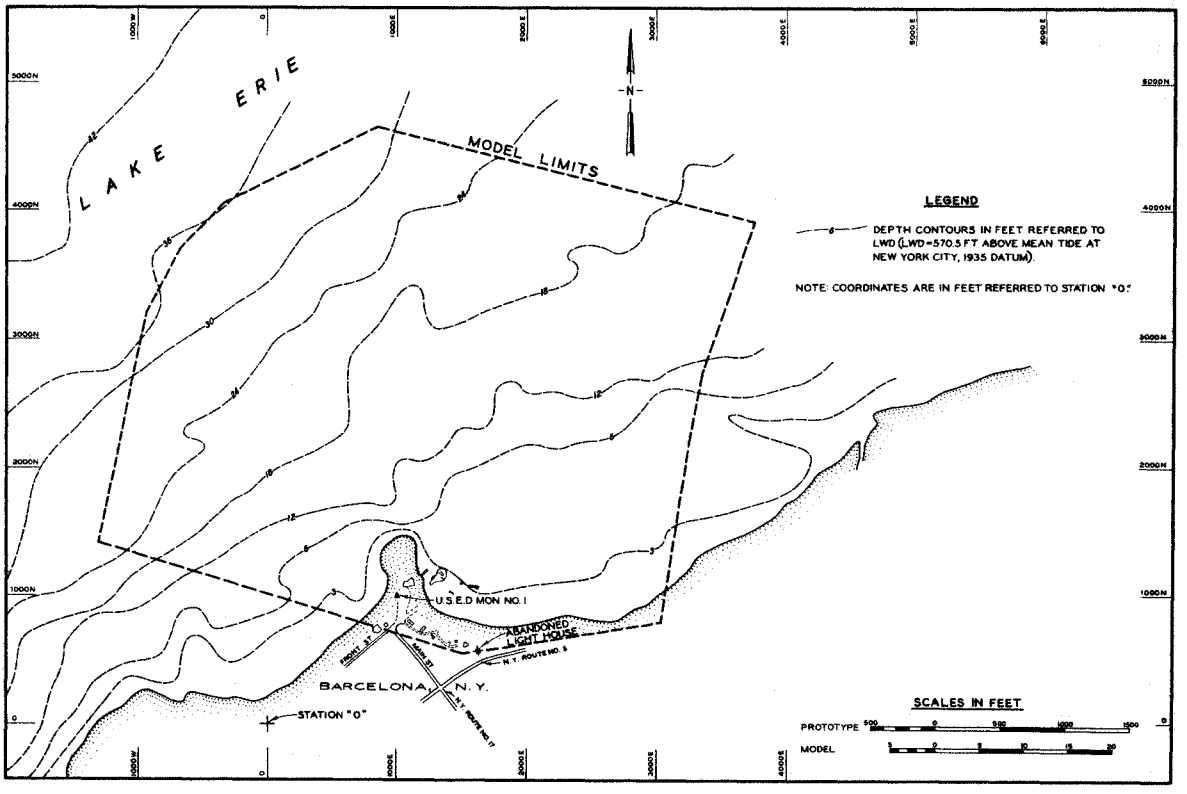

Fig. 2. Vicinity map and model limits

The model breakwaters were constructed of concrete, and reproduced to scale the proposed cellular breakwaters.

5. Model waves were generated to scale by a 30-ft-long, plunger-type wave machine. The vertical motion of the plunger caused a periodic displacement of the water incident to this vertical motion. The plunger stroke and speed were infinitely variable over the range necessary to generate waves with characteristics at the selected model scales. In addition, the wave machine was mounted on casters which permitted the machine to be moved in order to generate waves from the various directions. Wave heights were recorded on photosensitive paper by an electrically operated oscillograph. The input to the oscillograph was the electrical output of wave-height gages which measured the changes in water-surface elevations with respect to time. The output of each wave-height gage is directly proportional to the submergence of the gage.

PART III: THE TEST PROGRAM

Selection of Test Conditions

Still-water level

6. Still-water levels (swl) for harbor wave-action models are selected so that the effects of water depths on wave refraction, diffraction, and reflection are accurately reproduced. For the present problem, however, variations in water depths in Lake Erie have more effect on wave refraction than on either the diffraction or reflection of waves. It is usually unnecessary in harbor model studies to perform tests using the complete range of lake levels which occur during storms of different intensities throughout the year. For most wave-action models, it is sufficient to conduct the tests using a still-water level equal to the average lake level in the problem area during a storm of moderate intensity.

7. Water levels of the Great Lakes vary from year to year and from month to month. Also, at particular localities, the water levels vary from day to day and from hour to hour. Continuous records of the levels of the Great Lakes have been tabulated by the U. S. Army Engineer District, Lake Survey, since the year 1860.[8*] Low-water datum (lwd) for Lake Erie is 570.5 ft above mean tide at New York City, 1935 datum. The usual pattern of seasonal variation of water levels in the Great Lakes consists of highs in summer and lows in late winter. The highest and lowest monthly average levels in Lake Erie usually occur in June and February, respectively. Occasionally, however, monthly fluctuations have departed considerably from the usual pattern. The average level of Lake Erie during the period 1860-1952 was 572.3 ft above mean tide at New York City. The highest one-month average level of 574.6 ft occurred in April 1952, and the lowest one-month average level of 569.4 ft occurred in February 1936. The seasonal variation in the mean monthly level of Lake Erie usually ranges between 1 and 2 ft, with an average variation of 1.6 ft. The following tabulation shows the percentage of time that the annual high monthly level of Lake Erie reached various elevations (above mean tide at New York City) during the period from 1860 to 1952:

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* Superscript numerals refer to similarly numbered items in the list of references.

Annual Maximum Monthly Mean Levels, ft	Frequency of Occurrence, per cent*
569.4 (minimum)	100
570.0	99.9
571.0	98
572.0	89
572.3 (average)	82
573.0	55.5
573.2	47
574.0	14
574.6 (maximum)	1

* Example: Lake Erie reached a monthly average level of 572.0 ft 89 per cent of the years between 1860 and 1952, or 83 times.

8. Seasonal and longer-period variations in Great Lakes' levels 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 superimposed on the longer-period variations in lake level. These fluctuations are caused by the tractive force of wind blowing over the water surface, and differential atmospheric pressures associated with fronts and squall lines. Records of the frequancy of occurrence of short-period fluctuations at the site of the proposed harbor are not available. However, such data for Buffalo Harbor are available[9] and are presented in the following tabulation:

Short-Period Rise Above General Lake Level at Buffalo, ft	Interval Between Occurrence of Given Rise, months
1	1/2
2	1
3	2
4	5
5	13
6	37
7	94
8	368

Because of the proximity of Buffalo to Barcelona, these data can be used to estimate the magnitude and frequency of corresponding fluctuations in the local lake level at Barcelona.

9. Wind tides pertinent to the selection of the still-water level for the Barcelona harbor study are caused by winds blowing from west to east, and from east to west, along the longitudinal axis of Lake Erie. Winds blowing from west to east cause an increase in lake level at Barcelona; winds from east to west cause a decrease. Because of the short fetch length, wind tides caused by winds moving normal to the longitudinal axis of the lake are small.

10. Wind data[7] show that the predominant winds are from directions between southwest and northwest, although severe winds also blow from the northeast. Wave and wind data indicate that a westerly wind with a speed of about 35 mph represents a storm of average severity at Barcelona from this direction. According to Keulegan,[3,4] a westerly wind with a speed of 35 mph causes a rise of 3.8 ft at Buffalo. In a study of wind tides in Lake Erie, Hellström[2] locates the nodal line about 20 miles east of Cleveland, Ohio. Thus, based on the slope of the water surface from the nodal line to the loop at Buffalo, a +3.8-ft wind tide at Buffalo corresponds to a wind tide of about +1.9 ft at Barcelona.

11. The tabulation in paragraph 7 shows that the annual high monthly mean lake level is equal to or greater than the average lake level (572.3 ft) 82 per cent of the years of record (or 76 times in 93 years). From the tabulation in paragraph 8 it is seen that a short-period rise of 3.8 ft in the water level at Buffalo occurs about once in five months. Since the frequency of occurrence of short-period fluctuations at Buffalo and Barcelona are assumed equal, a short-period rise of 1.9 ft may be assumed to occur about once in five months at Barcelona. Assuming that a wind tide of +1.9 ft can occur with equal probability in any month of the year, an annual high mean monthly lake level of 572.3 ft will coincide in time with a wind tide of +1.9 ft about once in 10 months. If a mean monthly lake level of 572.3 ft is combined with a short-period rise of 1.9 ft, a still-water level of 574.2 ft, or +3.7 ft lwd, is obtained. During the navigation season, the frequency of occurrence of lake levels greater than 574.2 at the proposed harbor site will be rare because the most severe storms, which are required to generate the higher wind tides, usually occur in the winter months when the general lake level is low. Therefore, a still-water level of +3.7 ft lwd

was used in the Barcelona harbor model for all tests conducted.

Wave dimensions, directions, and durations

12. Deep-water waves. As stated in paragraph 1, the harbor at Barcelona will be exposed to surface wind waves generated by storms from all directions from about west-southwest clockwise to northeast. Surface wind waves are generated and sustained by the transfer of energy from the wind to the water. The waves receive energy from the normal force of the wind against the wave crests and from the tangential force exerted by the wind blowing over the water surface. Waves generated in this manner are referred to as deep-water waves if they travel in water of depths greater than one-half the wave length. The dimensions of the waves are determined by the duration and speed of the wind, and the fetch distance over which the wind blows.

13. Only a few experimental wave-recording stations are presently in existence throughout the world, and very few wave records are available for specific locations from which design waves for prototype structures, and test waves for model investigations, can be selected. However, wind records covering considerable periods of time are usually available, and recent developments in the technique of wave forecasting and hindcasting have made it possible to convert such records into statistical wave data. The wave forecasting relations proposed by Sverdrup and Munk,[6] and revised by Bretschneider[1] are now in general use.

14. Information from which the duration of deep-water waves, of different heights and from the various directions, in the vicinity of Barcelona can be estimated is contained in a report by Saville.[5] The report includes a three-year record (1948-1950) for a wave station near Erie, Pennsylvania. Because of the proximity of Erie to Barcelona, the fetch distances for the different storm directions at these two locations are about the same. Consequently it was assumed that differences in the dimensions of waves at the two stations would not be large enough to affect the accuracy of the model test results. The wave-occurrence data shown in table 1 were reduced from Saville's data for wave station C, near Erie, and were used for estimating the duration of deep-water waves from the various directions in the vicinity of Barcelona.

15. Shallow-water waves. Wave heights and wave-front orientations are affected by the bottom configuration for water depths less than one-half the deep-water wave length. Therefore, since the depths of water in the Barcelona area are less than one-half the deep-water wave lengths, it was necessary to compute the shallow-water wave heights and directions of travel for the waves selected for testing. Shallow-water wave heights were determined for the area immediately lakeward of the navigation opening into the proposed harbor. These data were reduced from the frequency-of-occurrence data for deep-water waves (table 1) using refraction coefficients calculated from wave-refraction diagrams. These diagrams were constructed by the direct orthogonal method, using smoothed depth contours. Table 2 shows durations of shallow-water waves corresponding to the various deep-water wave directions.

16. Selection of the wave dimensions and directions used in the model tests was based on consideration of: (a) the need for good navigation conditions in the entrance channel during storms of mild intensity (small waves); (b) the need for relative calm in the mooring area during storms of near maximum intensity (large waves); (c) the duration of waves of various heights from the different directions; (d) the alignment, width, and position of the navigation opening into the harbor; and (e) the alignment, length, and position of the various components of the breakwater plans. The dimensions and directions of the waves selected for use in testing the various breakwater plans were as follows:

Wave Period	Deep-Water Waves		Shallow-Water Waves*	
sec	Direction	Wave Height ft	Direction	Wave Height ft
6.0	West	8.0	N85°14'W	6.2
4.0	West	4.0	N87°07'W	3.1
6.0	N67°30'W	9.0	N60°15'W	8.6
4.0	N67°30'W	4.0	N66°45'W	3.8
5.0	N45°W	8.0	N44°25'W	7.4

(Continued)

* The wave machine was positioned and the plunger stroke and speed set so that the shallow-water wave conditions tabulated above obtained in the location designated "area of navigation opening (base conditions)" in fig. 4 (page 12).

Wave Period sec	Deep-Water Waves Direction	Deep-Water Waves Wave Height ft	Shallow-Water Waves Direction	Shallow-Water Waves Wave Height ft
4.0	N45°W	4.0	N44°40'W	3.7
4.0	N22°30'W	8.0	N22°30'W	7.0
4.0	N22°30'W	4.0	N22°30'W	3.5
5.0	N22°30'E	7.0	N8°04'E	5.6
4.0	N22°30'E	4.0	N12°57'E	3.2
5.0	N45°E	7.0	N22°30'E	5.6
4.0	N45°E	4.0	N22°30'E	3.2

Description of Plans Tested

17. Preliminary observational tests indicated that an arrowhead-type breakwater system would provide adequate protection during storms to boats moored in the harbor; consequently, to conserve time and money, the arrowhead breakwater system was the only type tested. Conditions tested included: base, or present, conditions, the proposed plan (designated plan 1), and six modifications of the proposed plan.

18. The elements of the base conditions were the shore line, structures, and bathymetry existing at the site of the proposed harbor at the time of the model investigation. Elements of plan 1 included a dredged harbor basin 9 ft deep, 350 ft wide, and 800 ft long; a west breakwater 794 ft long, extending in a northerly direction from the peninsula on the west side of the basin; a detached east breakwater 890 ft long, aligned in a northwesterly-southeasterly direction on the east side of the harbor basin; and a 200-ft-wide navigation opening between the lakeward ends of the east and west breakwaters. This plan also included a dredged entrance channel 100 ft wide and 11 ft deep, extending from the harbor basin to 11-ft-deep water in Lake Erie. The breakwaters are proposed to be of steel-sheet pile, cellular construction, with crown elevations of +6 and +8 ft lwd for the east and west breakwaters, respectively.

19. The modifications of plan 1, designated plans 1A through 1F, were tested to determine the effect of: (a) reducing the width of the navigation opening from 200 to 150 ft; (b) realigning the west breakwater;

(c) reducing the length of the east breakwater in decrements of 100 ft; and

(d) extending the east breakwater 100 ft lakeward.

20. Elements of the harbor plans tested are shown in fig. 3 and are summarized in the following tabulation:

Plans Tested	Elements of Plan
Plan 1	Dredged harbor basin 350 ft wide by 800 ft long by 9 ft deep; 794-ft west breakwater; 890-ft east breakwater; 200-ft navigation opening
Plan 1A	Same as plan 1 except navigation opening reduced from 200 to 150 ft
Plan 1B	Same as plan 1A except west breakwater realigned to eliminate the angle near lakeward terminus
Plans 1C, 1D, and 1E	Same as plan 1A except length of east breakwater reduced 100, 200, and 300 ft, respectively
Plan 1F	Same as plan 1 except east breakwater extended 100 ft lakeward

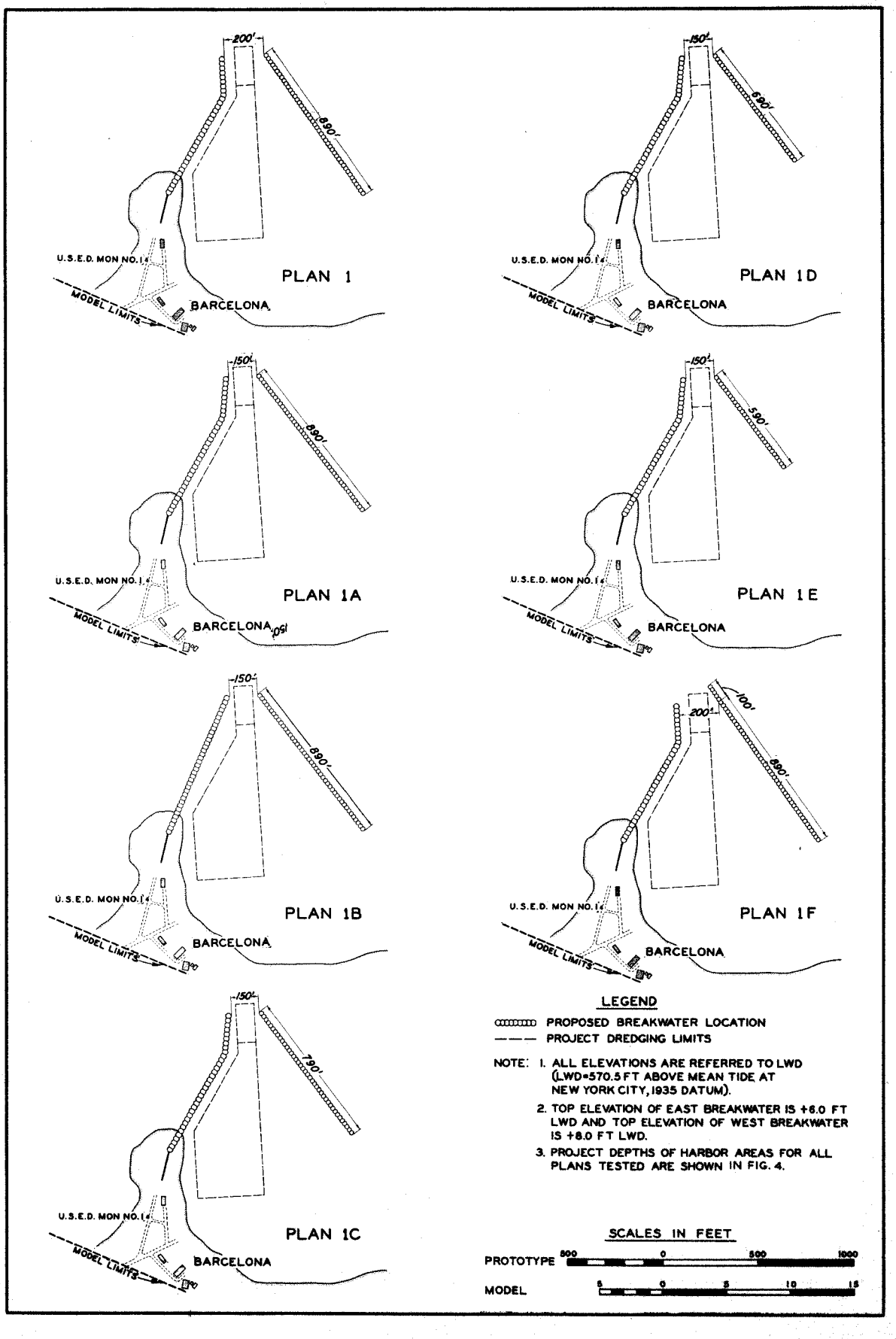


Fig. 3. Elements of plans

PART IV: RESULTS OF MODEL TESTS

Method of Analyzing Test Data

21. Wave-height-reduction coefficients for the different harbor areas (see fig. 4) were determined from the model test data. These reduction coefficients are defined as the ratios of average wave heights measured in the various problem areas to the corresponding shallow-water wave heights. The average coefficient for each deep-water wave direction was

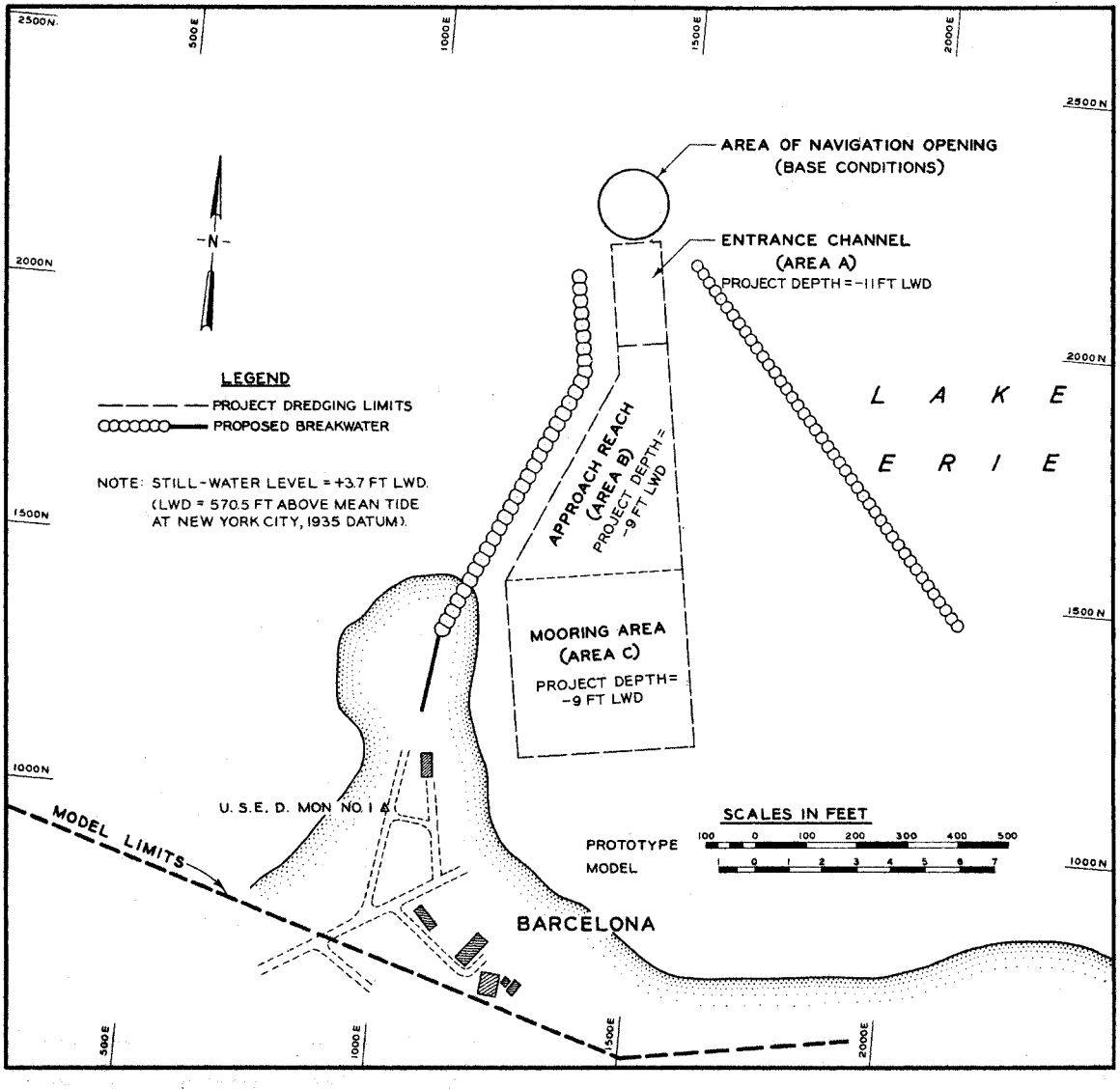


Fig. 4. Harbor areas

applied to the shallow-water wave statistics of table 2 to obtain wave durations for the four harbor areas. It was not considered necessary to conduct tests using all the different wave conditions for each plan; the wave-reduction coefficients for the wave conditions not tested were obtained by interpolation.

Presentation of Test Data

22. Selected wave conditions and wave heights in the problem areas of the harbor for tests of base conditions and the different plans, from which wave-height-reduction coefficients were calculated, are presented in table 3. Wave-front patterns for selected deep-water test waves are shown in photographs 1 to 31.

Test Results

Base conditions

23. The results of the redistribution of wave durations by the application of base-test wave-height-reduction coefficients to the shallow-water wave statistics are tabulated below.

Wave Height ft	Duration of Waves in Problem Areas hr per yr			
	Area of Navigation Opening	Area A	Area B	Area C
0-0.5	None	None	None	764
0.5-1	208	208	208	1114
1-2	1310	1408	1152	954
2-3	868	848	798	350
3-4	514	458	506	146
4-5	252	256	248	
5-6	98	104	12	
6-7	34	22	4	
7-8	18	12		
8-9	18	6		
9-10	2	None		
10-11	6	6		

24. After discussion with engineers familiar with navigation problems and the desired navigation conditions in small-boat harbors, it was decided that waves more than 2 ft in height in mooring areas are a hazard

to the safe anchorage of small craft. The data tabulated on the preceding page show that waves up to 4 ft high occur in the mooring area (area C); thus, for a remedial plan to be satisfactory, it should result in a wave-height reduction of at least 50 per cent.

Plan 1

25. The results of applying wave-height-reduction coefficients, determined from tests of plan 1, to the shallow-water wave statistics are presented in the following tabulation:

Wave Height ft	Duration of Waves in Problem Areas hr per yr		
	Area A	Area B	Area C
0-0.5	None	380	1022
0.5-1	164	1148	1864
1-2	1040	1522	430
2-3	976	258	12
3-4	660	16	
4-5	252	4	
5-6	172		
6-7	34		
7-8	18		
8-9	6		
9-10	6		

These data show maximum wave heights of 10, 5, and 3 ft in test areas A, B, and C, respectively, with plan 1 installed. The durations of these maximum waves are short, however, and area C mooring conditions should be satisfactory for all except severe storms.

Plan 1A

26. The results of tests to determine the effect of reducing the width of the navigation opening from 200 to 150 ft (plan 1A) are shown in the following tabulation of wave durations.

Wave Height ft	Duration of Waves in Problem Areas hr per yr		
	Area A	Area B	Area C
0-0.5	None	854	2058
0.5-1	164	1492	1028
1-2	1040	826	242
2-3	1356	148	
3-4	434	8	
4-5	180		
5-6	112		
6-7	30		
7-8	2		
8-9	10		

Comparing these data with the data for plan 1 (paragraph 25) reveals that the maximum wave heights in each of the three problem areas were reduced 1 ft by narrowing the navigation opening from 200 to 150 ft, and the limiting maximum height of 2 ft in area C was not exceeded.

Plan 1B

27. The results of tests to determine the effects of realigning the west breakwater are shown by the wave durations tabulated below:

Wave Height ft	Duration of Waves in Problem Areas hr per yr		
	Area A	Area B	Area C
0-0.5	None	1150	2196
0.5-1	208	1434	932
1-2	1830	648	200
2-3	842	96	
3-4	312		
4-5	92		
5-6	34		
6-7	6		
7-8	4		

Comparison of these data with that of plan 1A (paragraph 26) shows that straightening the west breakwater would reduce the maximum wave height 1 ft in both areas A and B. Although the maximum wave height in the mooring area (area C) for both plans 1A and 1B is 2 ft, the duration of these waves with plan 1B installed is slightly less than with plan 1A.

Plans 1C, 1D, and 1E

28. The results of tests to determine the effect of removing 100-, 200-, and 300-ft lengths, plans 1C, 1D, and 1E, respectively, from the shoreward end of the east breakwater are presented as wave durations in the mooring area in the following tabulation:

Wave Height ft	Duration of Waves in Mooring Area hr per yr		
	Plan 1C	Plan 1D	Plan 1E
0-0.5	2058	1904	1904
0.5-1	1028	1174	1078
1-2	242	250	342
2-3			4

Comparisons of these data with the data from plan 1A (paragraph 26) show that the shoreward end of the east breakwater could be shortened 200 ft without appreciable increase in wave action in the mooring area.

The above-listed data also show that removal of 300 ft would increase the maximum wave in the mooring area from 2 to 3 ft, and would increase the duration of 2-ft waves about 40 per cent.

Plan 1F

29. The results of tests to determine the effect of extending the east breakwater 100 ft lakeward are presented as wave durations in the problem areas in the following tabulation:

Wave Height ft	Duration of Waves in Problem Areas hr per yr		
	Area A	Area B	Area C
0-0.5	None	208	1844
0.5-1	208	1830	1232
1-2	1358	1120	252
2-3	1064	160	
3-4	388	10	
4-5	224		
5-6	42		
6-7	18		
7-8	20		
8-9	6		

Comparison of these data with the results of tests of plan 1 (paragraph 25) shows that the maximum wave heights in areas A, B, and C are each reduced 1 ft by the 100-ft extension of the east breakwater.

Summary of Results

30. To facilitate direct comparisons of the several plans tested, the results of all the tests conducted in this investigation are summarized in table 4, which presents estimated durations of waves of various heights in the four problem areas of the harbor. It can be seen from this table that plans 1A, 1B, 1C, 1D, and 1F meet the criterion of a maximum wave height of 2 ft in the mooring area.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

31. Based on analysis of the model test results, consideration of the function of the proposed harbor, and the assumption that the largest wave that can be tolerated in the mooring area of the harbor is 2 ft in height, it is concluded that:

a. An arrowhead-type breakwater system similar to that tested in this investigation would provide adequate protection to small craft moored in the mooring area of the proposed harbor during the most severe storms likely to occur on Lake Erie.

b. The navigation opening should be 150 ft in width.

c. The west breakwater should have a straight alignment, as in plan 1B.

d. Wave action in the mooring area would not be increased by removal of 200 ft of the shoreward end of the originally proposed east breakwater, as in plan 1D.

e. Extending the originally proposed east breakwater 100 ft lakeward, as in plan 1F, would not provide sufficient additional protection to justify the cost.

f. None of the plans tested provide better than moderate reduction in wave heights in the entrance channel for a majority of the storm-wave directions; it would be advisable, therefore, that all boats seeking refuge from storms enter the harbor immediately after receipt of storm warnings.

Recommendations

32. It is recommended that consideration be given to adoption of the following modifications in the elements of the original breakwater plan proposed for the harbor of refuge at Barcelona:

a. Reduce the width of the navigation opening of the original plan from 200 ft to 150 ft.

b. Eliminate the angle in the west breakwater (this results in a simple arrowhead-type breakwater system).

c. Reduce the length of the east breakwater of the original plan by removing 200 ft from its shoreward end.

REFERENCES

1. Bretschneider, C. L., "Revised wave forecasting relationships." Proceedings, Second Conference on Coastal Engineering (1952), pp 1-5.

2. Hellström, B., Wind Effect on Lakes and Rivers. Handlingar, Ingeniörs Vetenskaps Akademien, No. 158, 1941.

3. Keulegan, G. H., "Wind tides in small closed channels." Journal of the National Bureau of Standards, vol 46, No. 5 (1951), pp 358-381.

4. _____, "Hydrodynamical evaluation of storms on Lake Erie." Proceedings, Second Conference on Coastal Engineering (1952), pp 37-47.

5. Saville, T., Jr., Wave and Lake Level Statistics for Lake Erie. Beach Erosion Board Technical Memorandum No. 37, Washington, D. C., 1953.

6. Sverdrup, H. U., and Munk, W. H., Wind, Sea, and Swell: Theory of Relations for Forecasting. U. S. Navy Hydrographic Office Publication No. 601, Washington, D. C., 1947.

7. U. S. Army Engineer District, Buffalo, CE, Definite Project Report on Barcelona Harbor, New York. Buffalo, New York, 1945.

8. U. S. Army Engineer District, Lake Survey, CE, Variations in Great Lakes Levels. Detroit, Michigan, 1952.

9. U. S. Army Engineer Division, Great Lakes, CE, Preliminary Examination Report on Property Damage on the Great Lakes, Resulting From Changes in Lake Levels. Chicago, Illinois, 1952.

Table 1

Duration of Deep-Water Waves at Station C,*

Generated by Storm Winds From Various Directions

Wave Height ft	Duration, hr/yr, for Wave Period of 1-2 sec	2-3 sec	3-4 sec	4-5 sec	5-6 sec	6-7 sec
			Wind From S67-1/2°W			
0.5-1	14	8	2			
1-2	2	72	38			
2-3		42	10	8		
3-4		6	28	14		
4-5			14	8		
5-6			2	4	4	
6-7			2	6		
7-8						
8-9					2	2
9-10						
10-11					4	
			Wind From West			
0.5-1	16	4	2			
1-2	2	138	58	2		
2-3		114	94	22		
3-4		14	100	40		
4-5			32	26		
5-6			16	24	12	
6-7			18	20	6	
7-8				8	4	
8-9				4	2	
9-10					4	
10-11					4	
11-12					2	
			Wind From N67-1/2°W			
0.5-1	16	2				
1-2	12	74	28			
2-3		30	68			
3-4		10	64	4		
4-5			30	24		
5-6			4	16		
6-7			2	6		
7-8				6		
8-9				4	2	4
9-10						
10-11					6	

(Continued)

* Data in this table were reduced from Saville's data[5] for wave station C, near Erie, Pennsylvania, and were used for estimating the duration of deep-water waves in the vicinity of Barcelona.

Table 1 (Continued)

Wave Height ft	Duration, hr/yr, for Wave Period of 1-2 sec	2-3 sec	3-4 sec	4-5 sec	5-6 sec	6-7 sec
			Wind From N45°W			
0.5-1	20	4				
1-2	10	158	10			
2-3		38	106			
3-4			58			
4-5			34	6		
5-6			2	12		
6-7				4		
7-8				4		
8-9				4		
			Wind From N22-1/2°W			
0.5-1	18	8				
1-2	8	166	8			
2-3		48	62			
3-4		2	26			
4-5			22			
5-6			8			
6-7						
7-8						
8-9			4			
			Wind From North			
0.5-1	18	10				
1-2	14	138	2			
2-3		26	14			
3-4			8			
4-5						
5-6			2			
			Wind From N22-1/2°E			
0.5-1	32	16				
1-2	6	156	16			
2-3		34	68			
3-4			66			
4-5			16			
5-6			10	8		
6-7				2		

(Continued)

Table 1 (Concluded)

Wave Height ft	Duration, hr/yr, for Wave Period of 1-2 sec	2-3 sec	3-4 sec	4-5 sec	5-6 sec	6-7 sec
			Wind From N45°E			
0.5-1	12	6				
1-2	6	98	28			
2-3		28	68			
3-4		2	30			
4-5			20	8		
5-6			2	12		
6-7				4		

Table 2

Duration of Shallow-Water Waves in Area of Navigation Opening

at Barcelona, Generated by Storm Winds From

Various Deep-Water Wave Directions

Wave Height ft	Duration, hr/yr, for Wave Period of 1-2 sec	2-3 sec	3-4 sec	4-5 sec	5-6 sec	6-7 sec
			Wind From S67-1/2°W			
0.5-1	14	8	2			
1-2	2	114	48	8		
2-3		6	28	14		
3-4			16	12	4	
4-5			2	6		
5-6					2	2
6-7					4	
			Wind From West			
0.5-1	16	4	2			
1-2	2	138	58	2		
2-3		114	94	22		
3-4		14	132	66		
4-5			16	24	12	
5-6			18	20	6	
6-7				12	6	
7-8					4	
8-9					4	
9-10					2	
			Wind From N67-1/2°W			
0.5-1	16	2				
1-2	12	74	28			
2-3		30	68			
3-4		10	64	4		
4-5			30	24		
5-6			4	16		
6-7			2	6		
7-8				6		
8-9				4	2	4
9-10						
10-11					6	

(Continued)

Table 2 (Concluded)

Wave Height ft	Duration, hr/yr, for Wave Period of 1-2 sec	2-3 sec	3-4 sec	4-5 sec	5-6 sec	6-7 sec
			Wind From N45°W			
0.5-1	20	4				
1-2	10	158	10			
2-3		38	106			
3-4			58			
4-5			34	6		
5-6			2	12		
6-7				4		
7-8				4		
8-9				4		
			Wind From N22-1/2°W			
0.5-1	18	8				
1-2	8	166	8			
2-3		48	62			
3-4		2	26			
4-5			22			
5-6			8			
6-7						
7-8			4			
			Wind From North			
0.5-1	18	10				
1-2	14	138	2			
2-3		26	14			
3-4			8			
4-5						
5-6			2			
			Wind From N22-1/2°E			
0.5-1	32	16				
1-2	6	156	16			
2-3		34	68			
3-4			66			
4-5			26	8		
5-6				2		
			Wind From N45°E			
0.5-1	12	6				
1-2	6	98	28			
2-3		28	68			
3-4		2	30			
4-5			22	20		
5-6				4		

Table 3

Summary of Model Test Data

Deep-Water Storm-Wind Direction	Shallow-Water Wave Dimensions		Average Wave Heights in Harbor Areas, ft		
	Period, sec	Height, ft	Area A	Area B	Area C
		Base Conditions			
West	6.0	6.2	4.7	3.4	1.9
West	4.0	3.1	2.6	3.0	0.6
N67-1/2°W	6.0	8.6	8.8	3.3	1.9
N67-1/2°W	4.0	3.8	3.0	2.8	1.3
N45°W	5.0	7.4	7.4	3.6	2.2
N45°W	4.0	3.7	3.6	2.7	1.4
N22-1/2°W	4.0	7.0	6.3	3.9	2.9
N22-1/2°W	4.0	3.5	3.7	3.5	2.1
N22-1/2°E	5.0	5.6	5.7	4.3	2.5
N22-1/2°E	4.0	3.2	3.2	3.1	2.8
N45°E	5.0	5.6	7.6	3.9	2.5
N45°E	4.0	3.2	3.6	3.5	2.7
		Plan 1			
West	6.0	6.2	4.7	1.7	1.0
West	4.0	3.1	2.8	0.7	0.5
N67-1/2°W	6.0	8.6	7.8	2.3	1.4
N67-1/2°W	4.0	3.8	3.1	0.8	0.5
N45°W	5.0	7.4	6.6	2.3	1.6
N45°W	4.0	3.7	2.9	0.9	0.7
N22-1/2°W	4.0	7.0	6.0	2.8	1.7
N22-1/2°W	4.0	3.5	4.2	2.2	1.3
N22-1/2°E	5.0	5.6	5.0	2.9	1.4
N22-1/2°E	4.0	3.2	2.9	1.8	1.1
		Plan 1A			
West	6.0	6.2	4.4	1.3	0.6
West	4.0	3.1	2.3	0.5	0.3
N45°W	5.0	7.4	5.7	2.0	1.4
N45°W	4.0	3.7	2.6	0.6	0.3
N22-1/2°W	4.0	7.0	6.9	2.4	1.2
N22-1/2°W	4.0	3.5	4.0	1.6	0.8
N22-1/2°E	5.0	5.6	4.7	3.1	1.4
N22-1/2°E	4.0	3.2	2.7	1.2	0.8
N45°E	5.0	5.6	6.3	3.1	1.9
N45°E	4.0	3.2	3.7	1.7	0.9

(Continued)

Table 3 (Concluded)

Deep-Water Storm-Wind Direction	Shallow-Water Wave Dimensions		Average Wave Heights in Harbor Areas, ft		
	Period, sec	Height, ft	Area A	Area B	Area C
		Plan 1B			
West	6.0	6.2	3.5	0.9	0.5
N22-1/2°W	4.0	7.0	6.8	2.4	1.3
N22-1/2°E	5.0	5.6	4.4	2.5	1.3
N45°E	5.0	5.6	5.6	2.6	1.7
N45°E	4.0	3.2	3.5	1.2	0.9
		Plan 1C			
N22-1/2°E	5.0	5.6	---	---	1.5
N22-1/2°E	4.0	3.2	---	---	0.8
N45°E	5.0	5.6	---	---	1.5
N45°E	4.0	3.2	---	---	0.9
		Plan 1D			
N22-1/2°E	5.0	5.6	---	---	1.5
N22-1/2°E	4.0	3.2	---	---	1.0
N45°E	5.0	5.6	---	---	1.6
N45°E	4.0	3.2	---	---	1.2
		Plan 1E			
N22-1/2°E	5.0	5.6	---	---	1.6
N22-1/2°E	4.0	3.2	---	---	0.9
N45°E	5.0	5.6	---	---	1.3
N45°E	4.0	3.2	---	---	1.5
		Plan 1F			
West	6.0	6.2	4.4	1.7	0.7
N45°W	5.0	7.4	6.4	2.4	1.4
N22-1/2°W	4.0	7.0	6.5	2.9	1.4
N45°E	5.0	5.6	4.7	2.7	1.3

Table 4

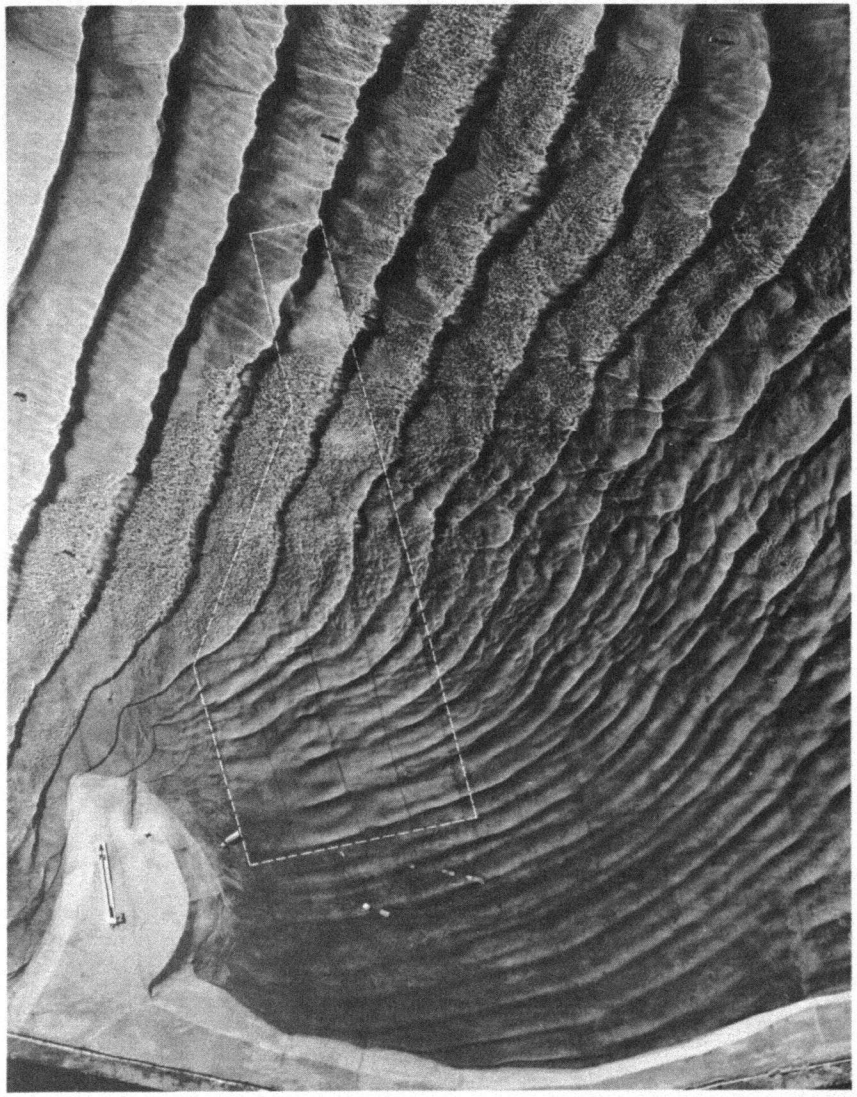
Estimated Duration of Waves in Area of Navigation Opening

and Areas A, B, and C

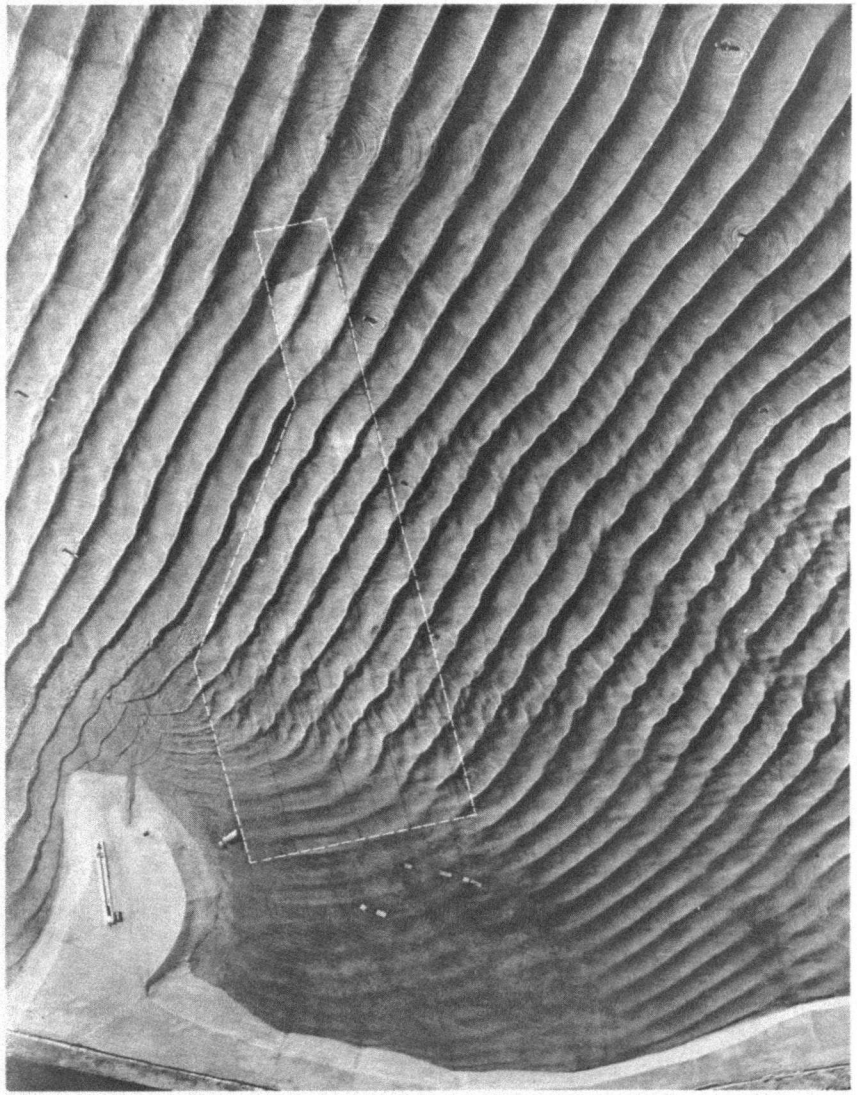
Summation of All Storm-Wind Directions From S67-1/2°W to N45°E, Inclusive

Wave Height ft	Duration, hr/yr								
	Area of Navigation Opening (Base Conditions)	Base Conditions	Plan 1	Plan 1A	Plan 1B	Plan 1C	Plan 1D	Plan 1E	Plan 1F
		Entrance Channel, Area A							
0.0-0.5	None	None	None	None	None				None
0.5-1	208	208	164	164	208				208
1-2	1310	1408	1040	1040	1830				1358
2-3	868	848	976	1356	842				1064
3-4	514	458	660	434	312				388
4-5	252	256	252	180	92				224
5-6	98	104	172	112	34				42
6-7	34	22	34	30	6				18
7-8	18	12	18	2	4				20
8-9	18	6	6	10					6
9-10	2	None	6						
10-11	6	6							
		Approach Reach, Area B							
0.0-0.5	None	None	380	854	1150				208
0.5-1	208	208	1148	1492	1434				1830
1-2	1310	1552	1522	826	648				1120
2-3	868	798	258	148	96				160
3-4	514	506	16	8					10
4-5	252	248	4						
5-6	98	12							
6-7	34	4							
		Mooring Area, Area C							
0.0-0.5	None	764	1022	2058	2196	2058	1904	1904	1844
0.5-1	208	1114	1864	1028	932	1028	1174	1078	1232
1-2	1310	954	430	242	200	242	250	342	252
2-3	868	350	12					4	
3-4	514	146							

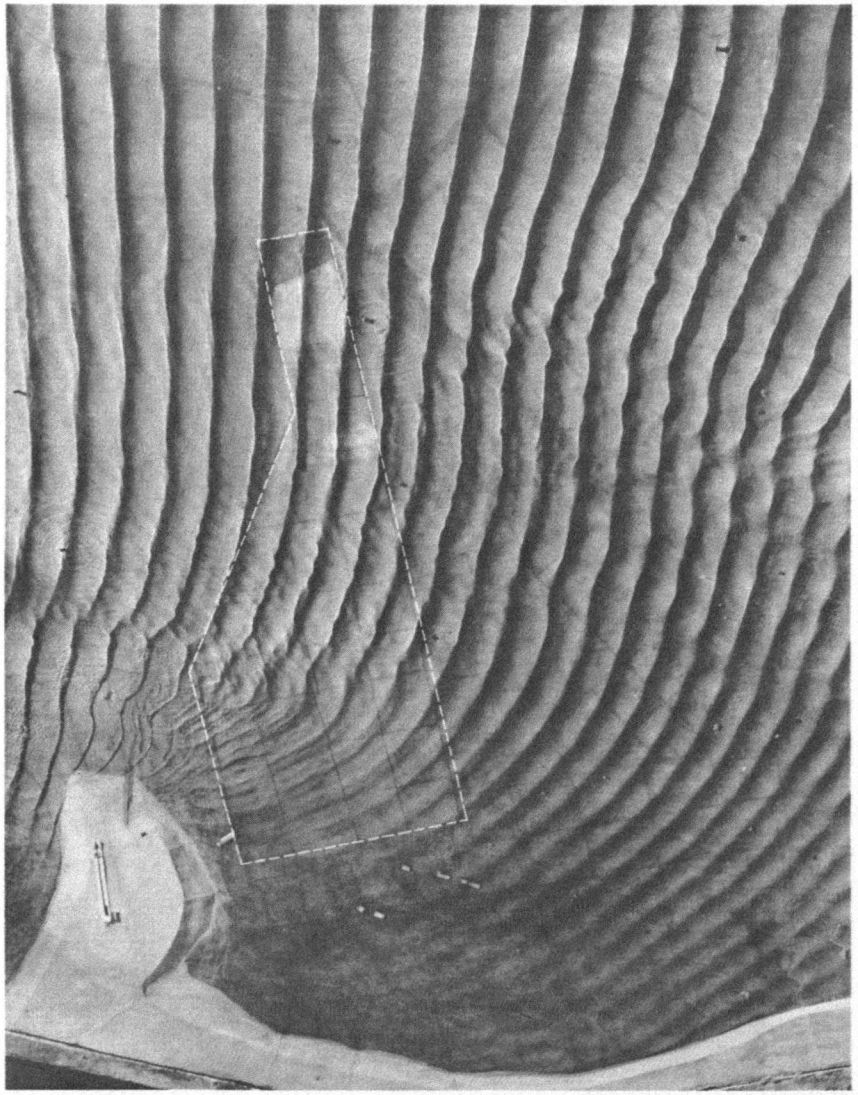
Photograph 1. Base conditions: 6.0-sec by 8.0-ft waves from west



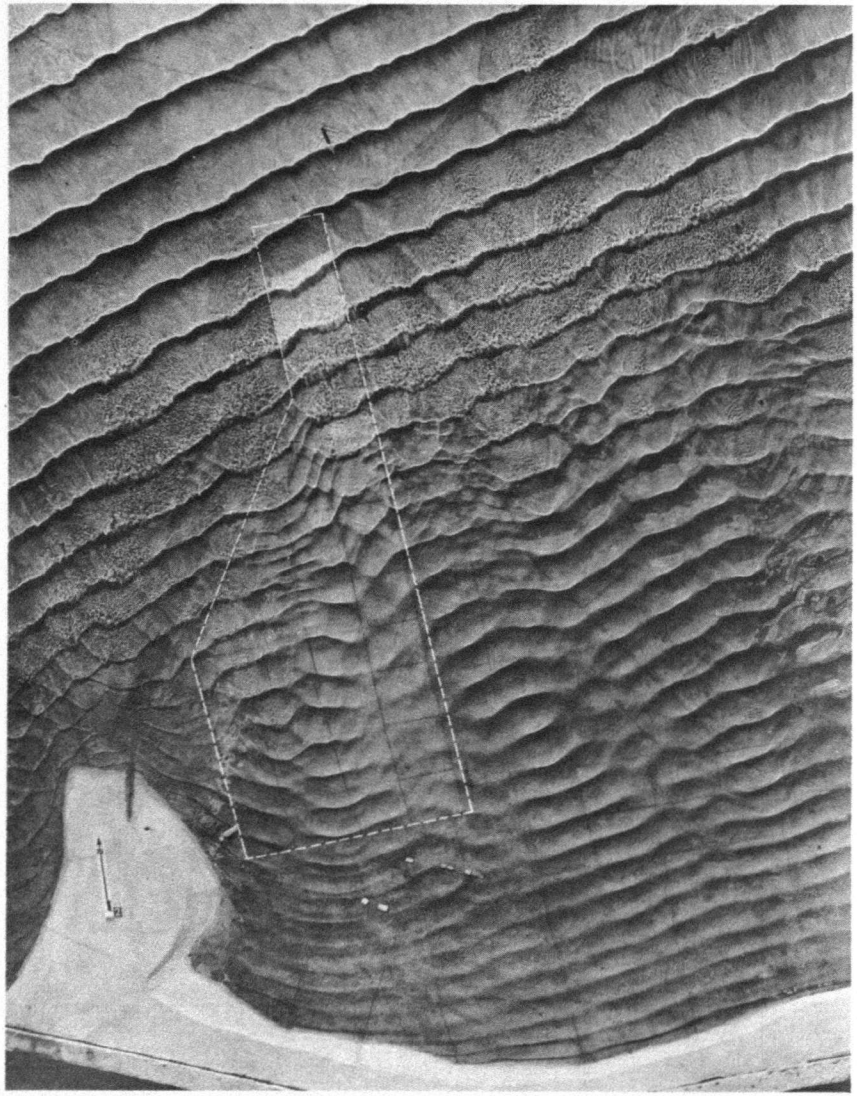
Photograph 2. Base conditions: 4.0-sec by 4.0-ft waves from west



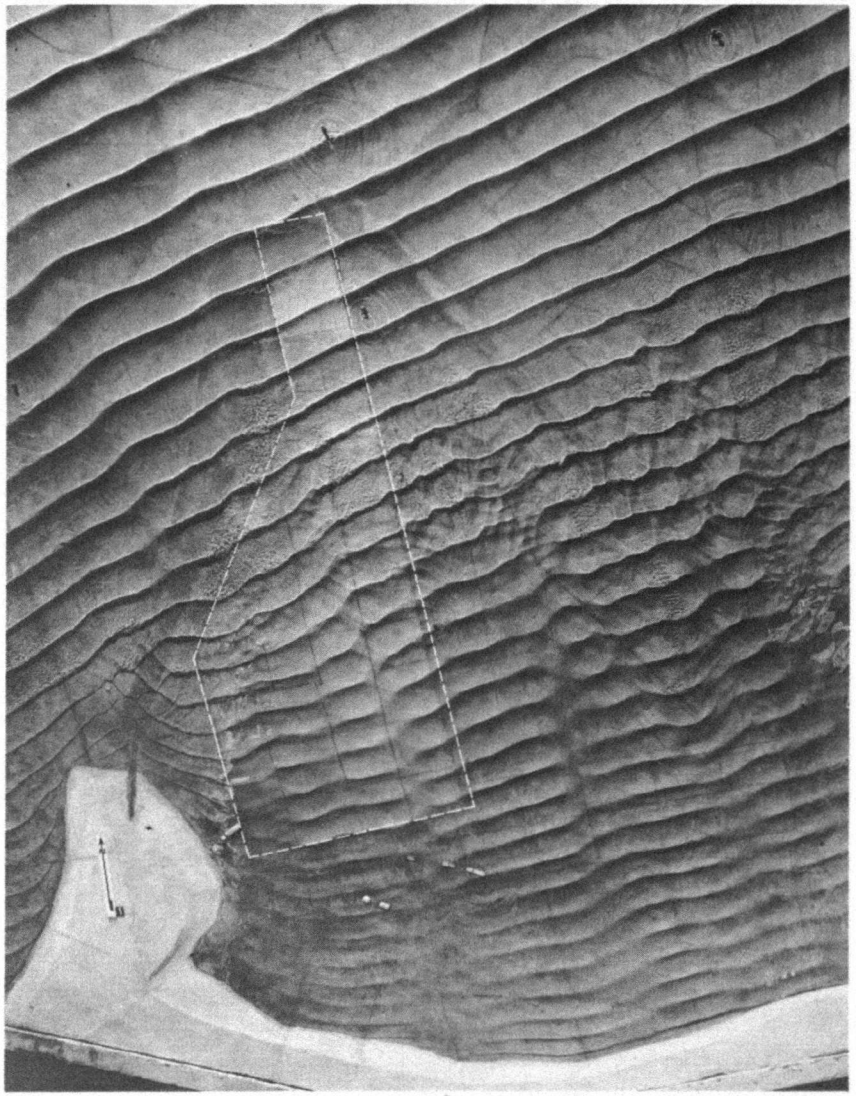
Photograph 3. Base conditions: 6.0-sec by 9.0-ft waves from N67-1/2°W



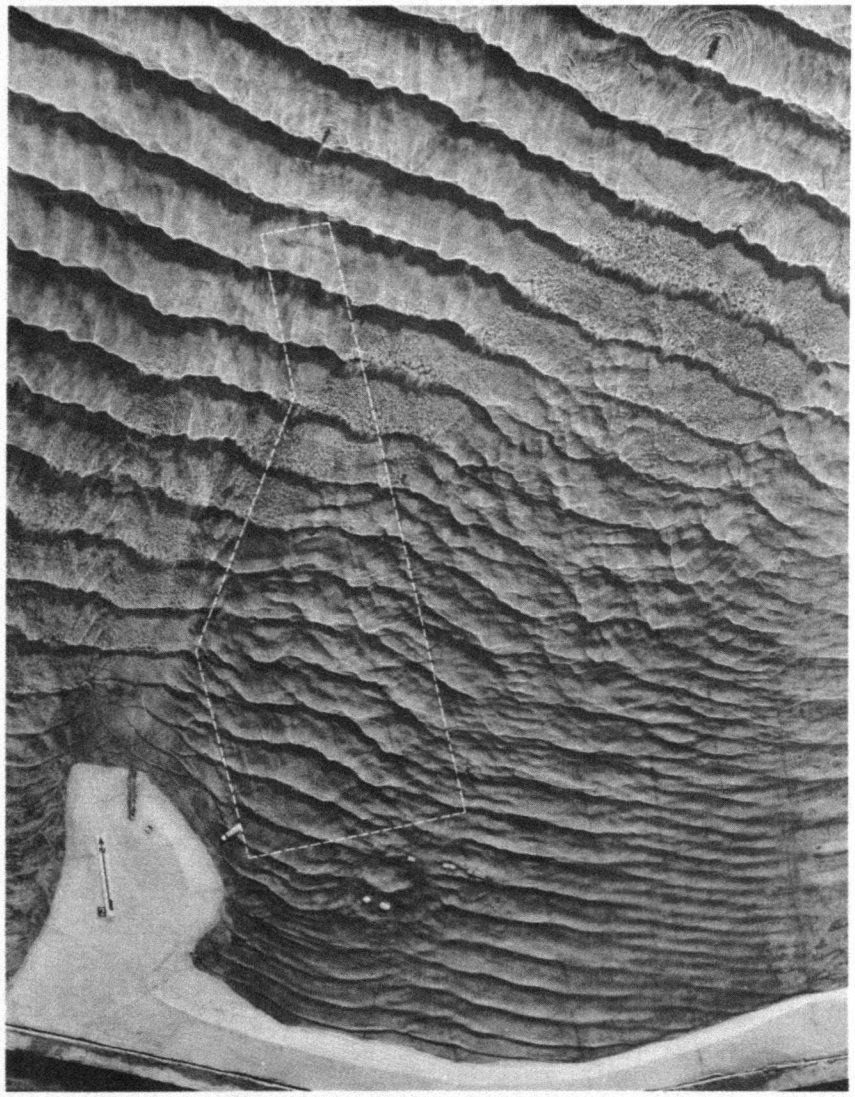
Photograph 4. Base conditions: 4.0-sec by 4.0-ft waves from N67-1/2°W



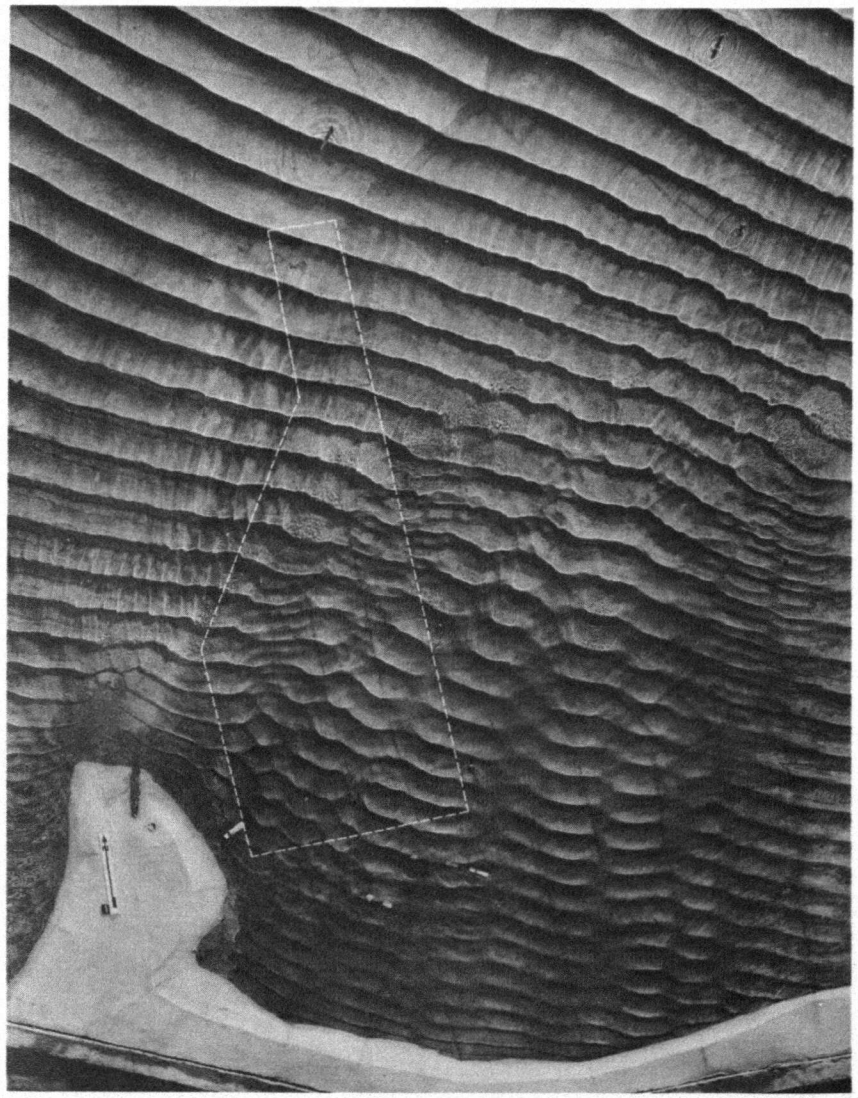
Photograph 5. Base conditions: 4.0-sec by 8.0-ft waves from N22-1/2°W



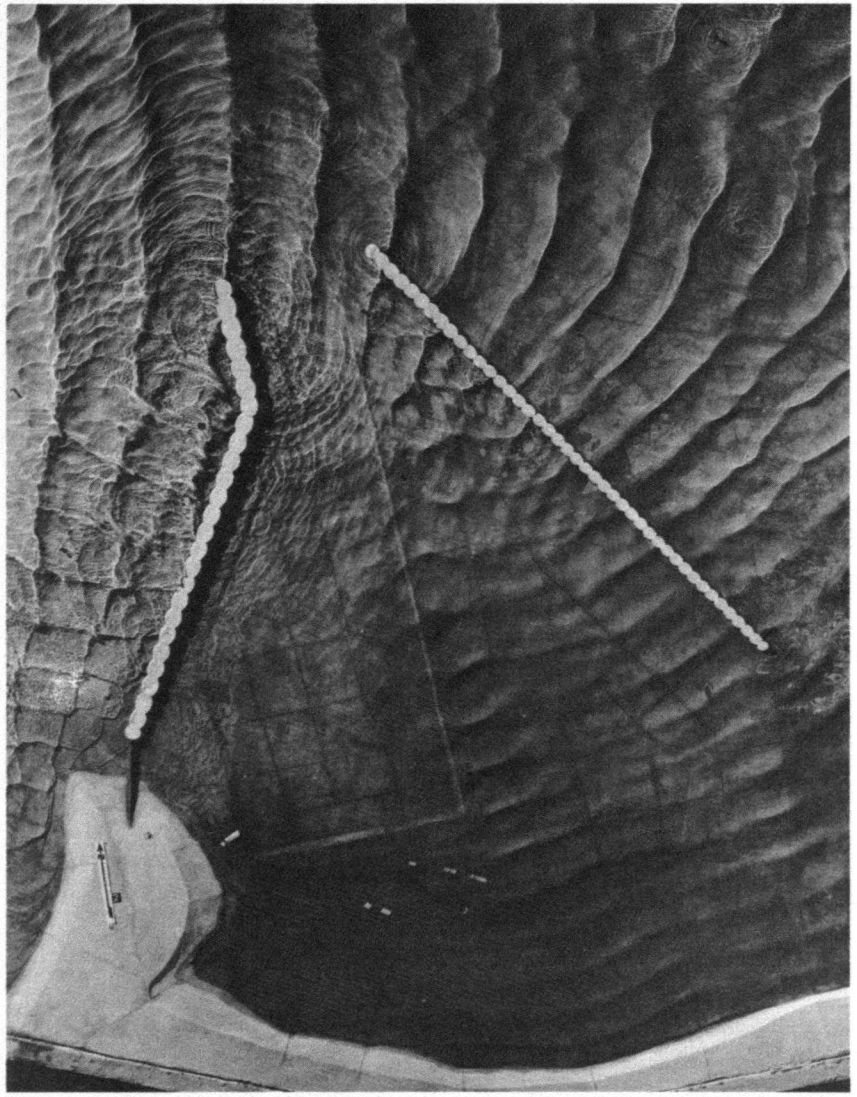
Photograph 6. Base conditions: 4.0-sec by 4.0-ft waves from N22-1/2°W



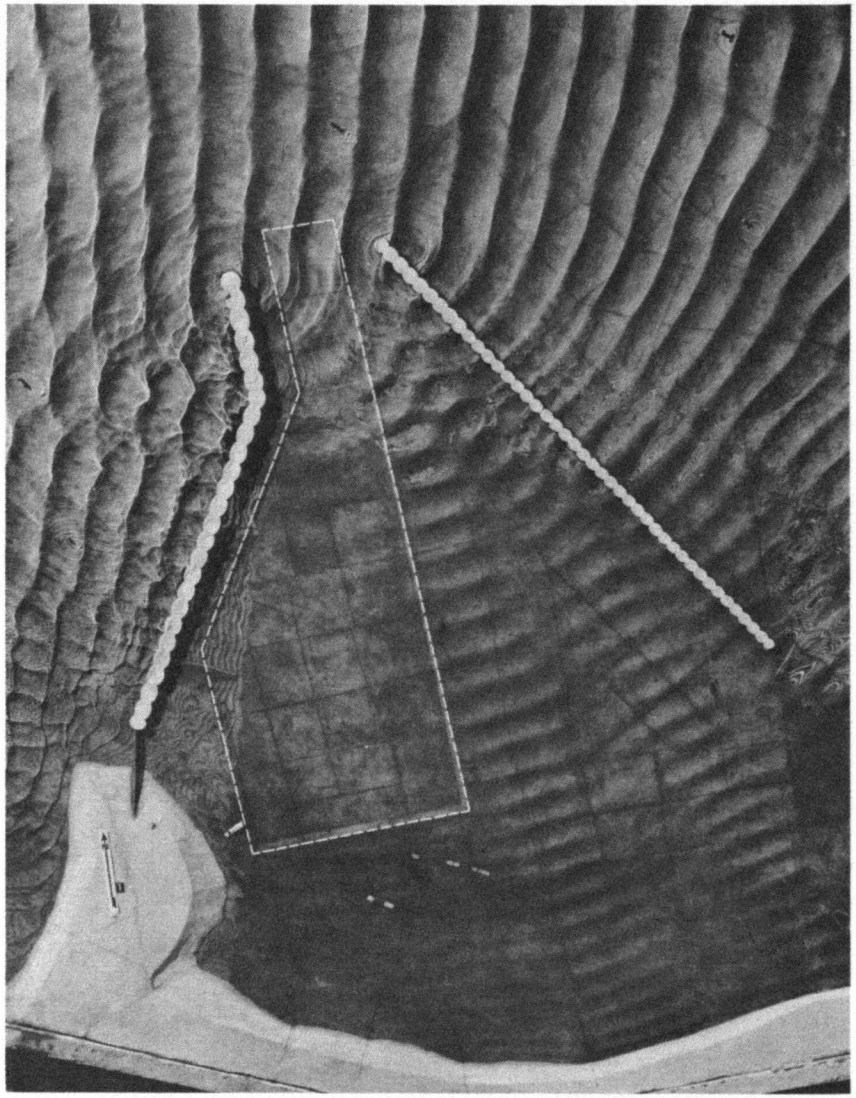
Photograph 7. Base conditions: 5.0-sec by 7.0-ft waves from N45°E



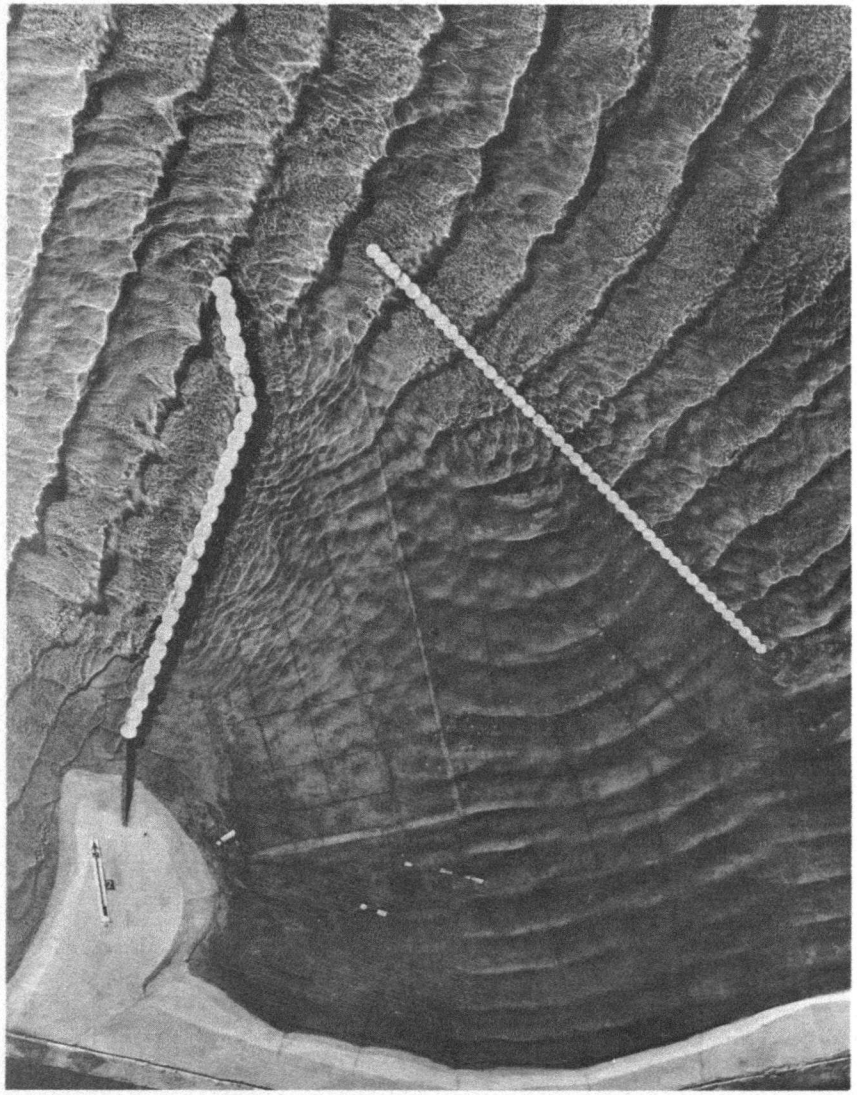
Photograph 8. Base conditions: 4.0-sec by 4.0-ft waves from N45°E



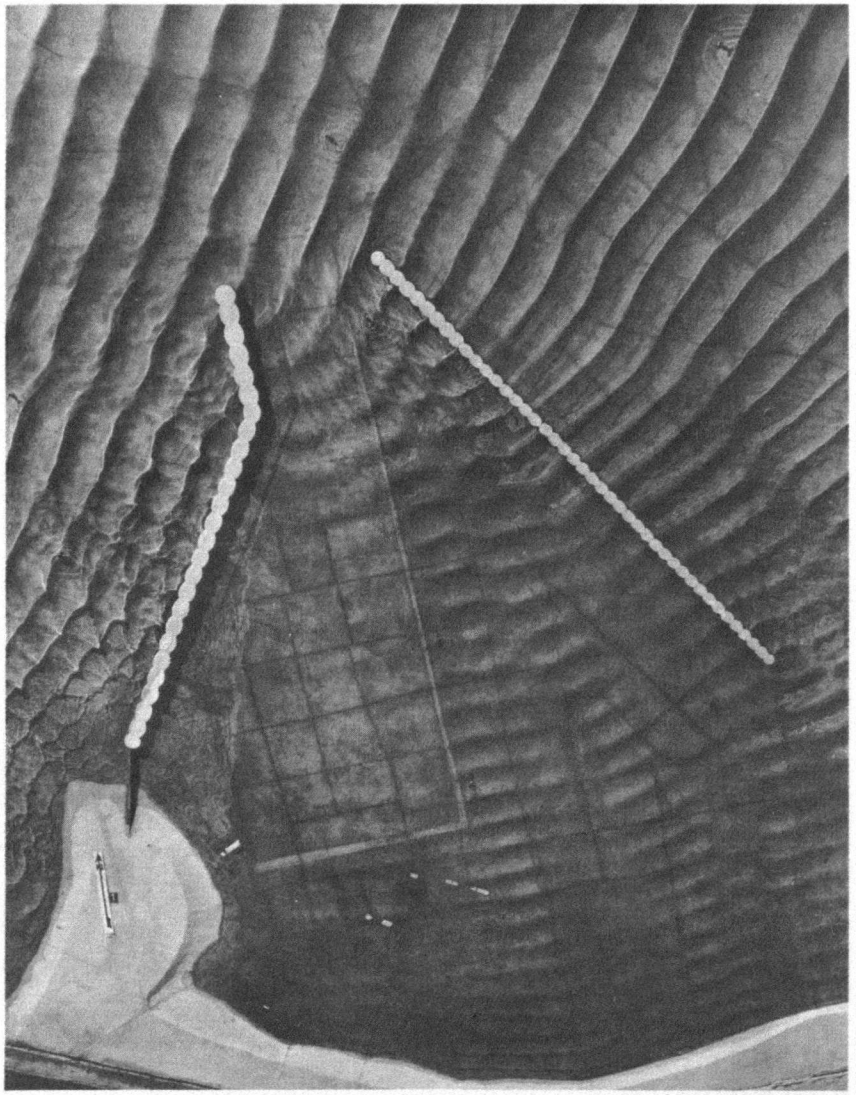
Photograph 9. Plan 1: 6.0-sec by 8.0-ft waves from west



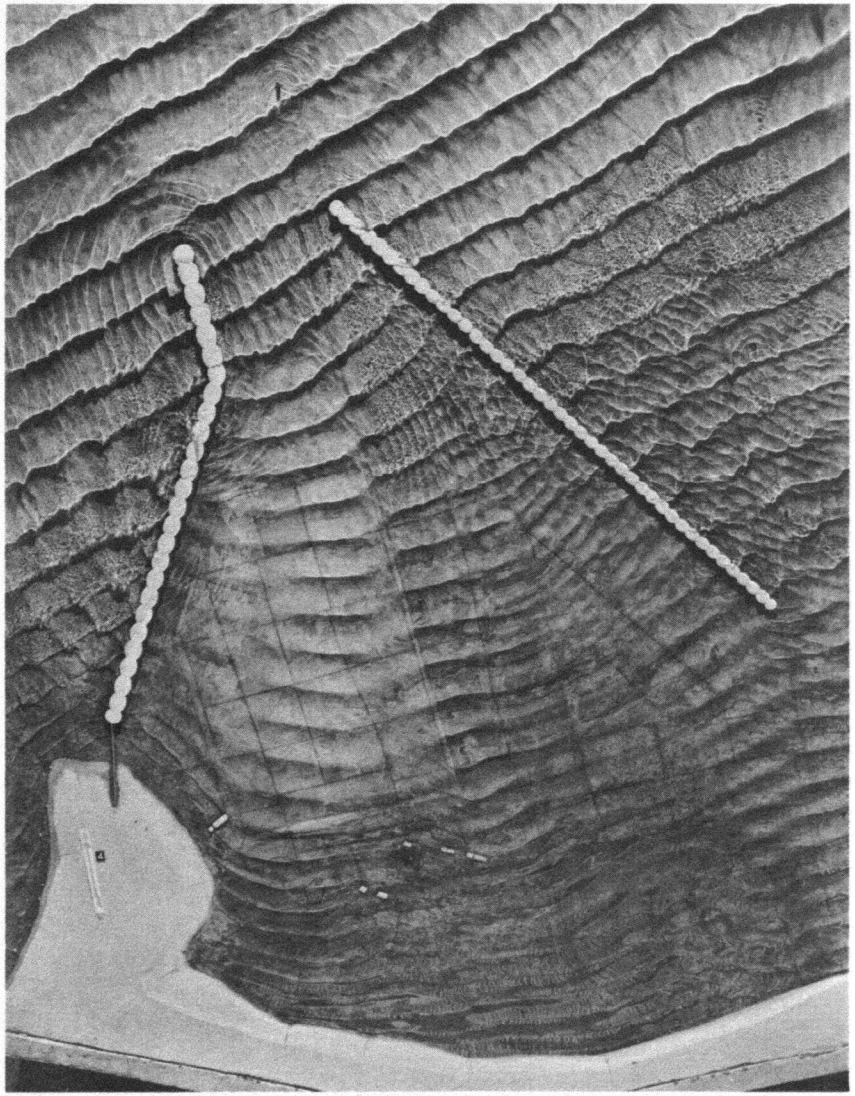
Photograph 10. Plan 1: 4.0-sec by 4.0-ft waves from west



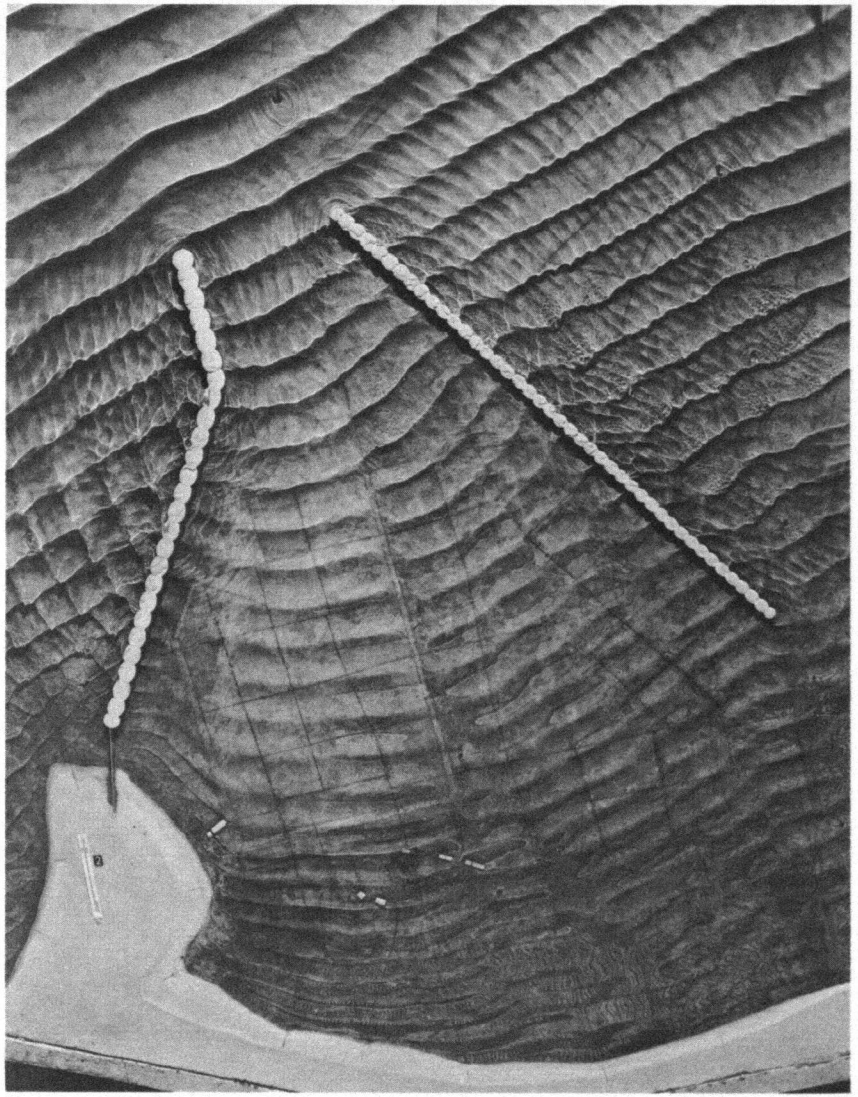
Photograph 11. Plan 1: 6.0-sec by 9.0-ft waves from N67-1/2°W



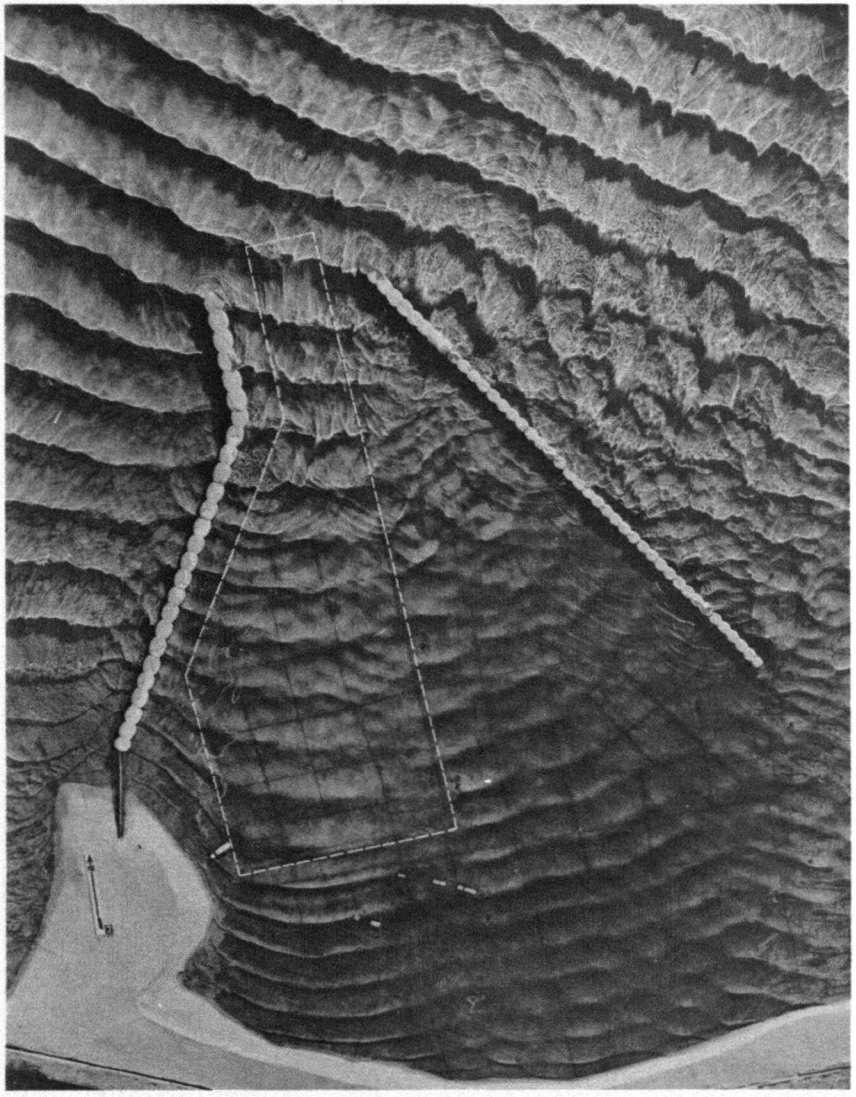
Photograph 12. Plan 1: 4.0-sec by 4.0-ft waves from N67-1/2°W



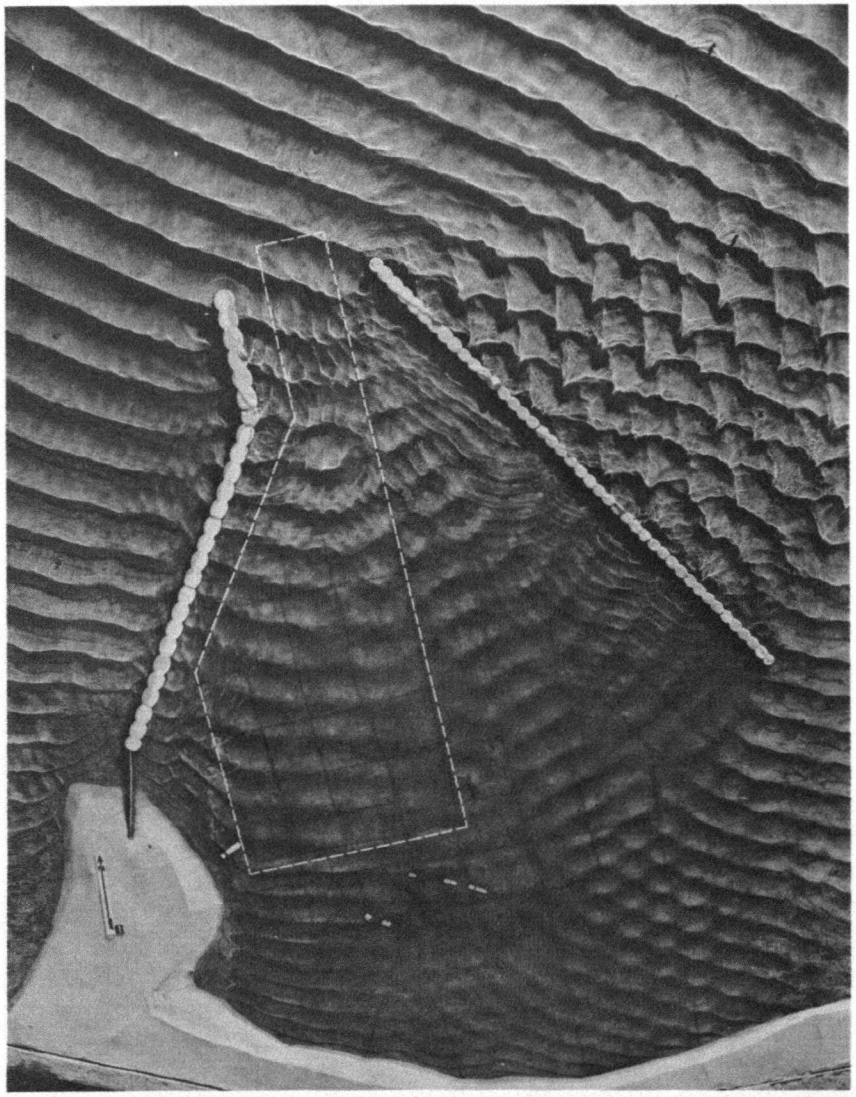
Photograph 13. Plan 1: 4.0-sec by 8.0-ft waves from N22-1/2°W



Photograph 14. Plan 1: 4.0-sec by 4.0-ft waves from N22-1/2°W

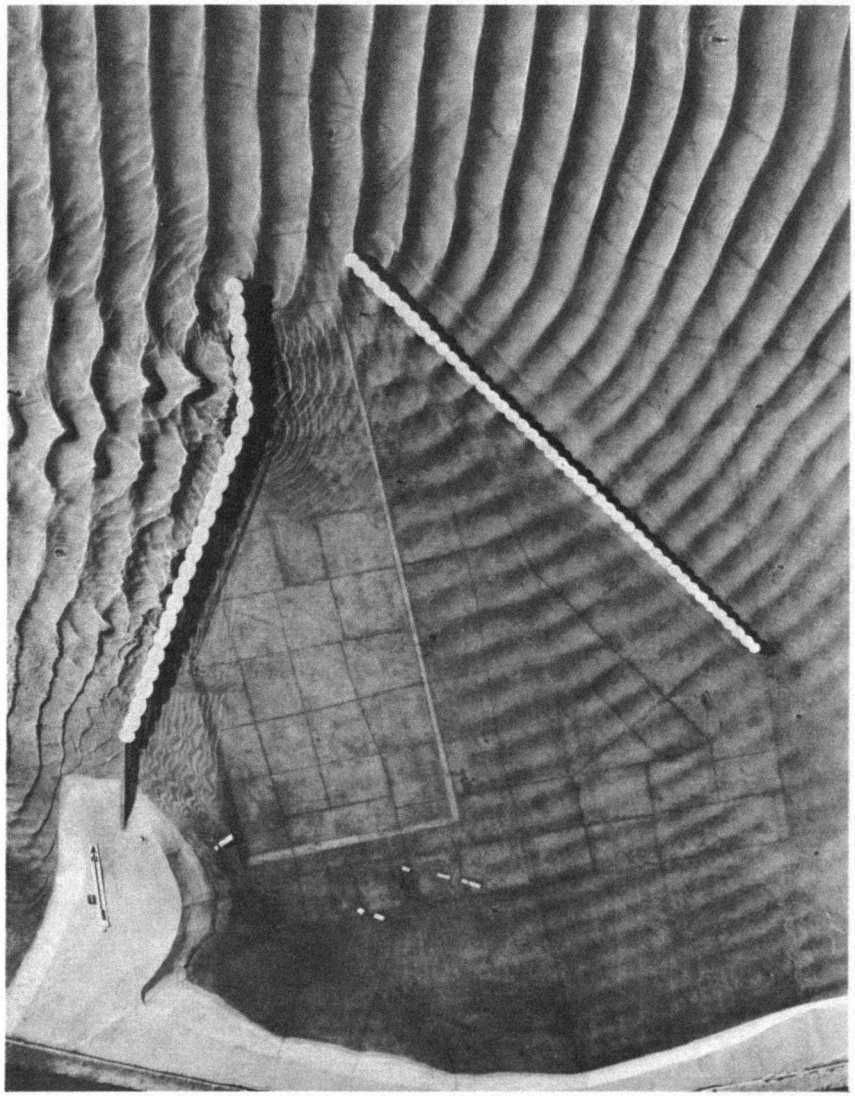


Photograph 15. Plan 1: 5.0-sec by 7.0-ft waves from N45°E

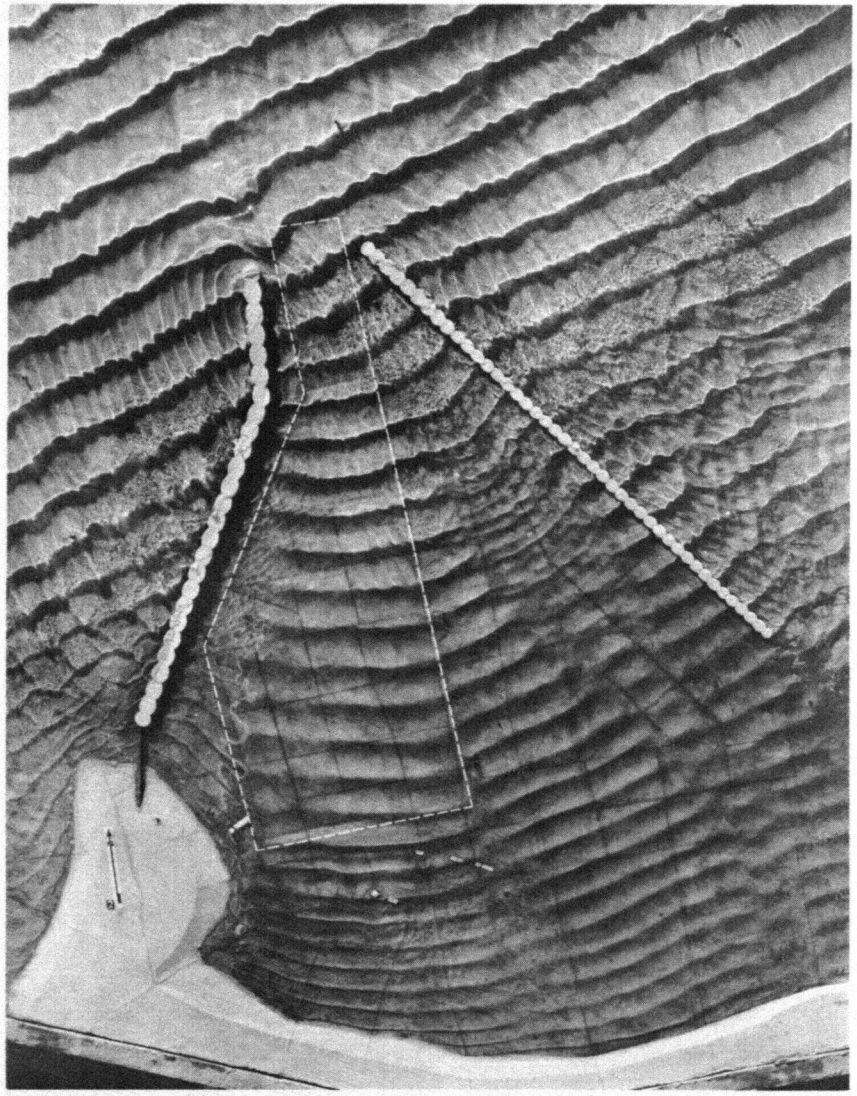


Photograph 16. Plan 1: 4.0-sec by 4.0-ft waves from N45°E

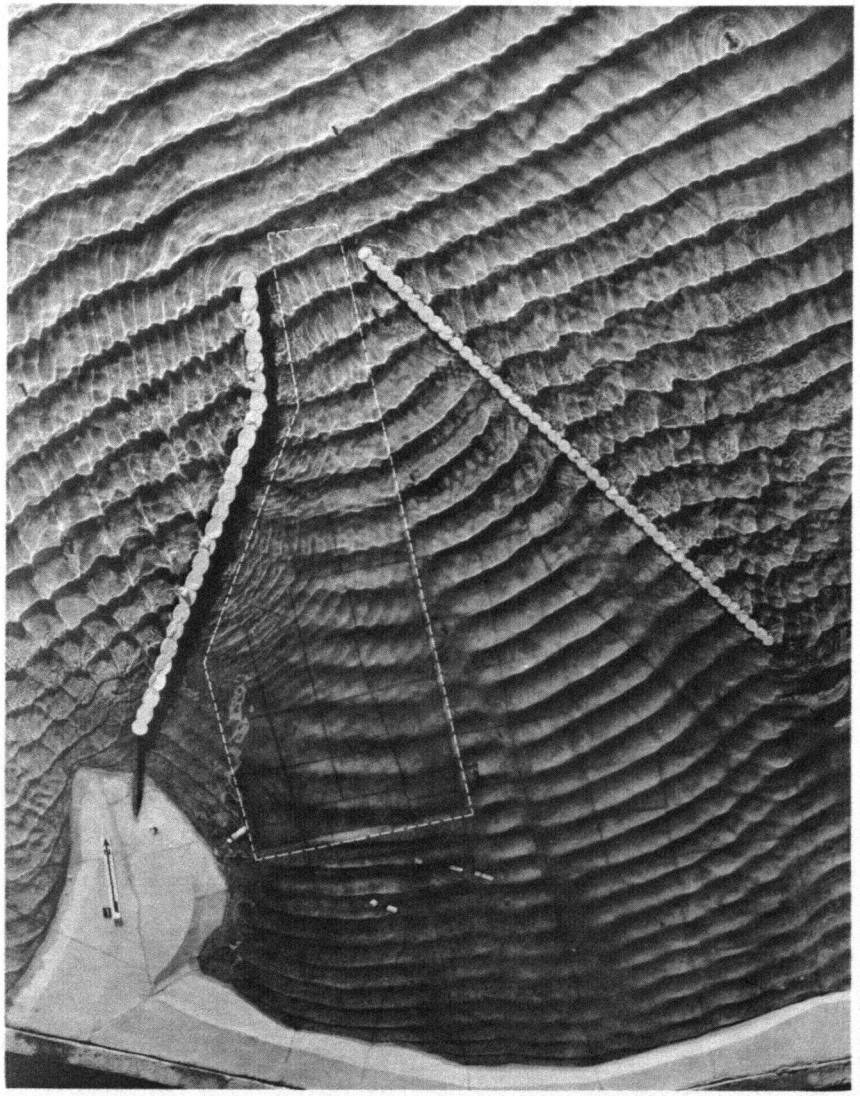
Photograph 17. Plan 1A: 6.0-sec by 8.0-ft waves from west



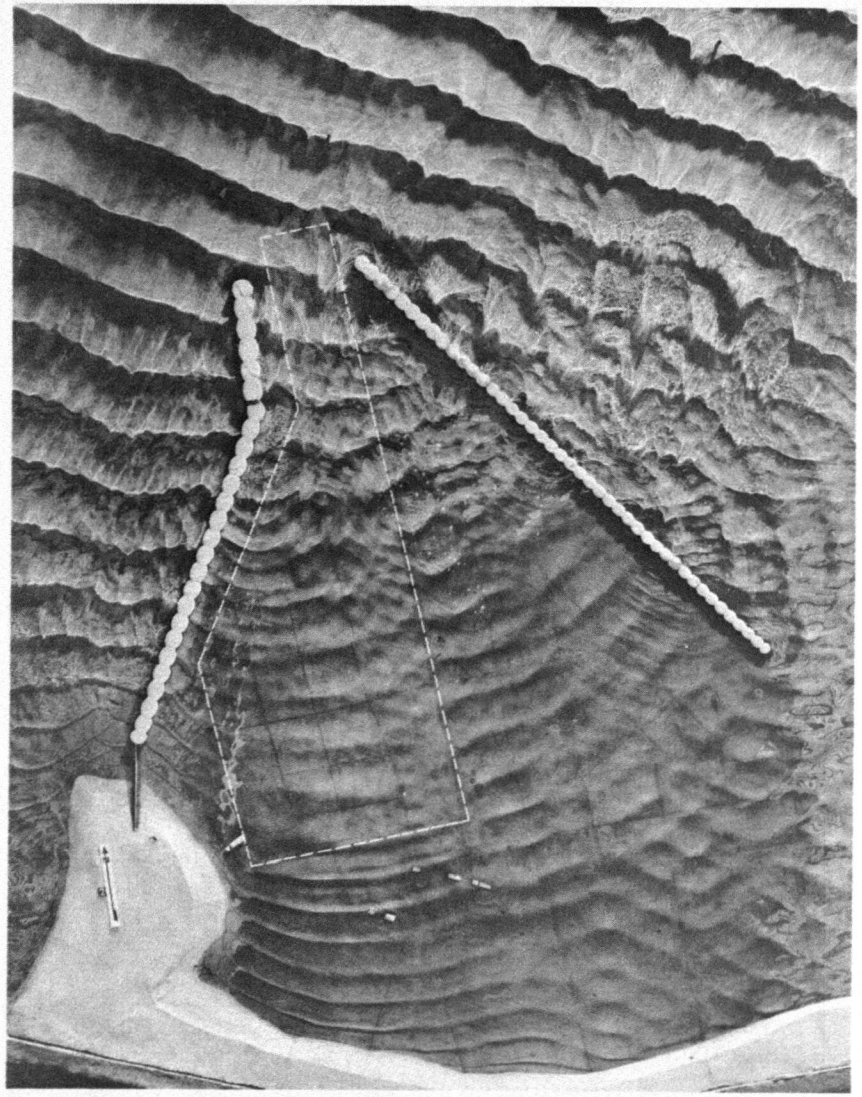
Photograph 18. Plan 1A: 4.0-sec by 4.0-ft waves from west



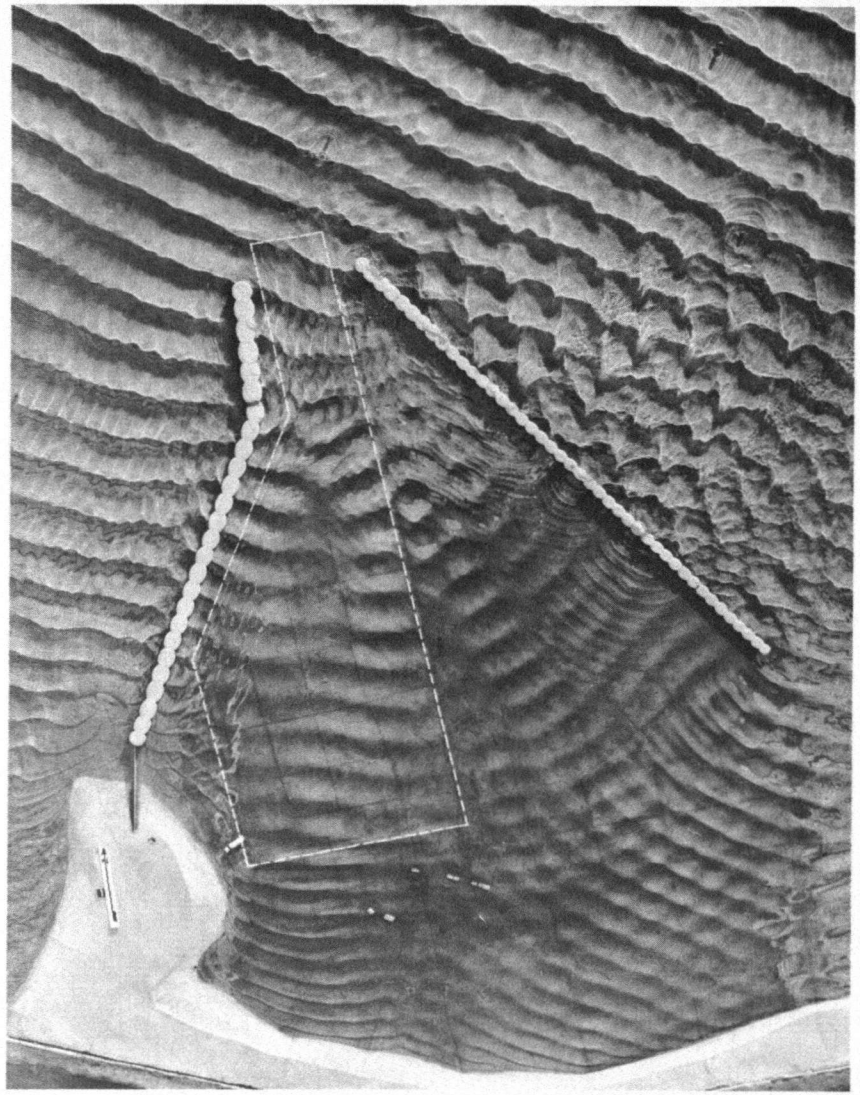
Photograph 19. Plan 1A: 4.0-sec by 8.0-ft waves from N22-1/2°W



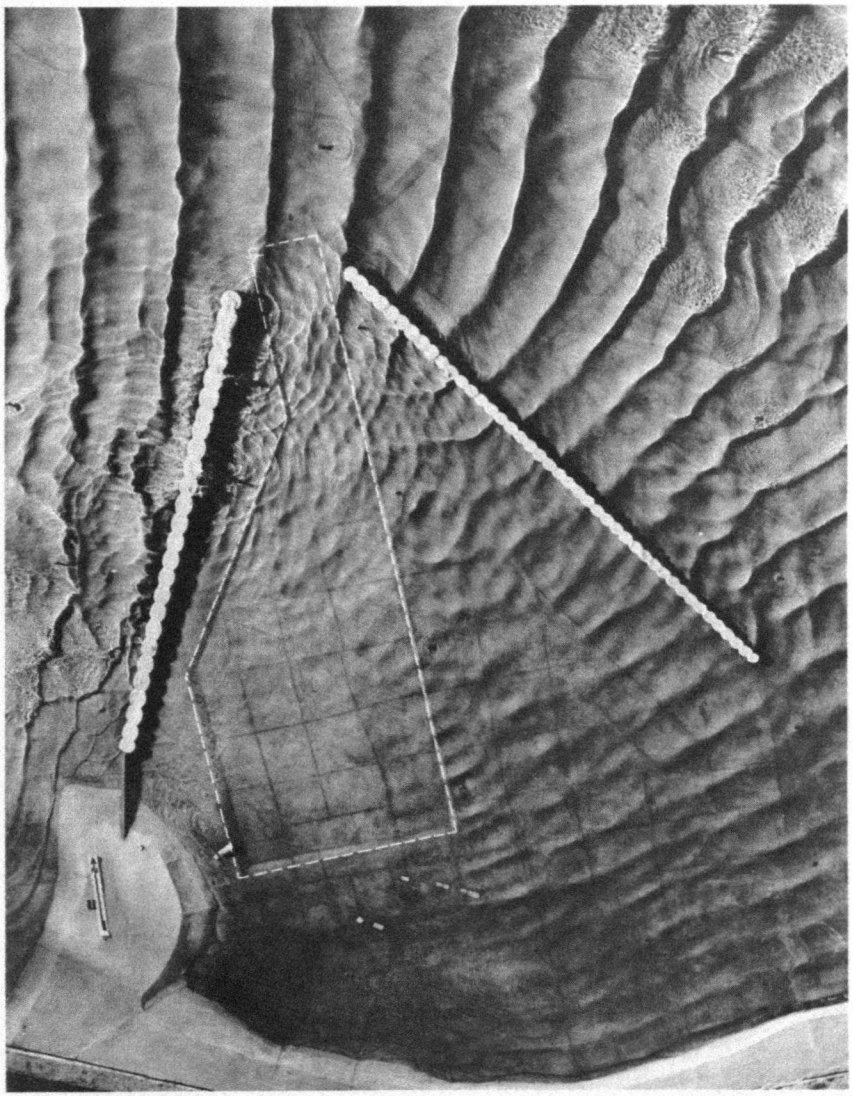
Photograph 20. Plan 1A: 4.0-sec by 4.0-ft waves from N22-1/2°W



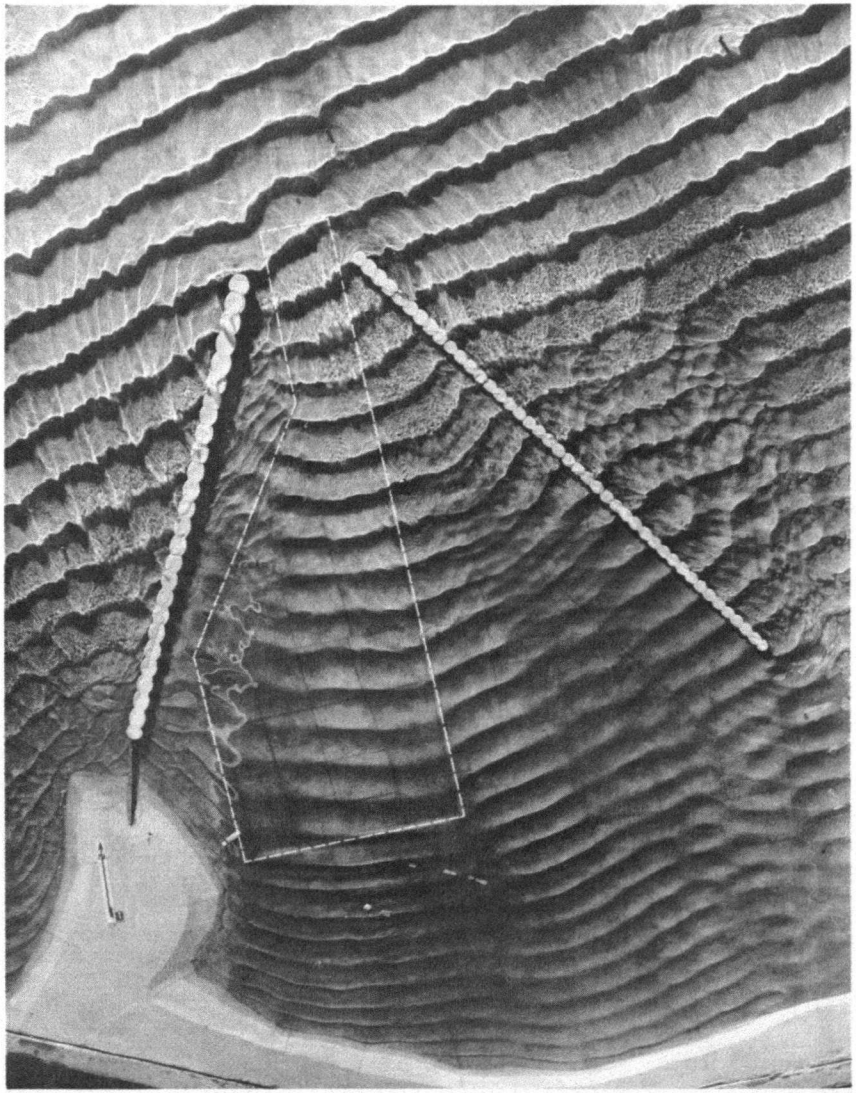
Photograph 21. Plan 1A: 5.0-sec by 7.0-ft waves from N45°E



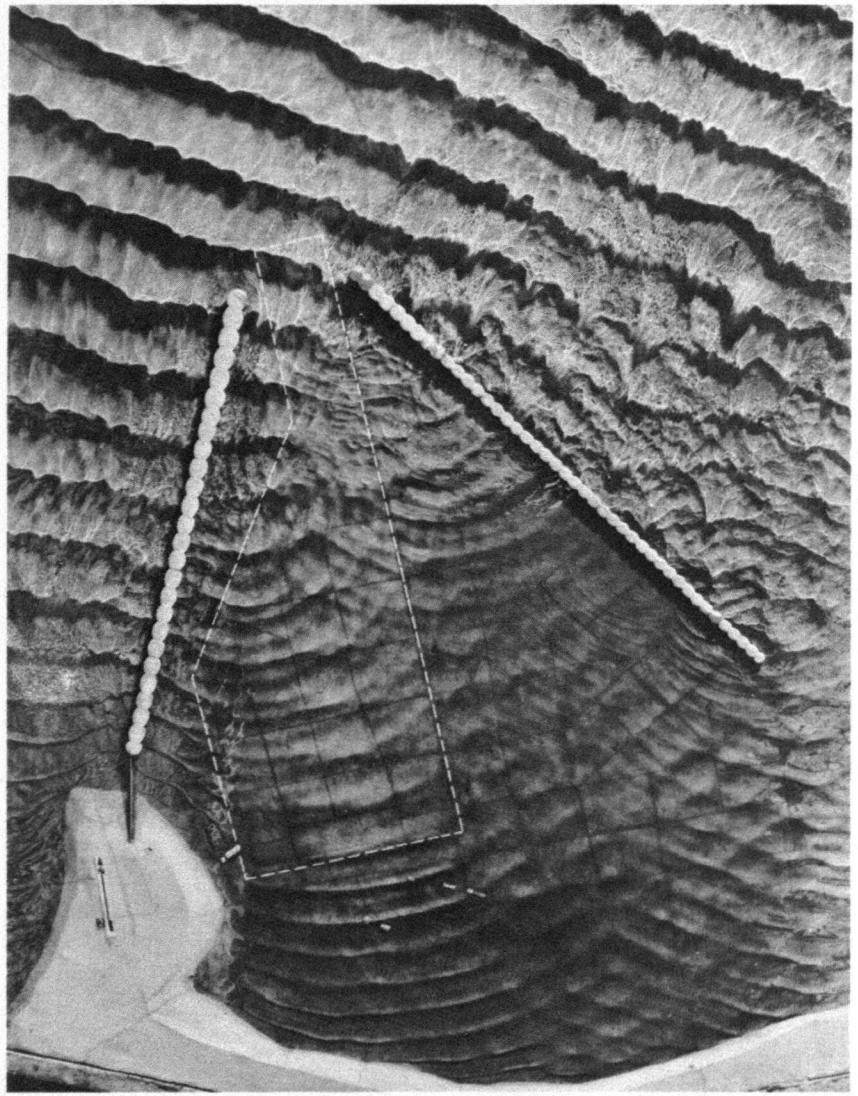
Photograph 22. Plan 1A: 4.0-sec by 4.0-ft waves from N45°E



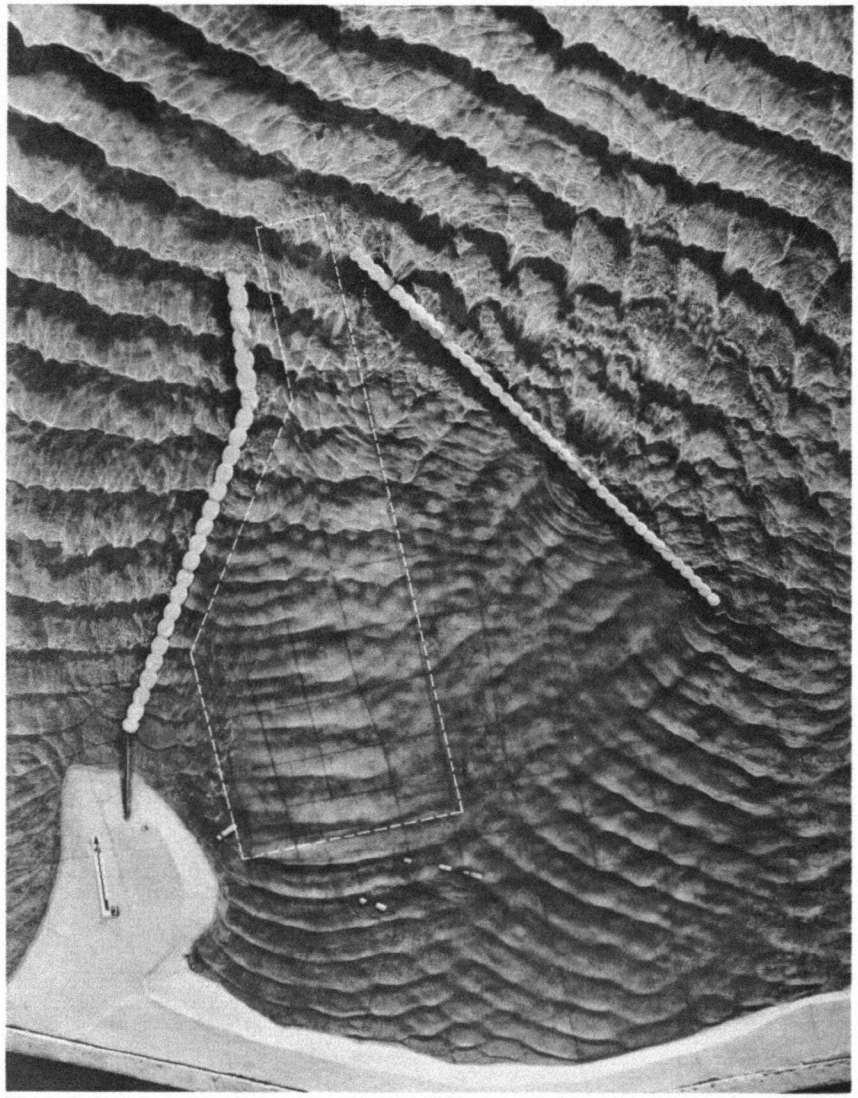
Photograph 23. Plan 1B: 6.0-sec by 8.0-ft waves from west



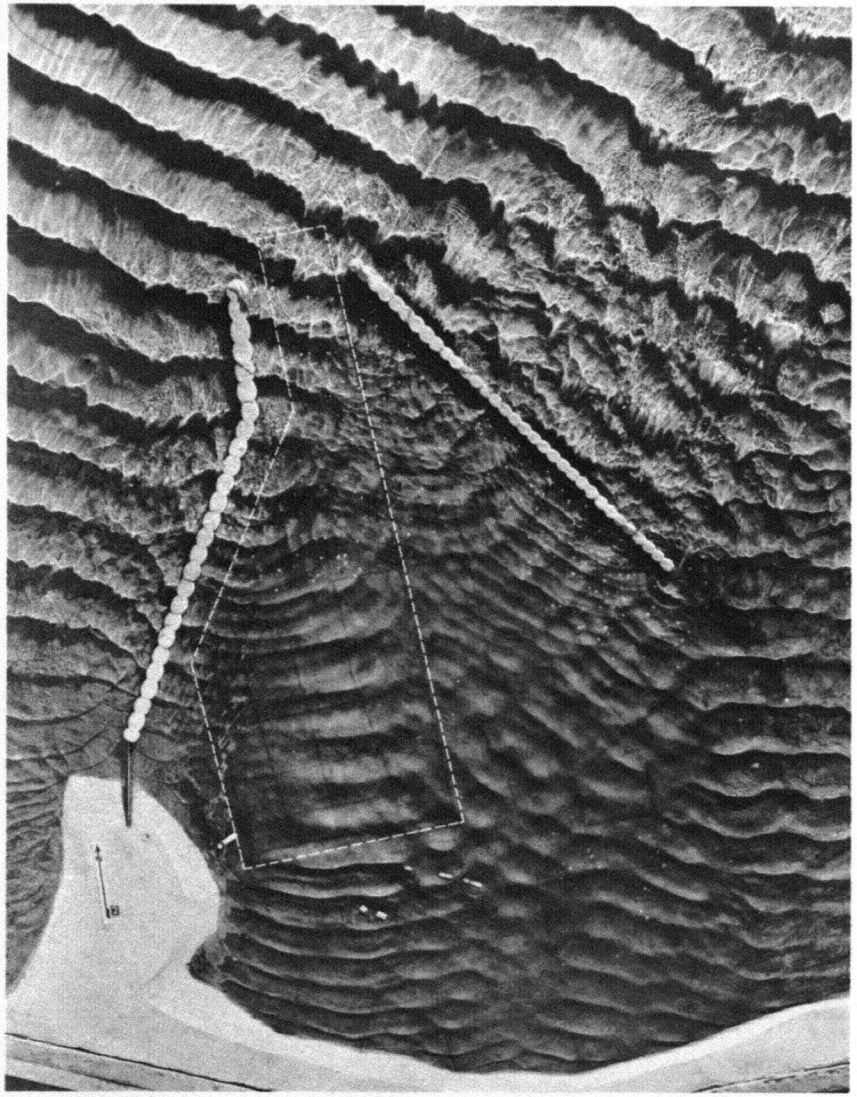
Photograph 24. Plan 1B: 4.0-sec by 8.0-ft waves from N22-1/2°W



Photograph 25. Plan 1B: 5.0-sec by 7.0-ft waves from N45°E



Photograph 26. Plan 1C: 5.0-sec by 7.0-ft waves from N45°E

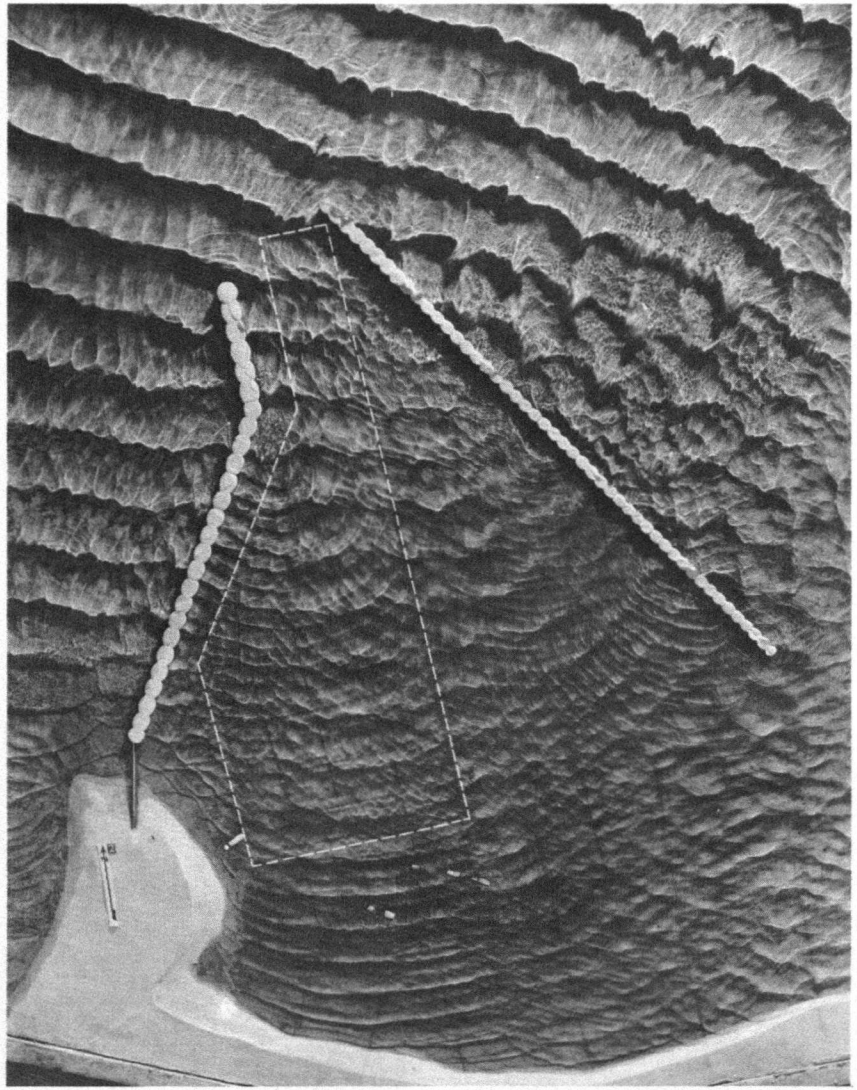


Photograph 27. Plan 1D: 5.0-sec by 7.0-ft waves from N45°E

Photograph 28. Plan 1E: 5.0-sec by 7.0-ft waves from N45°E

Photograph 29. Plan 1F: 6.0-sec by 8.0-ft waves from west

Photograph 30. Plan 1F: 4.0-sec by 4.0-ft waves from N22-1/2°W



Photograph 31. Plan 1F: 5.0-sec by 7.0-ft waves from N45°E