

CORPS OF ENGINEERS, U. S. ARMY

WAVE ACTION AND BREAKWATER LOCATION
TACONITE HARBOR (TWO ISLANDS)
LAKE SUPERIOR, MINNESOTA

HYDRAULIC MODEL INVESTIGATION



TECHNICAL MEMORANDUM NO. 2-405

CONDUCTED FOR

ERIE MINING COMPANY
CLEVELAND, OHIO

BY

WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI

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PREFACE

The Erie Mining Company, Cleveland, Ohio, requested the Waterways Experiment Station to conduct a hydraulic model study of Taconite Harbor in a letter dated 28 May 1954. Authority to perform the model study had been granted previously by the Chief of Engineers, Department of the Army, in a teletype dated 30 April 1954. Construction of the model was completed in June 1954, and the model tests were conducted during the period July to October 1954. The Erie Mining Company paid all costs in connection with the model study and this report.

Letter reports presenting the results of the model tests were forwarded periodically to Dr. L. G. Straub, Minneapolis, Minnesota, consulting engineer for the Erie Mining Company. Dr. Straub also visited the Waterways Experiment Station several times during the course of the investigation to review model test results and plan further test programs. Besides the visits of Dr. Straub, the following representatives of the companies interested in the Taconite Harbor project attended a conference on 17 August 1954 to witness model demonstrations and review test results:

- Mr. H. W. Campbell, engineer, Interlake Iron Corp.,
Cleveland, Ohio
- Mr. L. H. Chater, chief engineer, Steel Company of Canada,
Hamilton, Ontario
- Mr. A. D. Chisholm, general manager, Erie Mining Company,
Duluth, Minnesota
- Mr. Randall Cremer, engineer-contractor, New York, N. Y.
- Mr. L. J. Gould, chief engineer, Bethlehem Steel Company
- Mr. A. J. Hulse, chief engineer, Youngstown Sheet & Tube
Company, Cleveland, Ohio
- Mr. H. McCrodden, engineer, Frederick Snare Corp.,
Schroeder, Minnesota
- Mr. W. H. Prescott, chief engineer, Pickands, Mather & Co.,
Cleveland, Ohio
- Mr. Alonzo D. Quinn, chief engineer, Frederick Snare Corp.,
New York, N. Y.
- Dr. L. G. Straub, consulting engineer, Minneapolis, Minnesota

Mr. C. F. Trowbridge, manager, Taconite Operations, Erie Mining Company, Duluth, Minnesota

Mr. W. J. Williams, vice president, Taconite Contractors, Erie Mining Company, Duluth, Minnesota

The model study was conducted in the Hydraulics Division of the Waterways Experiment Station, under the supervision of Mr. E. P. Fortson, Jr., chief of the Hydraulics Division, Mr. F. R. Brown, chief of the Hydrodynamics Branch, and Mr. R. Y. Hudson, chief of the Wave Action Section. Waterways Experiment Station engineers actively connected with the model study were Messrs. R. Y. Hudson, H. B. Wilson, J. G. Housley, and J. B. Clark.

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SUMMARY

A hydraulic model investigation of Taconite Harbor, Two Islands, Minnesota, was conducted on a 1:150-scale hydraulic model, geometrically similar to and accurately reproducing in detail the prototype harbor, to determine whether the proposed harbor plan would adequately protect the docking area from wave action, and if it would not, to devise a plan that would provide sufficient protection at minimum cost. It was concluded from the model study that:

- a. The original plan of harbor construction would provide excellent protection to vessels moored along the harbor docks for all storm waves except extremely high waves from directions between N 75° E and east, and average severe storm waves from the south to southwest directions.
- b. The east breakwater of the original plan could be shortened 355 ft without a significant increase in wave action in the docking area.
- c. None of the plans tested would provide adequate protection from severe storms from directions between south and southwest.
- d. Rubble wave absorbers placed at selected positions in and adjacent to the harbor would improve wave conditions at the west navigation opening and in the eastern portion of the harbor.
- e. The west side of the outer end of the east breakwater should be constructed in such a way that a large portion of the incident wave energy would be absorbed.

WAVE ACTION AND BREAKWATER LOCATION

TACONITE HARBOR (TWO ISLANDS)

LAKE SUPERIOR, MINNESOTA

Hydraulic Model Investigation

PART I: INTRODUCTION

1. Taconite Harbor is being constructed on the north shore of Lake Superior at a site called Two Islands, about 75 miles northeast of Duluth, Minnesota, and about 27 miles northeast of the Reserve Mining Company's Silver Bay Harbor development. The harbor will provide berthing facilities and protection from storm waves for ships servicing the harbor and transporting processed ore to industrial cities along the southern shores of the Great Lakes. The deep water that prevails within a short distance of the shore along the north shore of Lake Superior makes the selection of a harbor site, and the design of the harbor and harbor breakwaters, unusually difficult.

2. The site of Taconite Harbor is exposed to wind waves generated by storms from all directions clockwise between N 60° E and southwest. These limiting directions are determined by the shape of Lake Superior and the location of Taconite Harbor with respect to the lake shores. The combinations of storm-wind velocities and fetch distances for the directions between N 65° E and east, and between south and southwest result in the most severe storm waves at Taconite Harbor. The directions between south and east have considerable fetch, measured from Taconite Harbor; however, severe winds from this quadrant are extremely rare.

3. The model study was performed to determine whether the breakwaters proposed in the original plan of construction would be adequate to protect the harbor from wave action during storms, and if it were not, to develop a plan that would provide sufficient protection from wind waves. It was especially desired to determine the breakwater plan that would provide the maximum protection at minimum construction cost.

4. The model investigation was initiated after construction of the

harbor had begun. Therefore, it was necessary to conduct the study at an accelerated pace to insure that the test results would become available before construction of the breakwaters had progressed too far. Completion of the east breakwater was of primary interest in the initial stages of construction operations at Taconite Harbor. Thus, the first phase of the model study was concerned with the development of an optimum design for the east navigation opening, and determination of the minimum length of east breakwater required to provide adequate protection to the harbor. The second phase of the model testing program was concerned with the west navigation opening and west breakwater.

PART II: THE MODEL

Design

5. The Taconite Harbor model was constructed using a linear scale of 1:150, 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 frictional resistance and surface tension effects; (b) the absolute size of the model waves; (c) available shelter and model-basin area; (d) efficiency of model operation; (e) characteristics of available wave-generating and wave-measuring apparatus; and (f) cost of model construction. A geometrically undistorted model was used to insure that accurate reproduction of the short-period wind waves would be obtained. After the linear scale had been selected, based on the above considerations, the model was designed and operated in accordance with Froude's* model laws. Based upon Froude's law, a linear scale (L_r) of 1:150, and a specific weight scale (γ_r) of 1:1, the following model-prototype relationships were derived:

<u>Characteristics</u>	<u>Dimensions**</u>	<u>Model-prototype Scales</u>
Length	L	$L_r = 1:150$
Area	L^2	$A_r = L_r^2 = 1:22,500$
Volume	L^3	$\bar{V}_r = L_r^3 = 1:3,375,000$
Time	T	$T_r = L_r^{1/2} = 1:12.25$
Velocity	L/T	$V_r = L_r^{1/2} = 1:12.25$
Unit pressure	F/L^2	$P_r = L_r \gamma_r = 1:150$
Force	F	$F_r = L_r^3 \gamma_r = 1:3,375,000$
Weight	F	$W_r = L_r^3 \gamma_r = 1:3,375,000$

* ASCE, "Hydraulic Models." Manual of Engineering Practice, No. 25, pp 9 and 43.

** In terms of force, length, and time.

Description

6. The model was constructed of concrete in an existing wave basin, and reproduced, to scale, the proposed prototype harbor and adjacent lake hydrography. A sufficient area was reproduced (6000 sq ft, equivalent to 4.8 sq miles in the prototype) upshore, downshore, and lakeward to permit generation of waves and wave-front patterns from the different wind directions selected for testing. The model breakwaters were constructed of crushed stone of sufficient size and density that they remained stable under attack of the test waves. Photograph 1 shows the model during construction, and photograph 2 is a general view of the model ready for operation.

7. Model waves were reproduced to scale by a movable, plunger-type wave machine, 40 ft in length, which generated the waves by periodic displacement incident to the vertical movement of the plunger in water. The wave machine may be seen in the foreground of photograph 2. The waves were reproduced in accordance with the same linear scale as that used for model construction. Wave heights in the model were measured with an electrical wave-height gage designed and constructed at the Waterways Experiment Station especially for this purpose. The gage consists of series-connected resistors installed in a direct-current circuit with the resistors so calculated that the current varies directly with submergence of the gage in water. Recordings of water-surface elevations (wave heights) with respect to time were obtained on sensitized paper by means of an oscillograph used in connection with the wave-height gage.

PART III: THE TESTING PROGRAM

Selection of Test ConditionsStill-water level

8. Still-water levels (swl) for wave-action models should be selected in such a manner that the refraction, diffraction, and reflection of waves are reproduced accurately. Levels of the Great Lakes vary from year to year and from month to month. Also, for particular locations, lake levels vary from day to day and from hour to hour. Continuous records of the lake levels have been tabulated by the U. S. Lake Survey, CE, since the year 1860*. The usual pattern of seasonal variation of the Great Lakes consists of high levels in summer and early fall, and low levels in winter. The highest and lowest monthly average levels are usually reached on Lake Superior in the months of September and March, respectively. The average level of Lake Superior during the period 1860-1951 was 602.2 ft above mean tide at New York City, 1935 Datum. The highest one-month average level was 604.1 ft and occurred in August 1876. The lowest one-month average level was 600.0 ft and occurred in April 1926. The average seasonal range in the mean monthly level of Lake Superior is 1.2 ft. The following tabulation shows the percentage of time that the seasonal high monthly level of Lake Superior reached various elevations during the period of record:

<u>Maximum Monthly Mean Levels during Period 1860-1951</u>	
<u>Elevation in ft</u>	<u>Per Cent of Time Seasonal**</u>
<u>above N. Y. Datum</u>	<u>High Equaled or Exceeded Given Elev</u>
600.0 - 601.5	100.0
601.5 - 602.0	99.5
602.0 - 602.5	91.5
602.5 - 603.0	71.0
603.0 - 603.5	33.0
603.5 - 604.0	7.5
604.0 - 604.1	0.5
604.1 (Maximum)	Occurred one time in 91 years of record

* Corps of Engineers, U. S. Army, Great Lakes Division, U. S. Lake Survey, Variations in Great Lakes Levels. Detroit, Michigan, Feb 1952.

** Example: Lake Superior reached a monthly average level between 602.5 and 603.0 ft 71 per cent of the years between 1860 and 1951, or 65 times.

9. Wind setup and seiches are relatively short-period fluctuations superimposed on the longer-period variations in lake level. Seasonal and longer-period variations in Great Lakes levels are caused by variations in precipitation and other factors that change the actual quantities of water contained in the lakes. Wind setup and seiches are caused by the tractive force of wind blowing over the water surface and differential atmospheric pressures. The frequency of occurrence of short-period fluctuations in the local water level at Two Harbors, Minnesota, as given in a report* by the Great Lakes Division Engineer, CE, are presented in the following tabulation:

Frequency of Occurrence of Short-period Fluctuations in Local Level at Two Harbors, Minnesota	
Rise above General Lake Level in ft	Interval in Months between Occurrence of Rise Equal to or Greater than Given Value
0.45 - 0.60	0.5
0.60 - 0.75	1.0
0.75 - 1.00	2
1.00 - 1.25	4
1.25 - 1.50	9
1.50 - 1.75	17
1.75 - 2.00	42
2.00	99

Because of the proximity of Two Harbors and Taconite Harbor, these data can be used to estimate the magnitude and frequency of corresponding fluctuations in the local lake level at Taconite Harbor.

10. Analysis of the data presented in the above paragraphs, for the purpose of selecting the still-water level for the Taconite Harbor model, is complicated by the fact that short-period fluctuations are superimposed on the seasonal variations in lake level. It is believed sufficient to select a representative swl corresponding to an average severe storm. Low-water datum (lwd) for Lake Superior is 601.6 ft above mean tide at New York City, 1935 Datum. Thus, the average lake level during the period of record (602.2 ft above the New York City

* Corps of Engineers, Department of the Army, Office of the Division Engineer, Great Lakes Division, Preliminary Examination Report on Property Damage on the Great Lakes, Resulting from Changes in Lake Levels. Chicago, Illinois, June 1952.

Datum) corresponds to +0.6 ft lwd. The table in paragraph 8 shows that the seasonal high monthly mean water level is equal to or greater than the average lake level almost 90 per cent of the time. The table in paragraph 9 shows that a short-period rise of 0.6 ft occurs in the local level with a frequency of once each month. Therefore, the probability of a short-period rise of 0.6 ft coinciding in time with a seasonal high of +0.6 ft lwd is about 90 per cent. The seasonal high level on Lake Superior occurs usually during the months of August, September, or October. The larger storm waves in the vicinity of Taconite Harbor occur during the period from January to May. Thus, the probability of a seasonal high lake level and a large wind tide occurring at the same time is relatively small.

11. Based upon the above analysis, it is believed sufficient to combine the average lake level with a short-period rise in local level of 0.6 ft ($602.2 + 0.6 = 602.8$ ft above New York Datum = +1.2 ft lwd) to obtain a swl for use in the model study. A swl of +1.2 ft lwd was used in the Taconite Harbor model for all tests conducted.

Wave dimensions and directions

12. In planning a testing program for model investigations of harbor wave-action problems, it is necessary to select the dimensions and directions of test waves in such a manner that the analysis of results of tests to determine the effects of different plans on wave-action conditions in the harbor can be accomplished judiciously. Surface wind waves are generated by the drag of the wind on the water surface and the push of the wind against the wave crests. The magnitude of the maximum wave that can be generated by a given storm is determined by the wind speed, the interval of time during which that wind speed exists (wind duration), and the water distance over which the wind blows with that speed (fetch). Thus, the factors influencing the selection of test waves include: (a) the fetch distances for the different directions from which waves may attack the harbor; (b) the frequency of occurrence and duration of winds of storm intensity blowing from the different directions, (c) the alignment, width, and position of navigation openings into the harbor, and (d) the alignment, length, and position of reflecting surfaces inside the harbor.

13. Taconite Harbor will be exposed to surface wind waves generated by storms from all directions clockwise between N 60° E and S 45° W. These limiting directions are determined by the general shape of Lake Superior, and the location of the harbor site with respect to the lake shores. After consideration of the factors enumerated in the previous paragraph, the following wave dimensions and directions were selected for use in testing the different breakwater plans:

<u>Direction</u>	<u>Wave Height, ft</u>	<u>Wave Period, sec</u>
N 82-1/2° E	10	7.0
S 65° E	7	5.5
S 20° E	7	5.5
S 22-1/2° W	10	5.5

A few observational tests were also conducted using waves 20 ft in height from the N 82-1/2° E direction.

14. Data concerning the frequency of occurrence of waves that can be expected at Silver Bay Harbor, Minnesota, (formerly called Beaver Bay Harbor) were available for use in the analysis of test results for the model study of Taconite Harbor. These data were prepared from the results of a wind-wave analysis performed in 1948 in connection with a similar model study of Silver Bay Harbor conducted by the Waterways Experiment Station for the Reserve Mining Company. The basic data upon which the wind-wave analysis was founded consisted of a 33-year wind record obtained from the U. S. Weather Bureau, Duluth, Minnesota. The dimensions, directions of approach, and number of occurrences of various-size storm waves were estimated from the wind records by application of the principles of wave forecasting developed by Sverdrup and Munk*. Some modifications in this theory have been made since that time; also, storm intensities at Duluth and Taconite Harbor are not identical, and there are some differences in the fetch distances for Silver Bay Harbor and Taconite Harbor. However, despite these differences it was considered

* 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., March 1947.

feasible to use the data prepared for Silver Bay Harbor in evaluating the relative effectiveness of the different plans tested in the model study of Taconite Harbor. The following tabulation presents a summary of the wind-wave analysis:

Estimated Frequency of Occurrence of Waves at Silver Bay, Minnesota					
Wave Height	Frequency of Storms Generating Waves of Given Height.				
ft	Wave Direction				
	Northeast	East	Southeast	South	Southwest
2-3	1 in 35 days	1 in 8 mo	1 in 1 yr	1 in 9 mo	1 in 35 days
3-4	1 in 40 days	1 in 10 mo	1 in 5 yr	1 in 15 mo	1 in 40 days
4-5	1 in 70 days	1 in 13 mo	1 in 11 yr	1 in 4 yr	1 in 80 days
5-6	1 in 80 days	1 in 20 mo	None	1 in 8 yr	1 in 5-1/2 mo
6-7	1 in 4-1/2 mo	1 in 5 yr	None	None	1 in 12 mo
7-8	1 in 5-1/2 mo	1 in 6 yr	None	None	1 in 3 yr
8-9	1 in 8-1/2 mo	1 in 11 yr	None	None	1 in 5 yr
9-10	1 in 13 mo	1 in 17 yr	None	None	1 in 11 yr
10-11	1 in 20 mo	1 in 33 yr	None	None	1 in 17 yr
11-12	1 in 21 mo	None	None	None	1 in 33 yr
12-13	1 in 3-1/2 yr	None	None	None	None
13-14	1 in 5-1/2 yr	None	None	None	None
14-15	1 in 8 yr	None	None	None	None
15-16	1 in 33 yr	None	None	None	None
16-17*	None	None	None	None	None

Description of Plans Tested

15. The original plan of harbor construction and twenty-three modifications of the original plan were tested in this investigation. The results of tests of the original plan were used to determine its efficacy in protecting the harbor from waves generated by storms from the different directions listed in paragraph 13. Data obtained in testing

* It is possible for waves as large as 20-25 ft in height, depending on wind speed and duration, to obtain at Taconite Harbor; however, the frequency of occurrence of these waves is so low that their importance with respect to the design of the harbor is not considered to be very great.

the original plan were also used as a reference to which test results of the various modifications were compared. Modifications in the original design were devised and tested to determine: (a) the most efficient east navigation opening; (b) the most efficient west navigation opening; (c) the effects of rubble wave absorbers at selected locations; and (d) the advantages of constructing breakwaters of the type that absorb, rather than reflect, a large proportion of the incident wave energy. Stability tests to determine the most economical design sections for the Taconite Harbor breakwaters were performed at the St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, under the supervision of Dr. L. G. Straub. The results of these stability tests are not included in this report.

16. Plate 1 shows the elements of the original breakwater plan. Plates 2 and 3 show the elements of the different modifications of the original plan. All the plans tested are described briefly in the following tabulation.

<u>Plan Designation</u>	<u>Elements of Plan</u>
Original plan (Base-test conditions)	The following breakwaters, the positions and lengths of which may be determined from plate 1, are included in the elements of the original plan: east, Bear Island, middle, inner, Gull Island, and west. Effective width of west navigation opening was 600 ft. Effective width of east navigation opening was 500 ft.
Base-E	Same as the original plan except that the west navigation opening was closed with a rubble mound.
Base-W	Same as the original plan except that the east navigation opening was closed with a rubble mound.
Base-ER	Same as base-E except that 740 ft of the west face of the lakeward end of the east breakwater was paved to form an impervious surface with a high reflection coefficient. See photograph 26.
Plan 1	Same as the original plan except that the Bear Island breakwater was removed to the junction of the curve and tangent. Effective width of east navigation opening was 675 ft.
Plan 1-E	Same as plan 1 except that the west navigation opening was closed with a rubble mound.

(Continued)

<u>Plan Designation</u>	<u>Elements of Plan</u>
Plan 1-ER	Same as plan 1-E except that 740 ft of the west face of the lakeward end of the east breakwater was paved to form an impervious surface with a high reflection coefficient. See photograph 28.
Plan 2	Same as plan 1 except that: (a) the east breakwater was shortened 125 ft, and (b) Bear Island breakwater was extended 200 ft from the junction of curve and tangent. Effective width of east navigation opening was 500 ft.
Plan 2-E	Same as plan 2 except that the west navigation opening was closed with a rubble mound.
Plan 2-ER	Same as plan 2-E except that 615 ft of the west face of the lakeward end of the east breakwater was paved to form an impervious surface with a high reflection coefficient. See photograph 30.
Plan 3	Same as the original plan except that the east breakwater was shortened 355 ft.
Plan 3-E	Same as plan 3 except that the west navigation opening was closed with a rubble mound.
Plan 3-ER	Same as plan 3-E except that 385 ft of the west face of the lakeward end of the east breakwater was paved to form an impervious surface with a high reflection coefficient. See photograph 32.
Plan 4	Same as the original plan except that: (a) Gull Island breakwater and west breakwater were removed, and (b) the inner breakwater and 1st alternate west breakwater were installed.
Plan 5	Same as the original plan except that the inner breakwater was removed.
Plan 6	West breakwater and Gull Island breakwater removed. A 450-ft west navigation opening was formed by the inner breakwater and the 2d alternate west breakwater. East navigation opening as in plan 3.
Plan 7	West breakwater, Gull Island breakwater, and inner breakwater removed. Third alternate west breakwater installed. A 450-ft west navigation opening between 3d alternate west breakwater and Gull Island was obtained by dredging the area immediately northwest of

(Continued)

<u>Plan Designation</u>	<u>Elements of Plan</u>
Plan 7 (Continued)	Gull Island to -27 ft lwd. East navigation opening as in plan 3.
Plan 8	West breakwater, Gull Island breakwater, and inner breakwater removed. A 450-ft west navigation opening formed by installation of arrowhead breakwaters. East navigation opening as in plan 3.
Plan 9	West breakwater and Gull Island breakwater removed. Inner breakwater installed. Beaches Nos. 1 and 2 installed. East navigation opening as in plan 3.
Plan 10	West breakwater and Gull Island breakwater removed. Inner breakwater installed. Beaches Nos. 1 and 2 installed. West navigation opening formed by arrowhead breakwaters. East navigation opening as in plan 3.
Plan 11	Same as plan 3 with beach No. 1 added.
Plan 12	East navigation opening and middle breakwater as in plan 3. All breakwaters and beaches omitted on the west end of the harbor.
Plan 13	Elements of plan 2 and plan 4 combined (i.e., the plan-2 east navigation opening and plan-4 west navigation opening).
Plan 13-A	Same as plan 13 with wave absorbers added. Locations of the wave absorbers are shown on plate 2.

PART IV: RESULTS OF MODEL TESTS

Presentation of Test Data

17. The results of tests conducted in this investigation are presented by photographs 3-32 and plates 4-14. Photographs 3-32 show wave-front patterns from which the effects of different plans on wave action conditions in the harbor can be determined qualitatively. Plates 4-14 show wave-height contours determined from wave heights obtained at gaging stations located at 2-ft intervals (model dimension) over the harbor area. Wave-height contours indicate, quantitatively, the relative effectiveness of the different plans in protecting the harbor from wave action. The urgency of the prototype construction schedule precluded preparation of wave-height contours for all the plans and test directions because of the length of time necessary to obtain this type test data.

Discussion of Results

Original plan (base-test conditions)

18. Test results for the original plan of harbor construction (including base-E and base-W) are shown on photographs 3-9 and plates 4-9. The original plan was tested over the full range of directions from which troublesome and damaging wave action can be expected. This was done to determine: (a) the effectiveness of the original plan in protecting the harbor from storm waves, (b) the most critical wave directions, and (c) the relative importance of the different directions in selection of the optimum breakwater plan. Except for the 20-ft-high waves used in one test, the test-wave dimensions represent waves generated by average severe storms. Because of the large distance (fetch) across Lake Superior for the directions between N 75° E and east (represented on the model by the test-wave direction N 82-1/2° E), storm waves 20 ft in height can occur at Taconite Harbor. However, waves of this magnitude will occur only at rare intervals (see paragraph 14). An observational test was made for this condition to determine the effects of

overtopping of the east, Bear Island, and middle breakwaters.

19. Effects of overtopping of breakwaters by 20-ft waves. Waves inside the harbor, generated almost entirely by waves overtopping the breakwaters on the south and east sides of the harbor, are shown in photograph 3. Waves along the docks measured from four to six feet in height. Ordinary severe storm waves (10 ft in height) will not overtop the breakwaters (see photograph 4). Since waves 20 ft in height will occur at Taconite Harbor with an estimated frequency of less than once in 40 years, it is not considered necessary to design the breakwaters with a height sufficient to prevent overtopping by these waves.

20. Effectiveness of original breakwater plan in protecting the harbor from wave action. The results of tests of the original breakwater plan show that it will provide excellent protection to the harbor from average severe storm waves from all directions except those between south and southwest (represented on the model by test-wave direction S 22-1/2° W). Comparison of wave-height data shown on plates 7, 8, and 9 shows that practically all of the wave energy entering the harbor from the S 22-1/2° W direction is by way of the west navigation opening. Because of this fact a large part of the rest of the testing program was concerned with the development of an improved west navigation opening. The east navigation opening of the original plan was very effective in protecting the harbor from wave action. However, it was believed that the breakwaters forming the east opening could be reduced in length without increasing appreciably the wave energy that could enter the harbor through this opening. Plans 1, 2, and 3 were tested to determine the optimum design of the east navigation opening.

Plans 1, 2, and 3 (design of east navigation opening)

21. Test results of plans 1, 2, and 3 are shown by photographs 10, 11, and 12, and plates 10, 11, and 12. The elements of these plans were designed to indicate the minimum length of the breakwaters forming the east navigation opening that would not increase wave-action conditions within the harbor resulting from waves from the N 75° E to east directions. Tests of the original plan had shown that wave conditions within

the harbor due to waves from the south to east directions would not be critical. Therefore, plans 1, 2, and 3 were tested using only waves from the N 82-1/2° E direction.

22. The results of these tests show that a considerable reduction in breakwater length can be effected without increasing appreciably the height of waves within the harbor. The following tabulation shows the average wave height along the docks, resulting from 7.0-sec by 10.0-ft waves from the N 82-1/2° E direction, for the original plan and the three plans tested in this series:

<u>Plan</u>	<u>Average Wave Height (H) in ft along Docks</u>
Original	1.8
1	2.1
2	2.1
3	2.3

The wave-height contours (plates 10-12) show that the greatest wave height along the docks for all of these plans was 3.0 ft. An increase of 0.5 ft in the average height of the waves over that of the original plan is not considered of sufficient magnitude to preclude the adoption of plan 3 for the east navigation opening.

Plans 4-12 (design of
west navigation opening)

23. The results of tests of plans 4-12 are shown on photographs 13-21, respectively; plates 13 and 14 present wave-height contours of plans 4 and 5, respectively. The elements of these plans involve different types and positions of structures forming the west navigation opening. The various types of navigation openings were tested in an attempt to reduce wave action along the docks due to storm waves from the south to southwest directions. Tests of these plans were conducted using only waves from the S 22-1/2° W direction. Plans 4-7 constitute a form of west navigation opening very similar to that of the original plan, and were devised in an attempt to reduce the length of breakwater required without increasing wave action along the docks. The plan 8

navigation opening is an adaptation of the arrowhead type opening. In plan 9 sand beaches were placed along the navigation channel in an attempt to refract the wave fronts away from the docks. Plans 10 and 11 involved different combinations of the sand beaches along the channel and breakwaters of the arrowhead and original plan types. Plans 8-11 were devised in an effort to reduce wave action along the docks using all applicable principles of navigation opening design, and without regard to increased cost of construction. In plan 12 all breakwaters and beaches on the west end of the harbor were omitted.

24. The following tabulation shows the average wave height along the docks, resulting from 5.5-sec by 10-ft waves from the S 22-1/2° W direction, for the original plan and the different plans tested in this series:

<u>Plan</u>	<u>Average Wave Height (H) in ft along Docks</u>
Original	7.8
4	8.7
5	8.0
6	9.6
7	6.9
8	5.5
9	5.1
10	3.6
11	6.5
12	5.8

These results show that plan 10 is the only plan that would afford an appreciable reduction in wave heights along the docks, compared with the original plan. However, plans 8, 9, and 12 are nearly as effective. The effectiveness of plan 12 was somewhat surprising. It was not expected that wave heights along the docks would be less with no protecting breakwaters than they were for a majority of the plans involving the construction of expensive breakwaters and beaches. Observational tests were conducted to determine the reason for the effectiveness of plan 12. It was found that this plan allowed littoral currents, caused by the waves, to flow into the harbor and along the docks in a north-easterly direction. The velocity of these currents varied from about 1.5-3.0 ft per sec. These currents changed the direction of the waves

entering the harbor sufficiently to provide considerable protection to an area along the docks about 100 ft wide (see photograph 21). Waves outside this protected area were not reduced.

Effects of wave absorbers placed at strategic locations (plans 13 and 13A)

25. Observational tests were conducted of plan 13 (a combination of the navigation openings of plans 2 and 4) to determine whether the addition of wave absorbers (plan 13A) placed at certain positions around the harbor perimeter would improve wave conditions in the harbor and at the west navigation opening. The wave absorbers were constructed of dumped rubble. The locations selected for testing the efficacy of absorbers in reducing wave action in critical areas are shown on plate 2 and photographs 23 and 25. Photographs 22-25 show the difference in wave patterns, with and without the wave absorbers installed, for two of the wave directions used in the observational tests. The west absorber and Gull Island absorber prevented cross-wave patterns from developing in the west navigation opening. The east absorber prevented reflections from the shore line east of the coal dock.

Reflection of waves into harbor from end of east breakwater

26. The west side of the east breakwater at the navigation opening should be constructed in such a way that waves from the south to southwest directions will not be reflected into the harbor from the end of the structure. Rubble breakwaters are good wave absorbers when the slopes are not too steep and when the upper portion of the structure is constructed of rubble with adequate voids. Structural design of the breakwaters was not one of the problems studied on the harbor model. However, the harbor model was used to show the relative effects on wave action in the harbor of reflecting- and absorbing-type breakwaters.

27. The critical wave direction for these tests is S 22-1/2° W, and the critical reach of breakwater is the outer (southern) 700-800 ft of the east breakwater. Tests were conducted on the original plan and plans 1, 2, and 3. The breakwaters normally used in all the tests in

this model study were constructed of rubble with about 40 per cent voids. These breakwaters were very good wave absorbers. Observational tests were conducted using the rubble breakwaters, and similar tests were conducted with the critical portion of the breakwater covered with sheet metal to provide a highly efficient reflecting surface (plans designated base-E and base-ER, plan 1-E and plan 1-ER, plan 2-E and plan 2-ER, and plan 3-E and plan 3-ER). The results of these tests are shown on photographs 8 and 26-32. The increased wave action in the harbor resulting from breakwaters with a high reflection coefficient is shown clearly by these photographs.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

28. It is concluded from the results of this model study and data available concerning the frequency of occurrence of wind waves in the vicinity of Taconite Harbor that:

- a. The original plan of harbor construction will provide excellent protection to vessels moored at the Taconite Harbor docks for all storm waves except extremely high waves from the east to N 75° E directions, and average severe storm waves from the south to southwest directions.
- b. The east breakwater of the original plan can be reduced 355 ft in length without a significant increase in wave action along the docks.
- c. None of the plans tested would provide adequate protection to the docks from average severe storms from the south to southwest directions. Plan 10 would provide adequate protection from a majority of storms (the majority of storms are of less intensity than the average severe storm); however, the cost of constructing the breakwaters and beaches forming the west navigation opening of plan 10 is considered prohibitive.
- d. Rubble wave absorbers placed along the shore line east of the docks, along the shore line west of the west navigation opening, and around the base of Gull Island immediately west of the west navigation opening of the original plan, would improve wave conditions at the west navigation opening and in the eastern part of the harbor.
- e. The west side of the south end of the east breakwater should be constructed in such a way as to absorb a maximum amount of the incident wave energy.

Recommendations

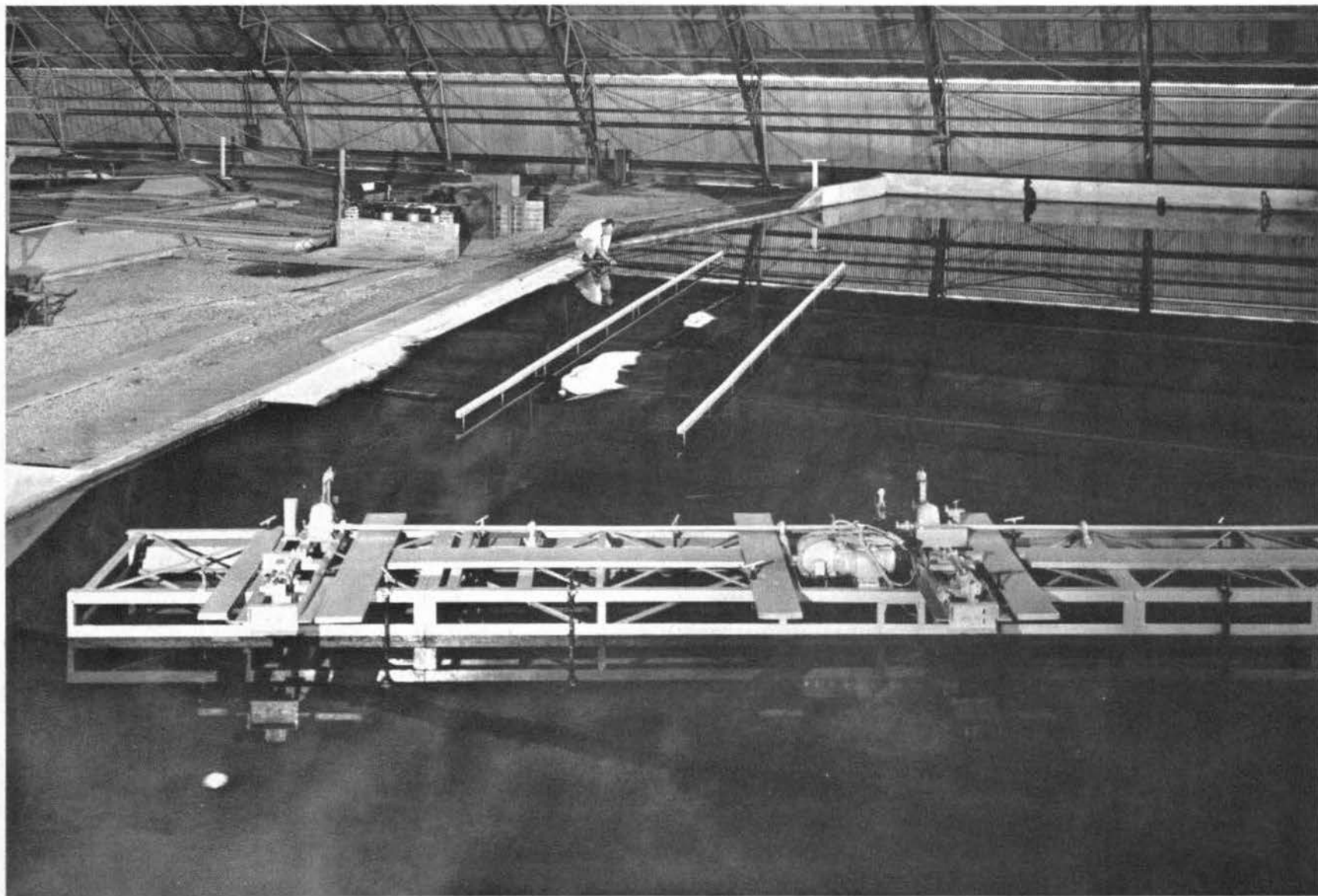
29. It is recommended that consideration be given to the adoption of the following changes in the elements of the original plan of constructing Taconite Harbor:

- a. Reduce the outer end of the east breakwater of the original plan by 355 ft.
- b. Omit the west breakwater, inner breakwater, and Gull Island breakwater of the original plan.

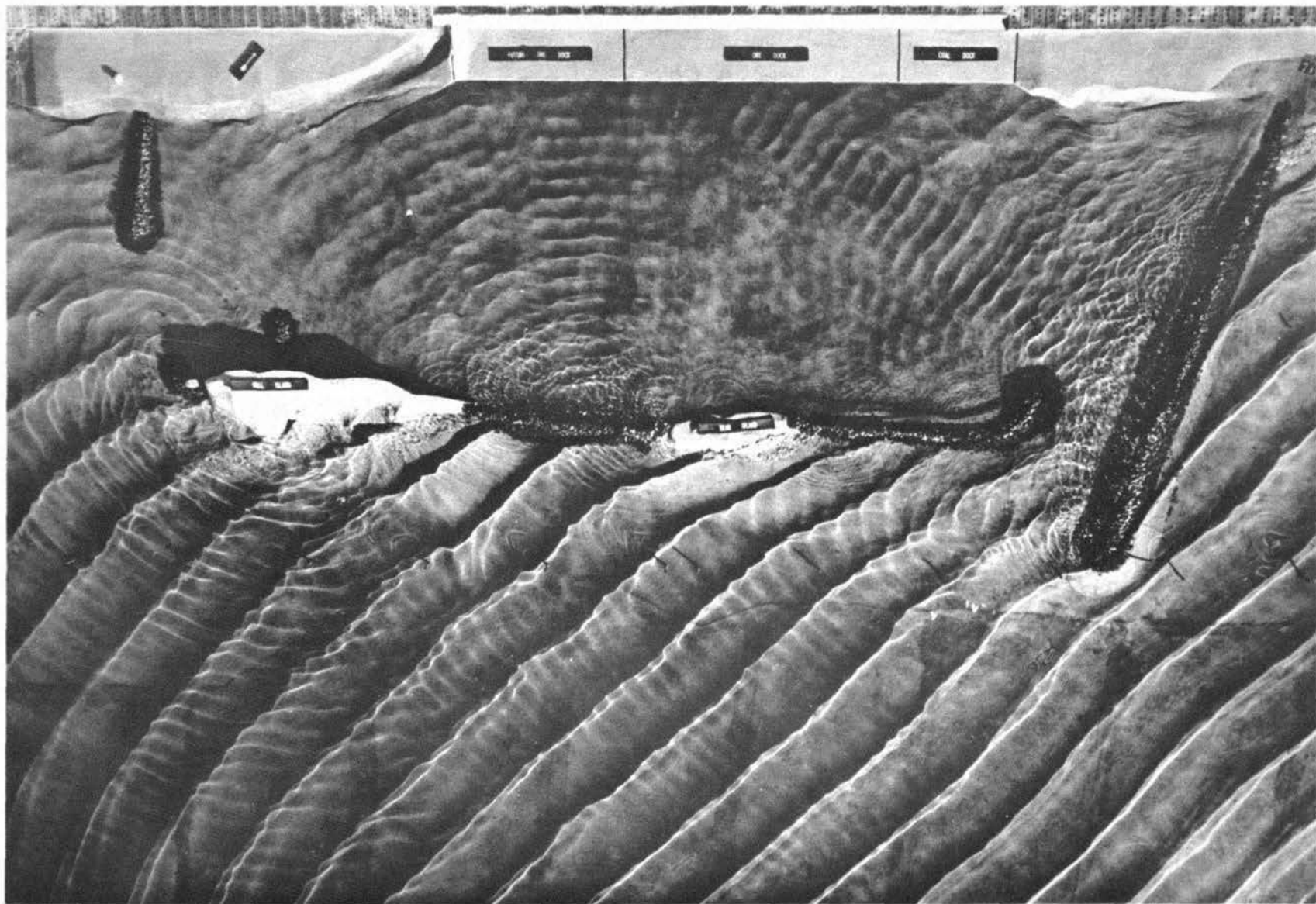
- c. Add the west wave absorber, east wave absorber, and Gull Island wave absorber to the elements of the original plan.
- d. Construct the east breakwater, middle breakwater, and Bear Island breakwater of sufficient height above low water datum to prevent their overtopping by waves 15 ft in height.
- e. Construct 375 to 400 ft of the west side of the outer end of the east breakwater such that a large portion of the incident wave energy will be absorbed.



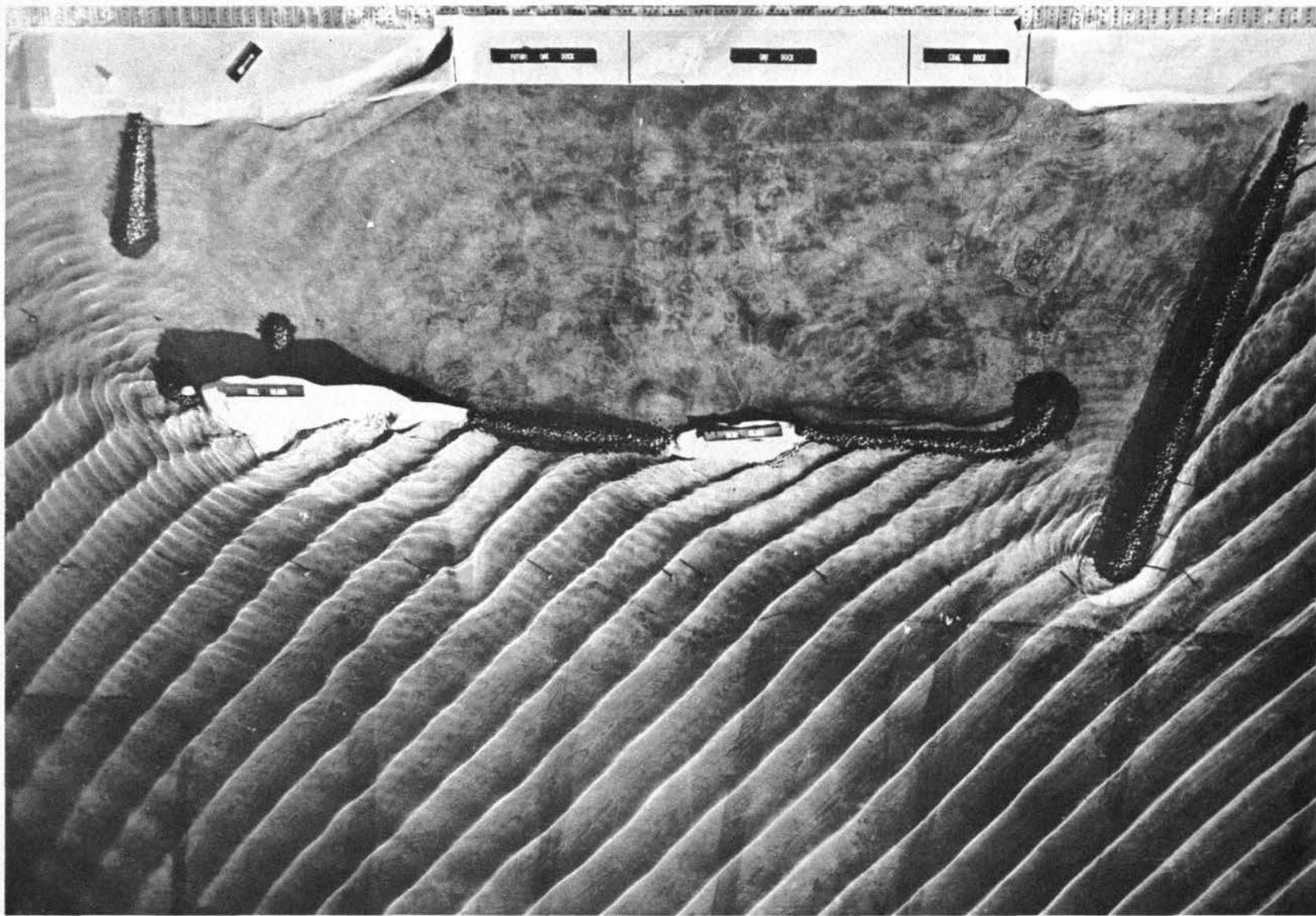
Photograph 1. Taconite Harbor model during construction



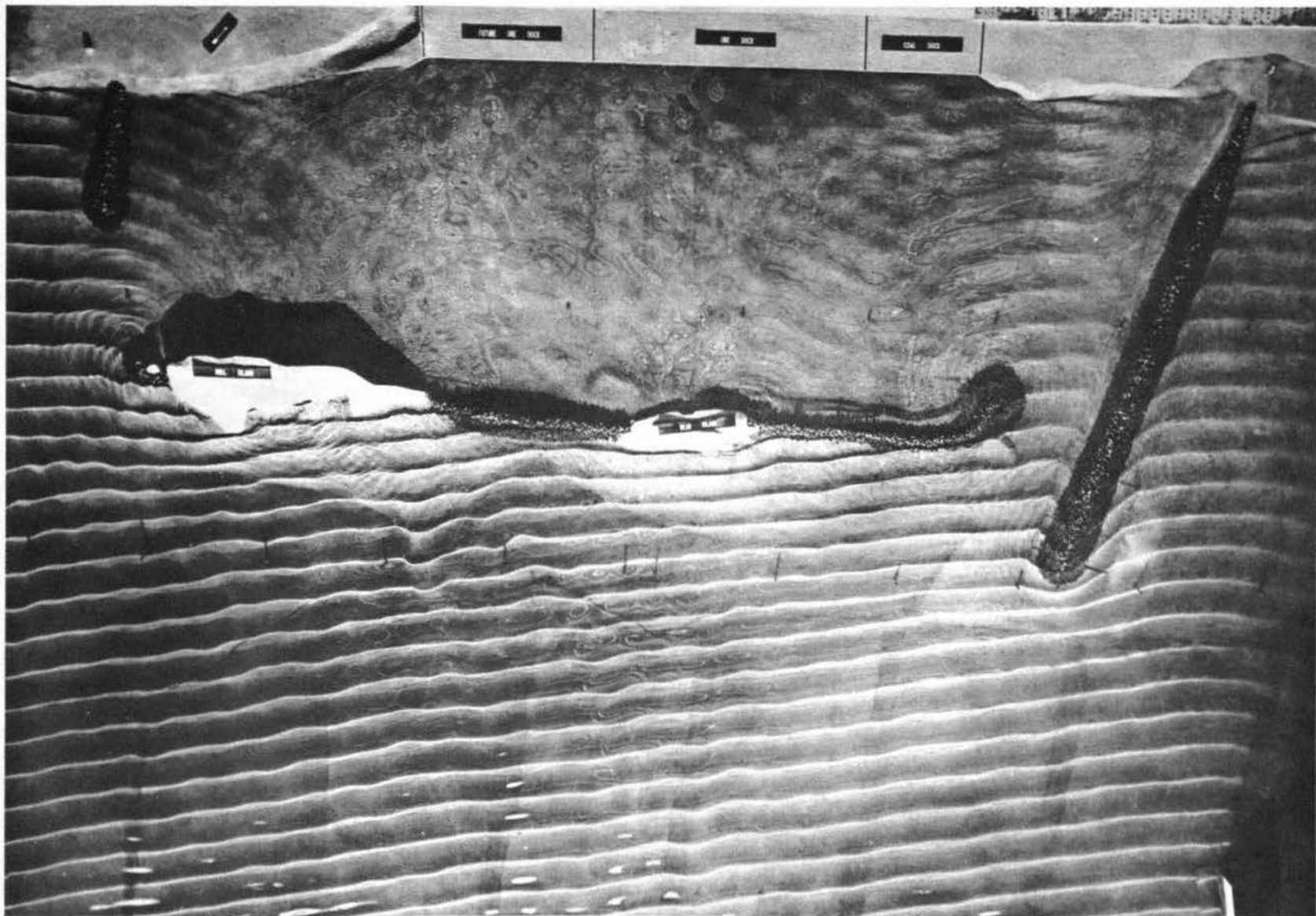
Photograph 2. Taconite Harbor model ready for operation



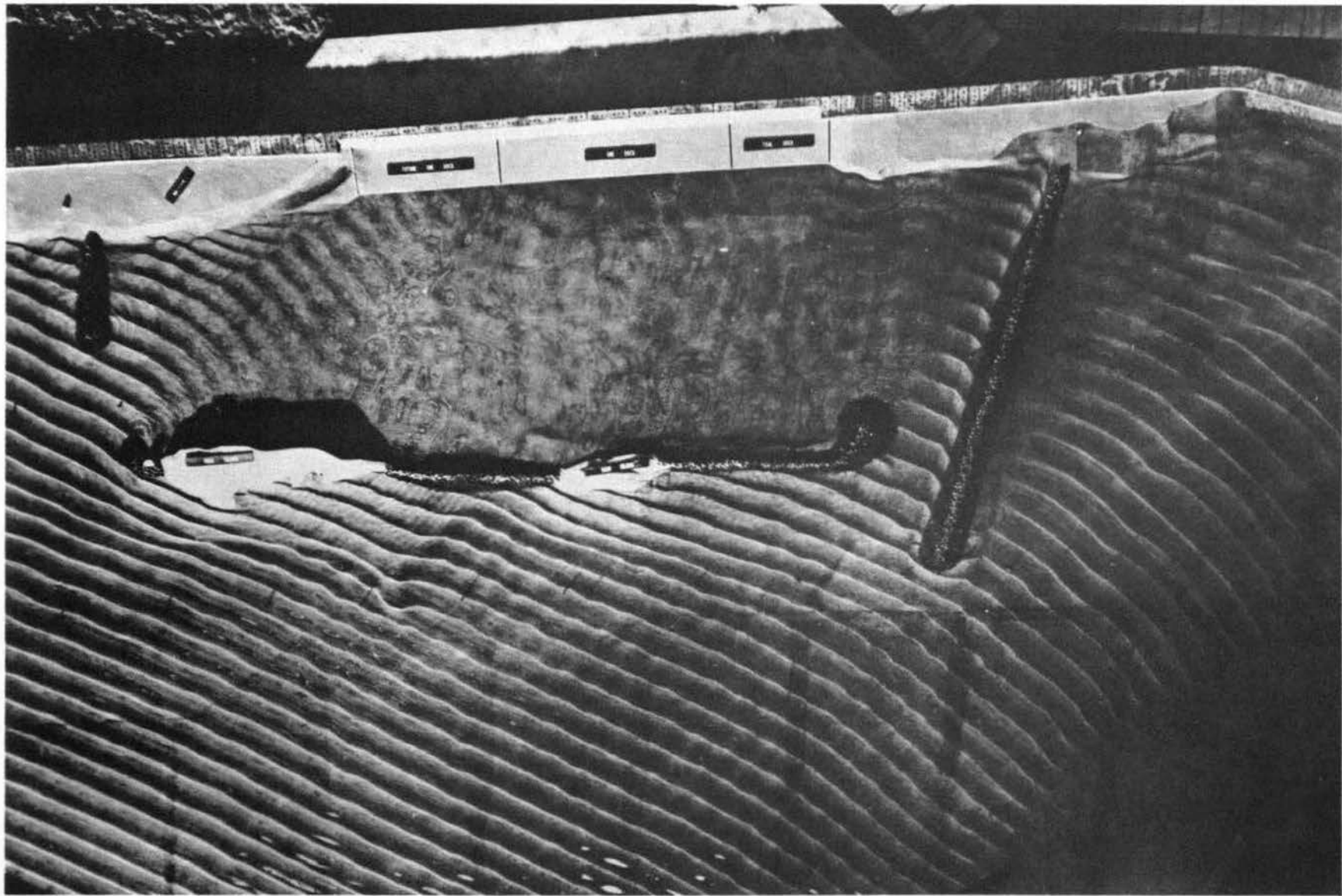
Photograph 3. Original plan: 8.5-sec by 20-ft waves from N $82\frac{1}{2}^{\circ}$ E



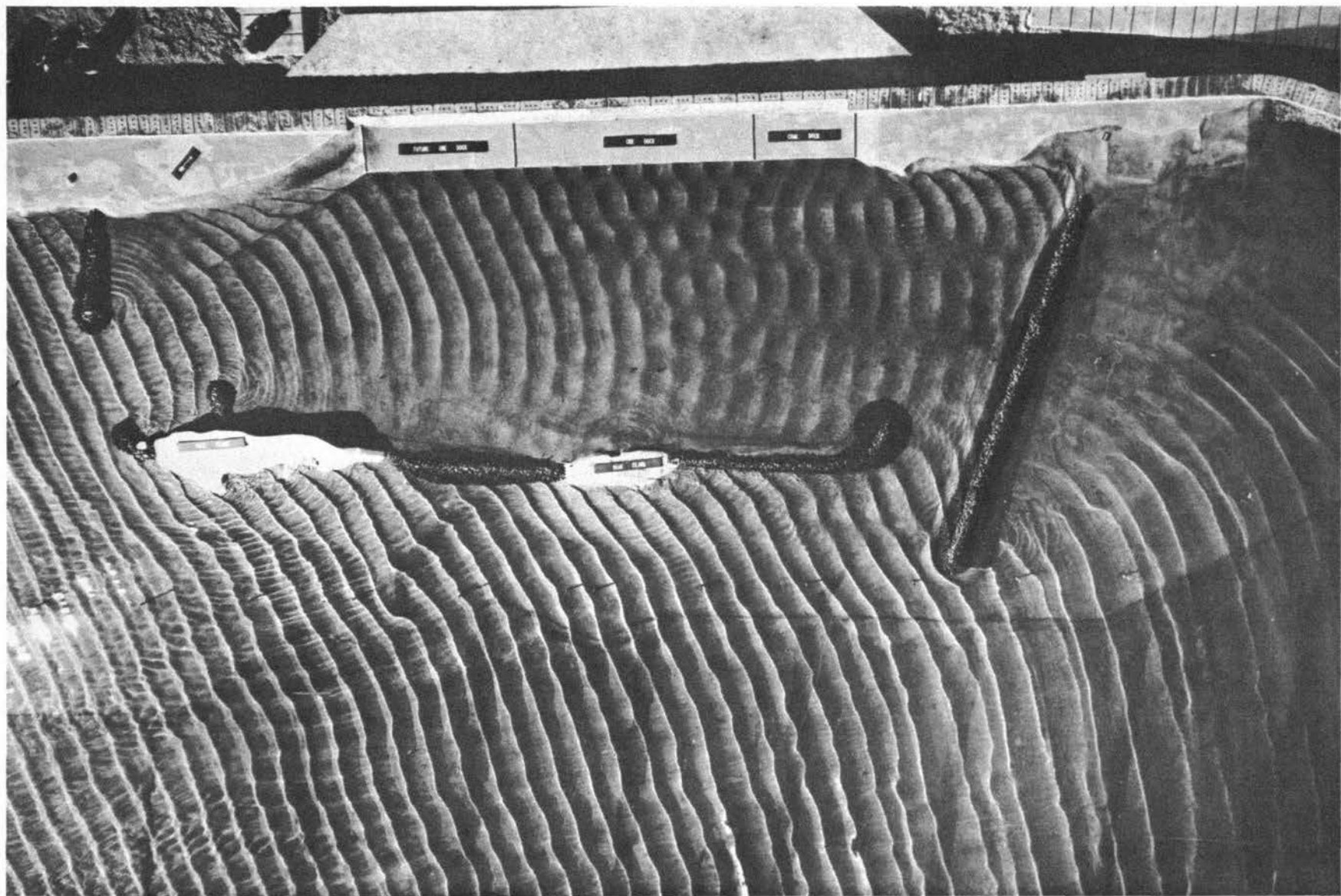
Photograph 4. Original plan: 7.0-sec by 10-ft waves from N 82-1/2° E



Photograph 5. Original plan: 5.5-sec by 7-ft waves from S 65° E



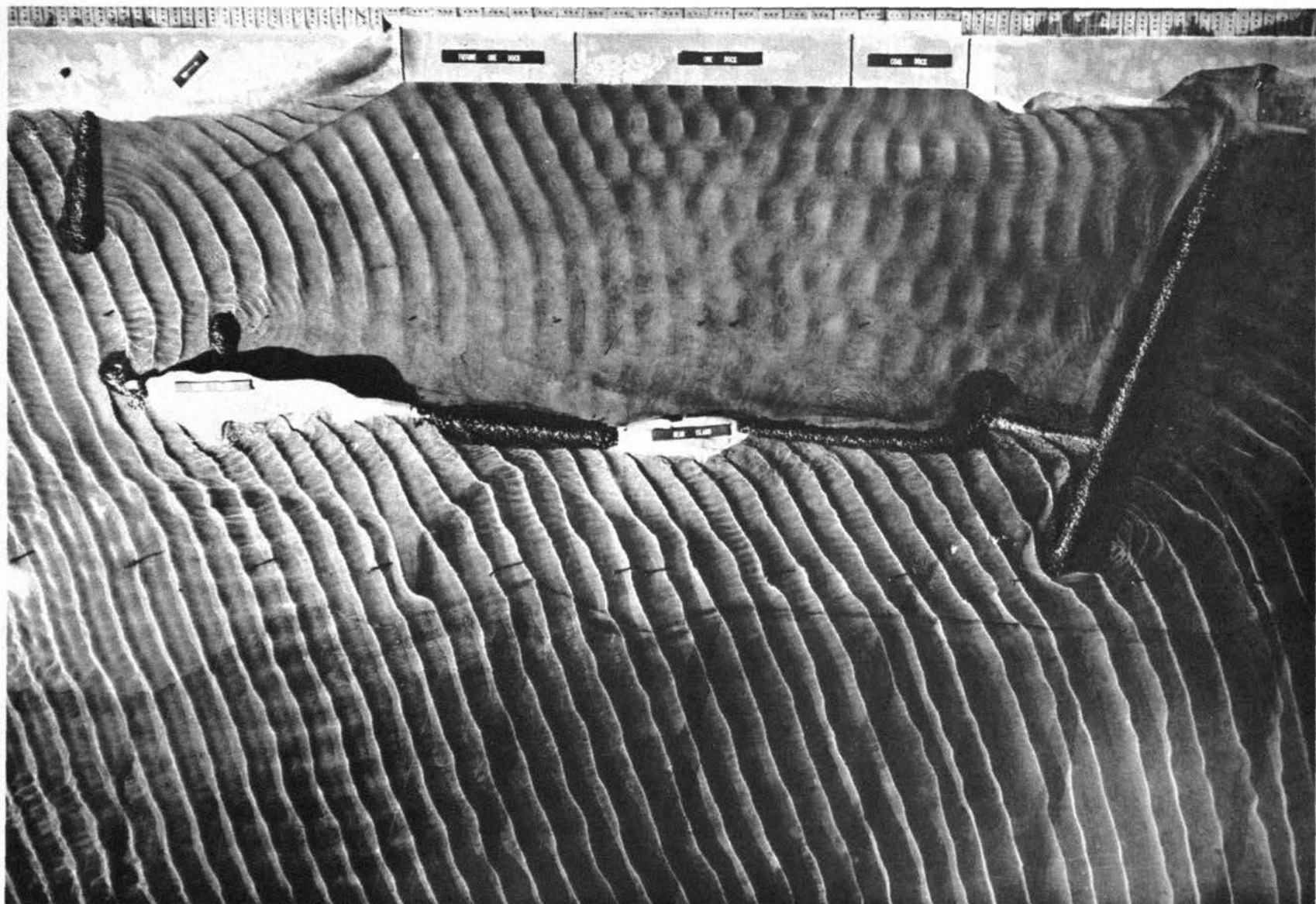
Photograph 6. Original plan: 5.5-sec by 7-ft waves from S 20° E



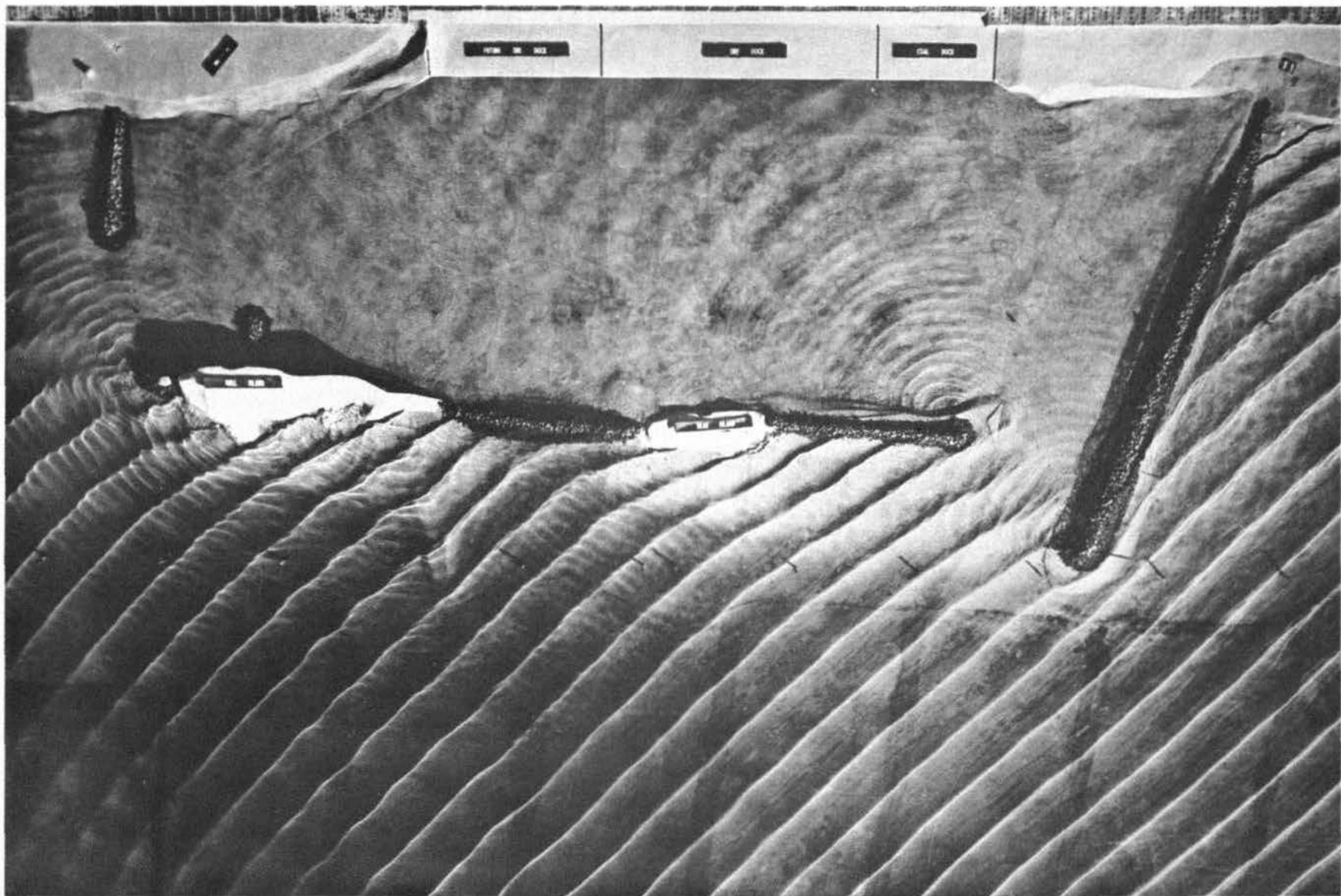
Photograph 7. Original plan: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



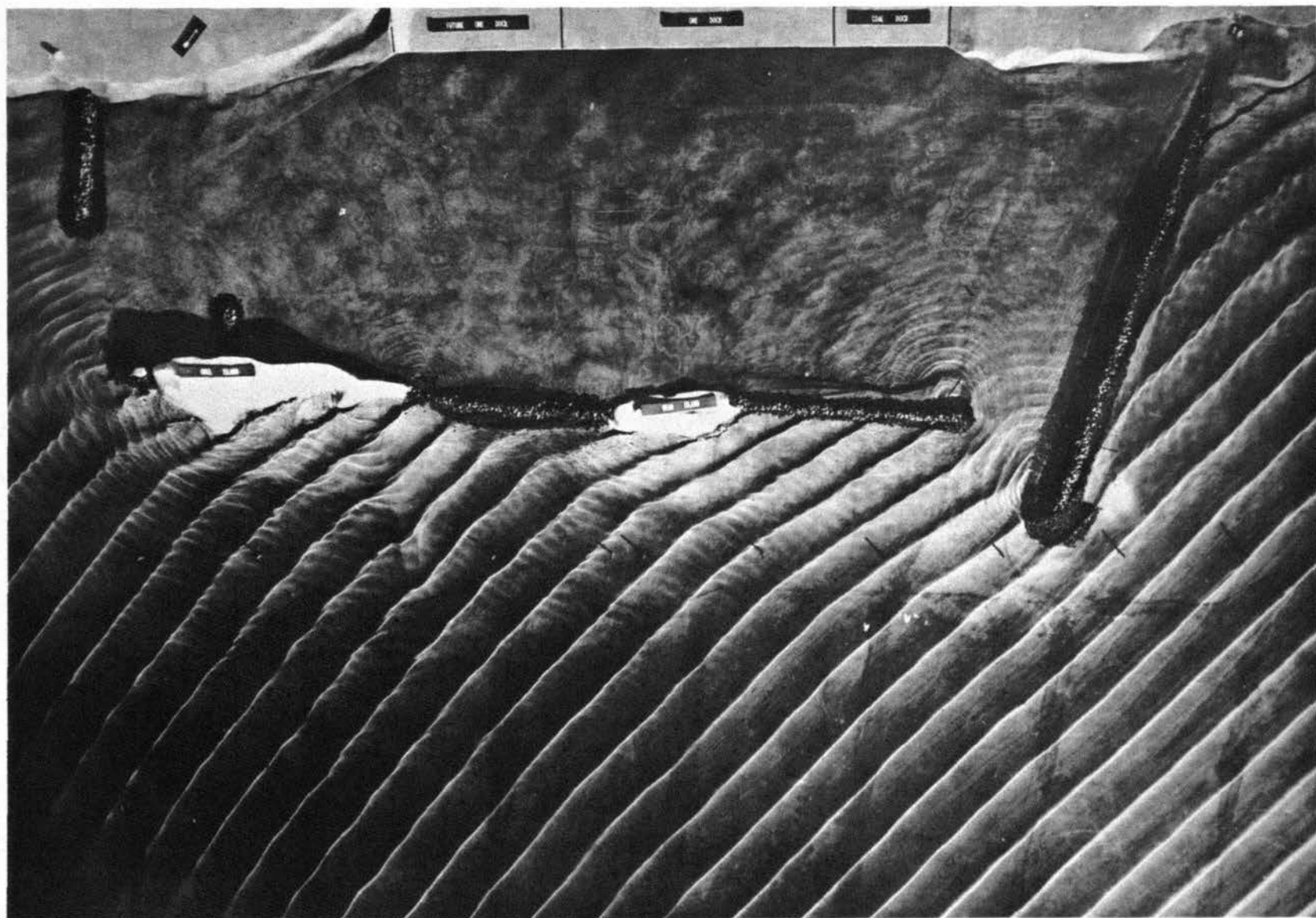
Photograph 8. Base-E: 5.5-sec by 10-ft waves from S $22\text{-}1/2^\circ$ W



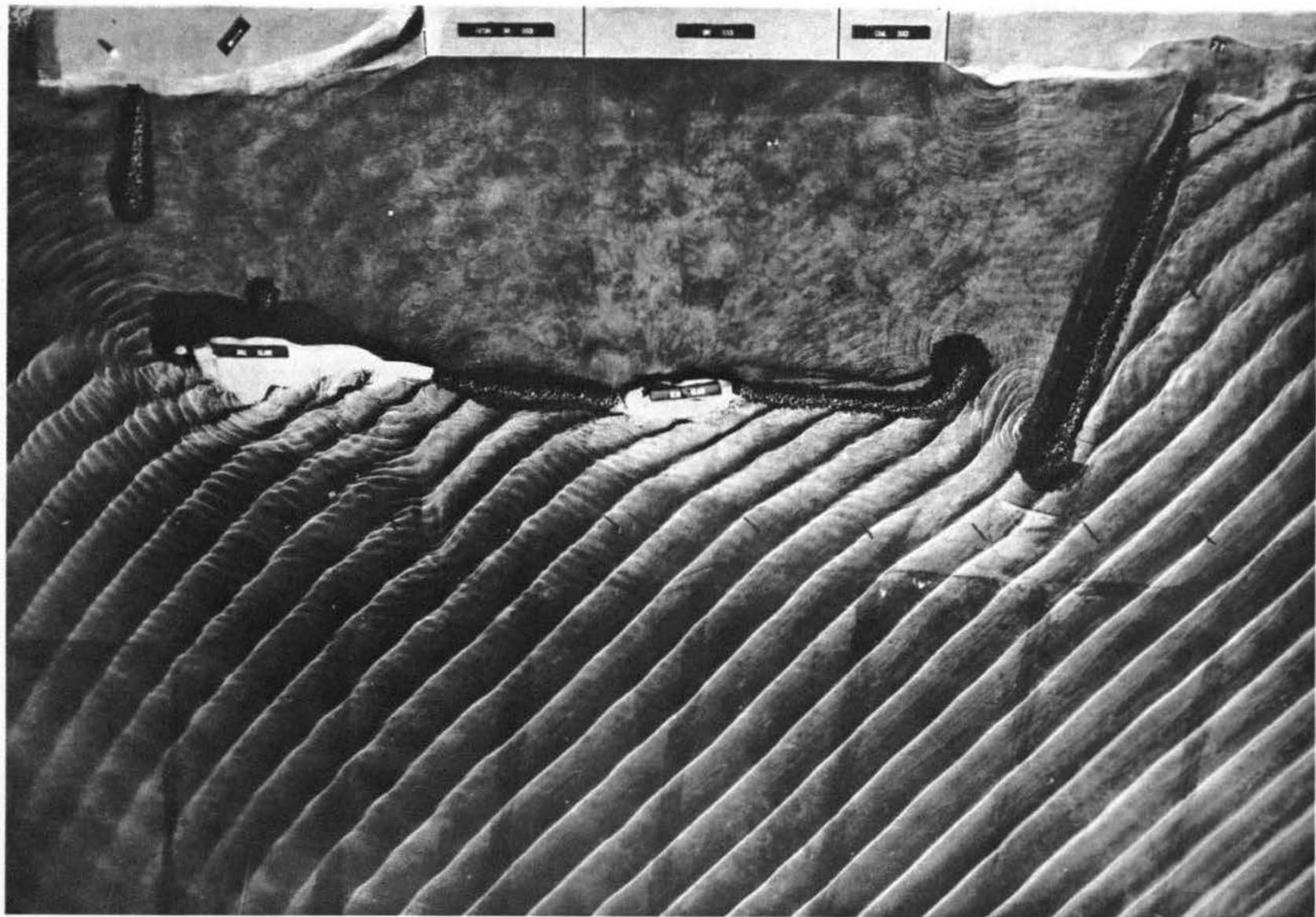
Photograph 9. Base-W: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



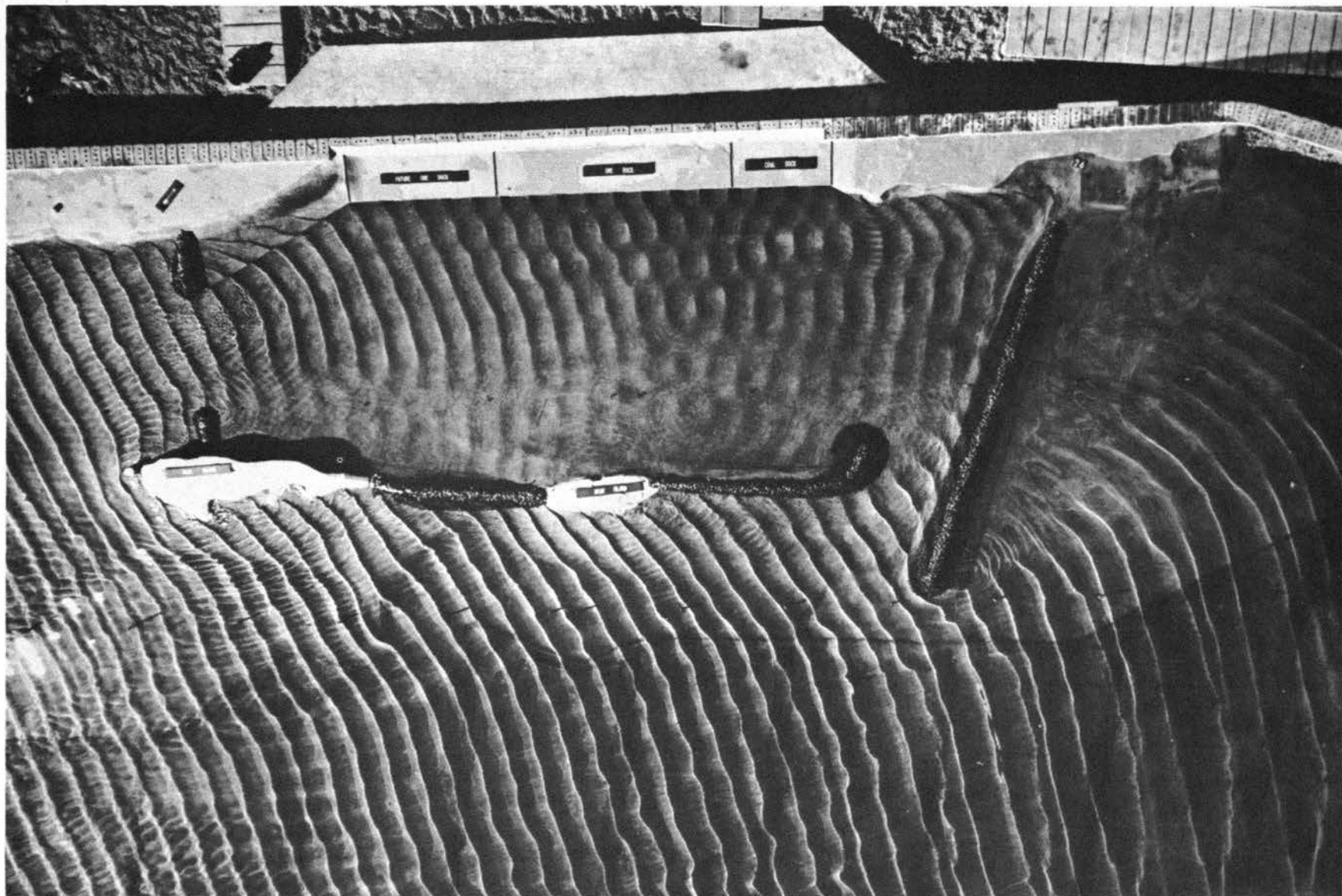
Photograph 10. Plan 1: 7.0-sec by 10-ft waves from N 82-1/2° E



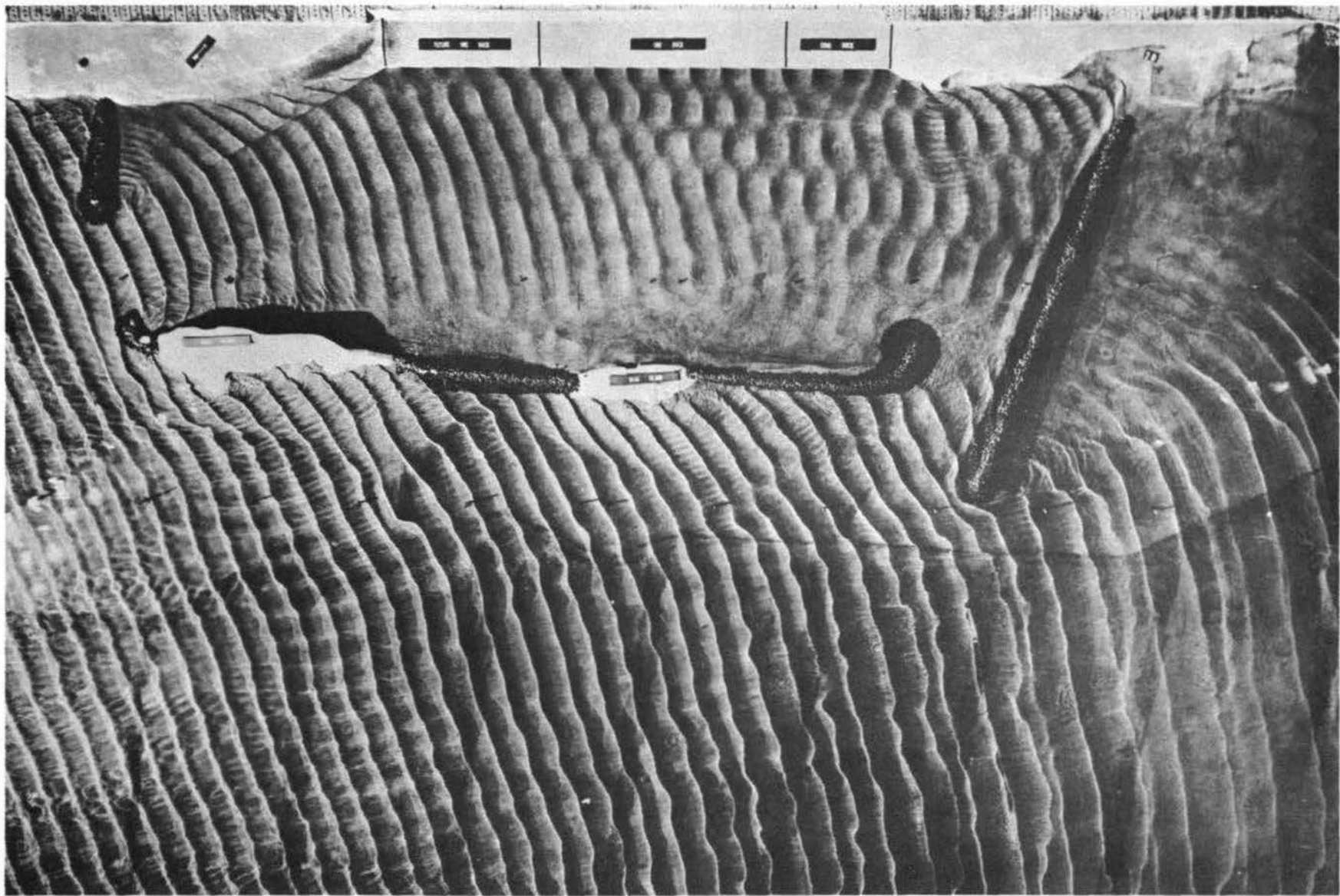
Photograph 11. Plan 2: 7.0-sec by 10-ft waves from N 82-1/2° E



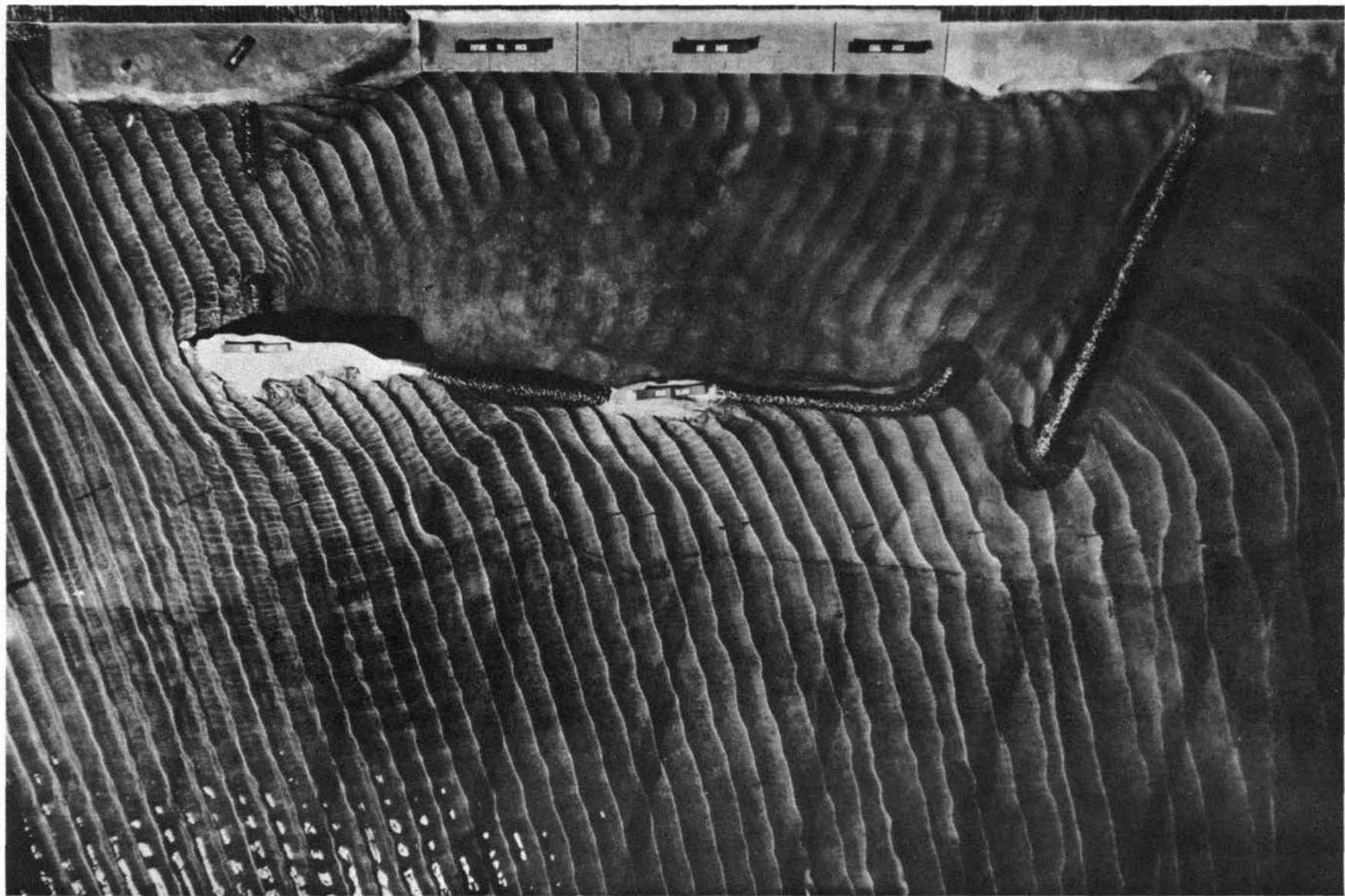
Photograph 12. Plan 3: 7.0-sec by 10-ft waves from N $82\text{-}1/2^\circ$ E



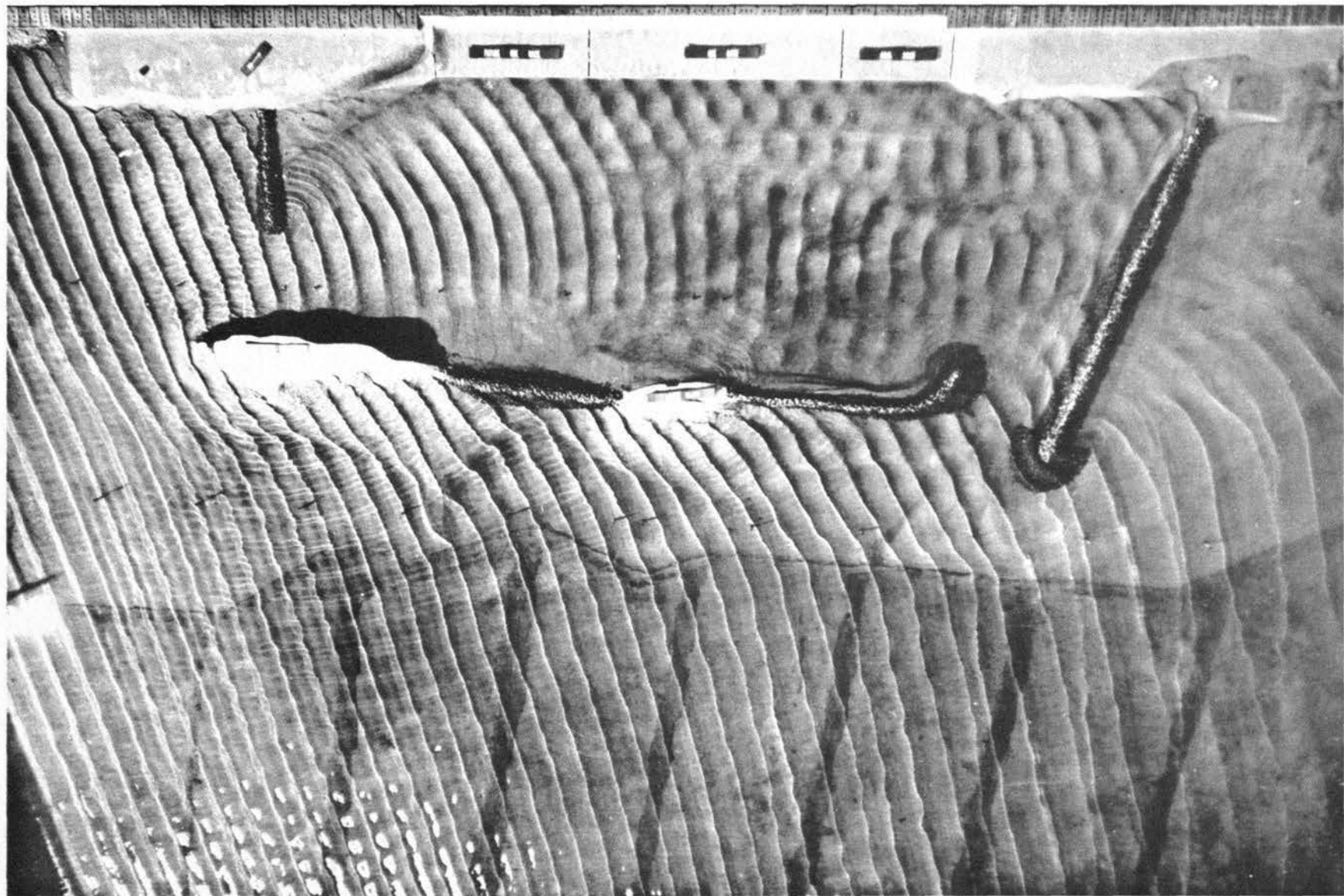
Photograph 13. Plan 4: 5.5-sec by 10-ft waves from S $22\text{-}1/2^\circ$ W



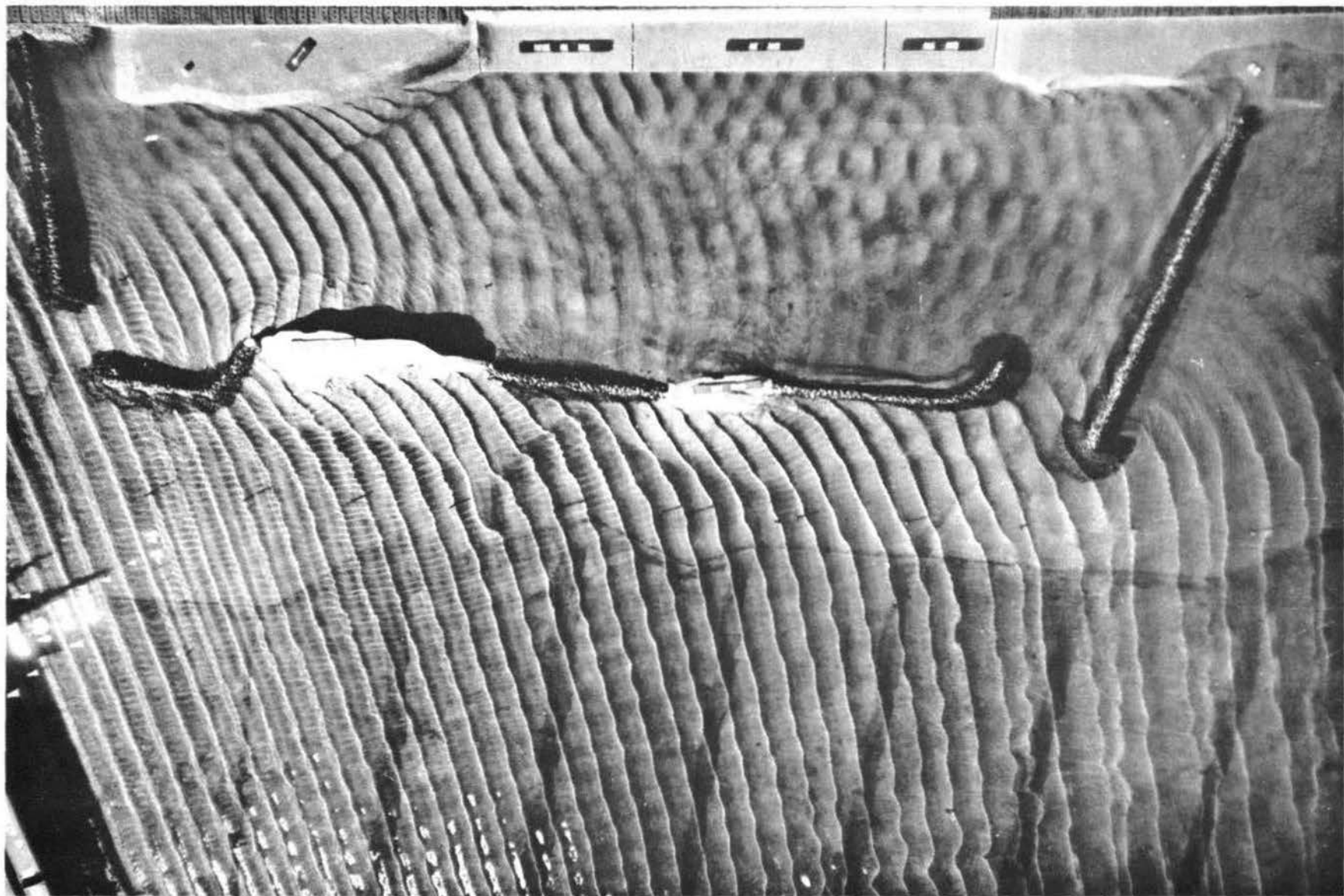
Photograph 14. Plan 5: 5.5-sec by 10-ft waves from S 22-1/2° W



Photograph 15. Plan 6: 5.5-sec by 10-ft waves from S 22-1/2° W



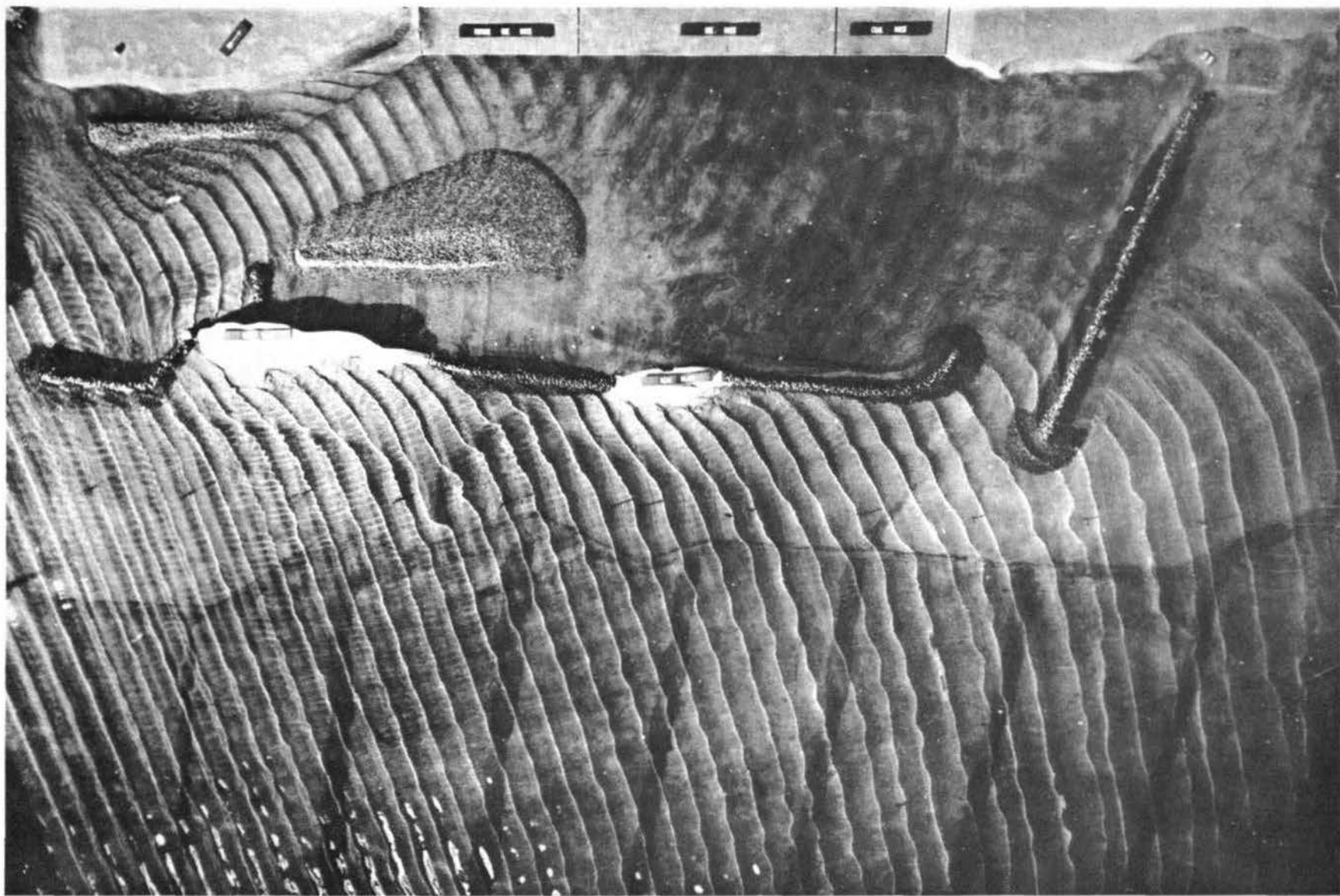
Photograph 16. Plan 7. 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



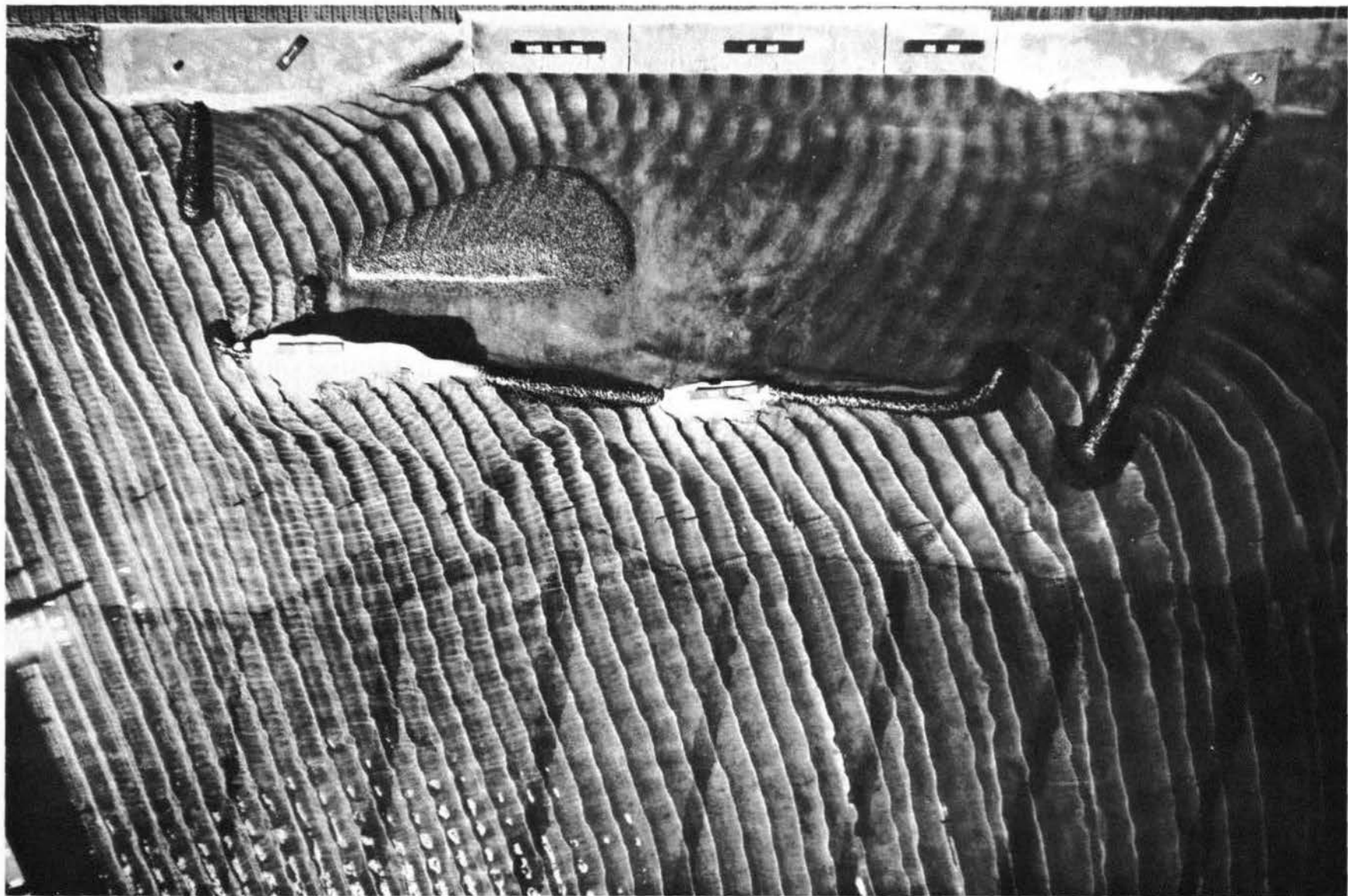
Photograph 17. Plan 8: 5.5-sec by 10-ft waves from S 22-1/2° W



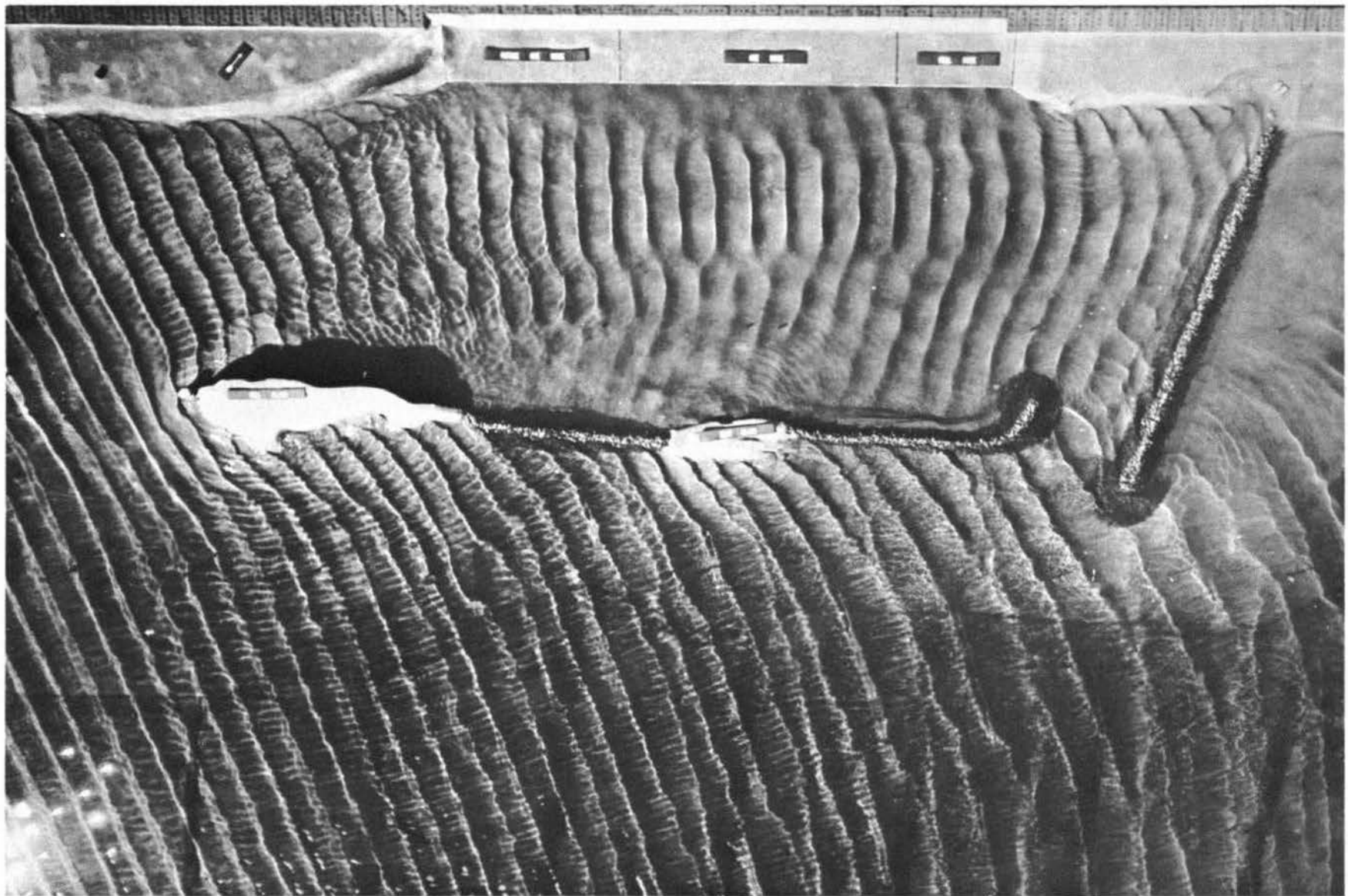
Photograph 18. Plan 9: 5.5-sec by 10-ft waves from S $22\text{-}1/2^{\circ}$ W



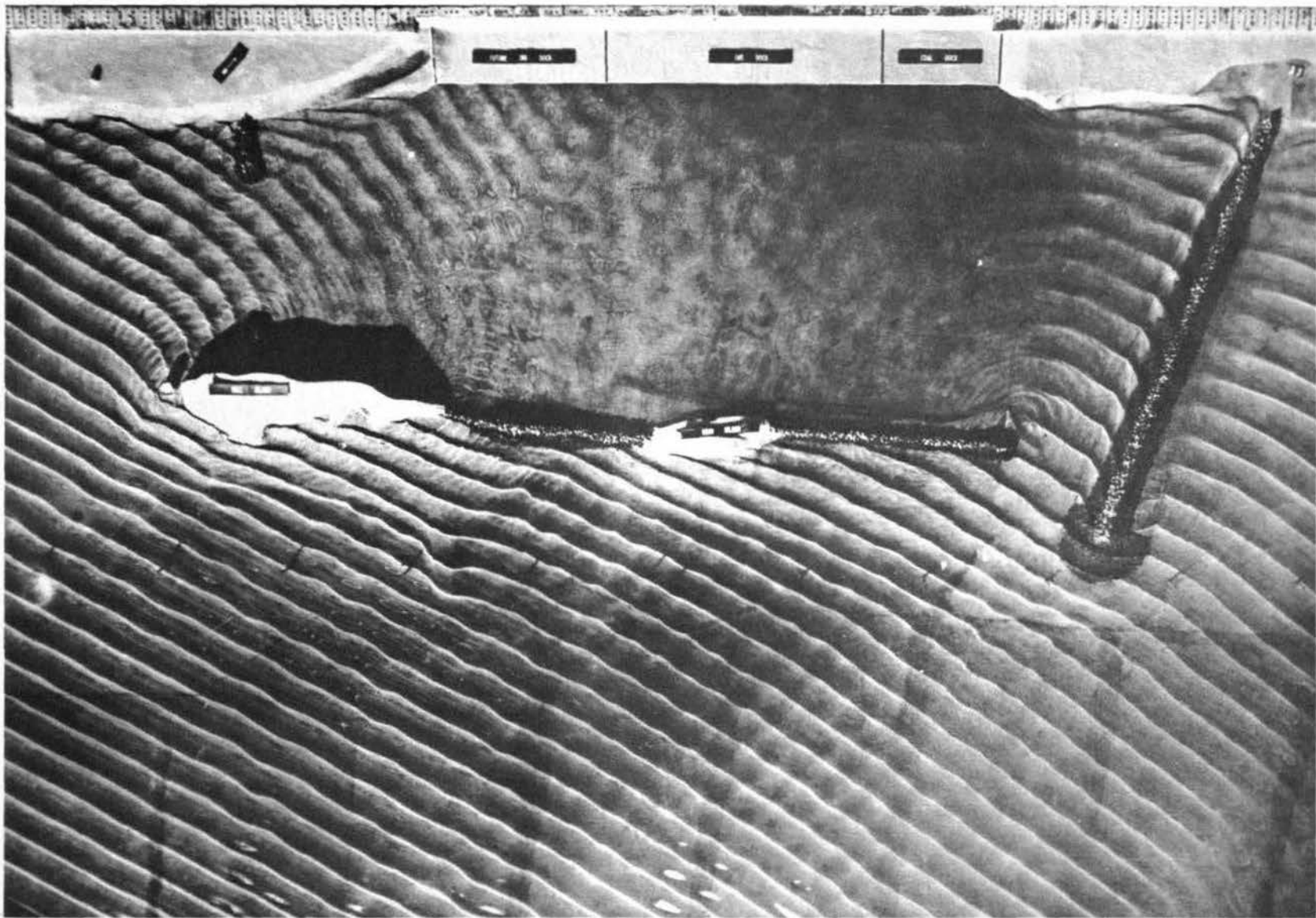
Photograph 19. Plan 10: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



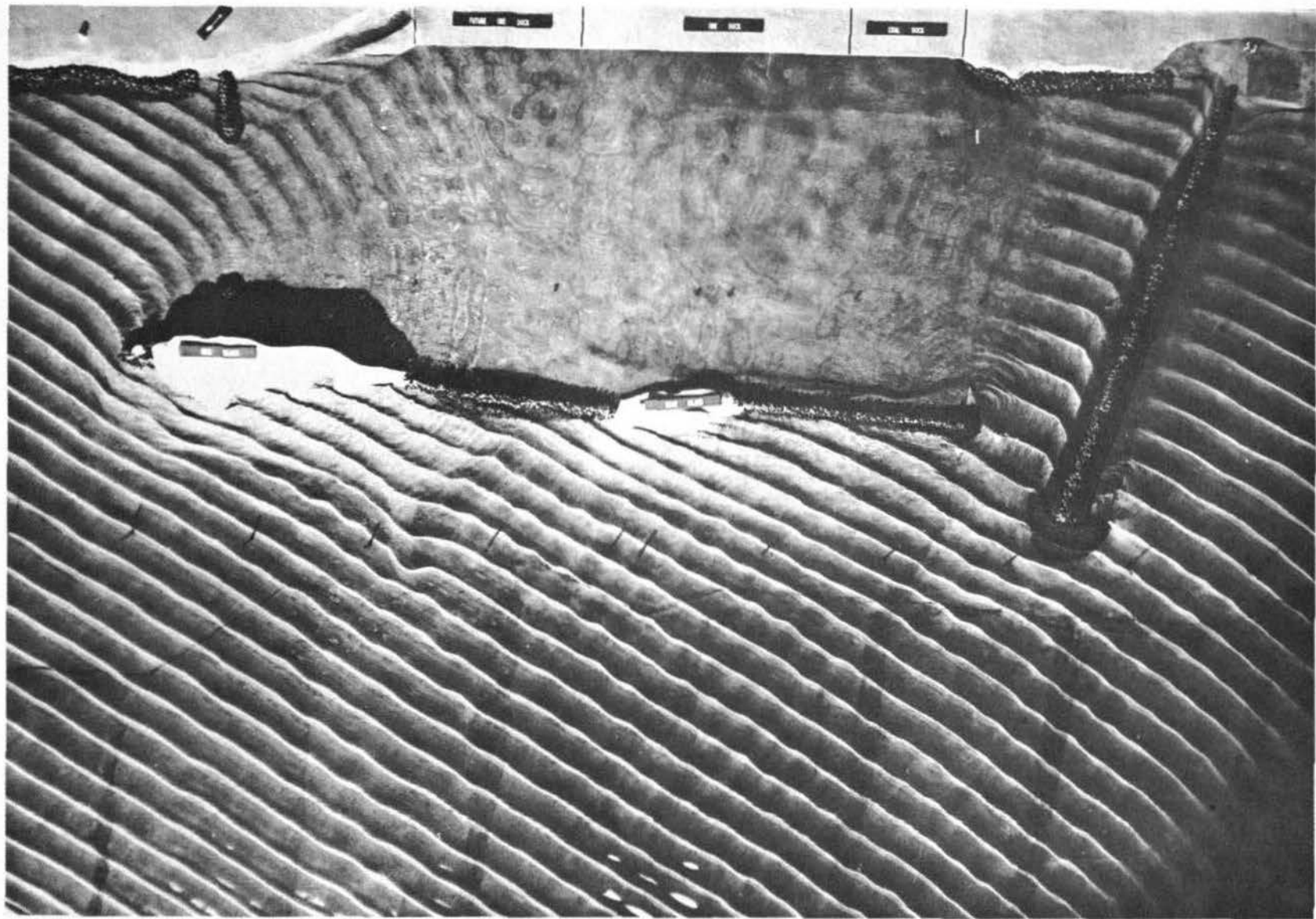
Photograph 20. Plan 11: 5.5-sec by 10-ft waves from S 22-1/2° W



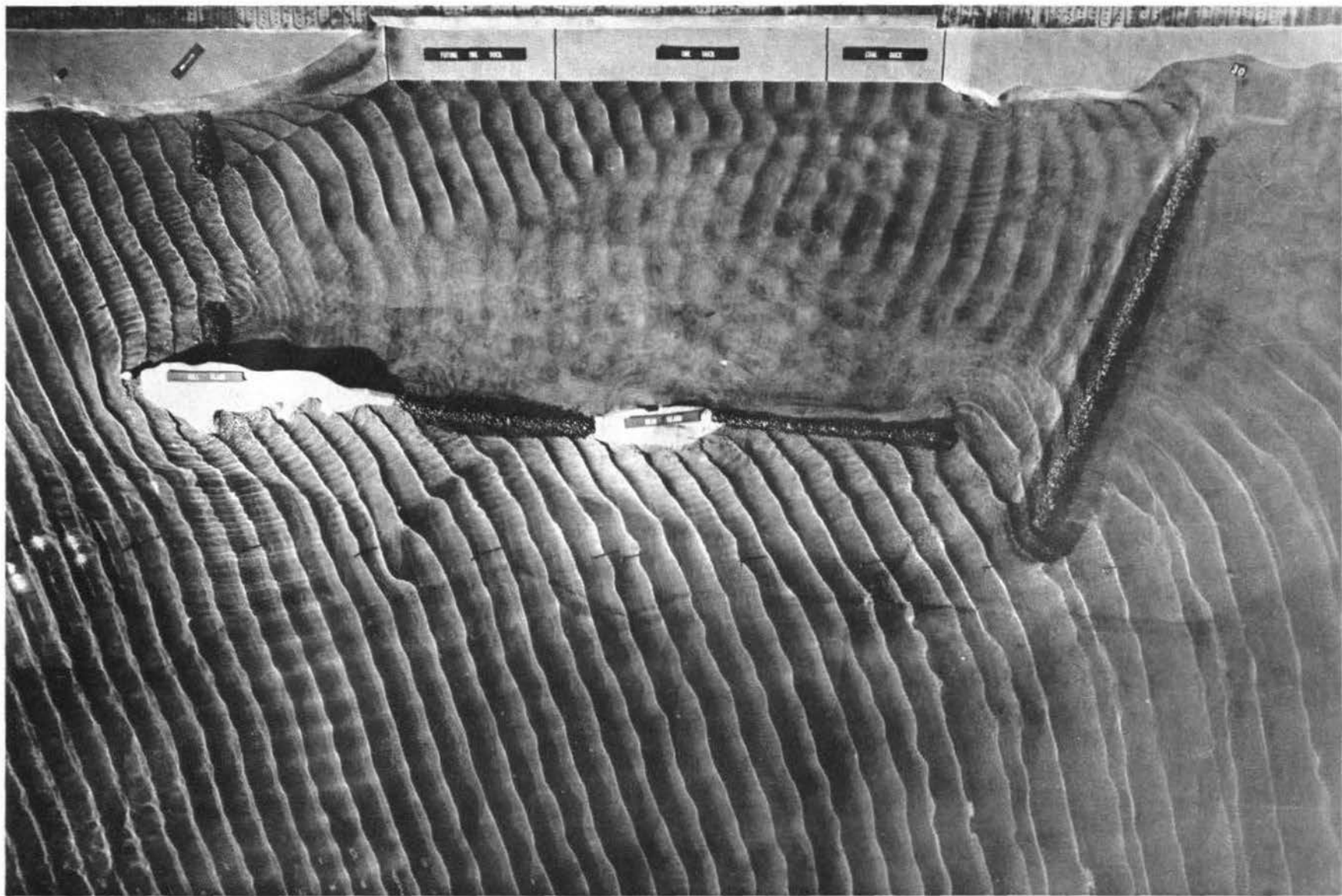
Photograph 21. Plan 12: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



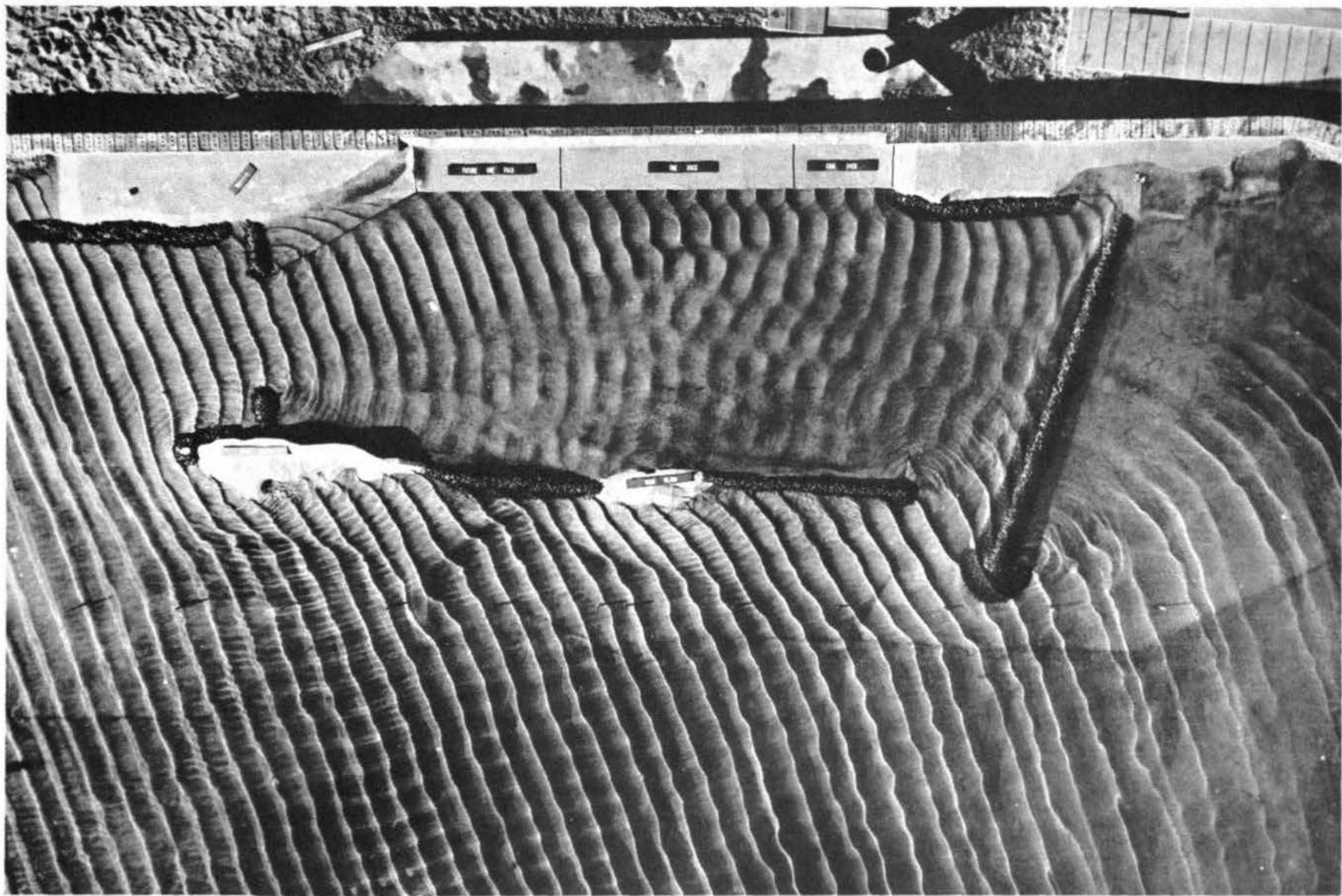
Photograph 22. Plan 13: 5.5-sec by 7-ft waves from S 20° E



Photograph 23. Plan 13-A: 5.5-sec by 7-ft waves from S 20° E



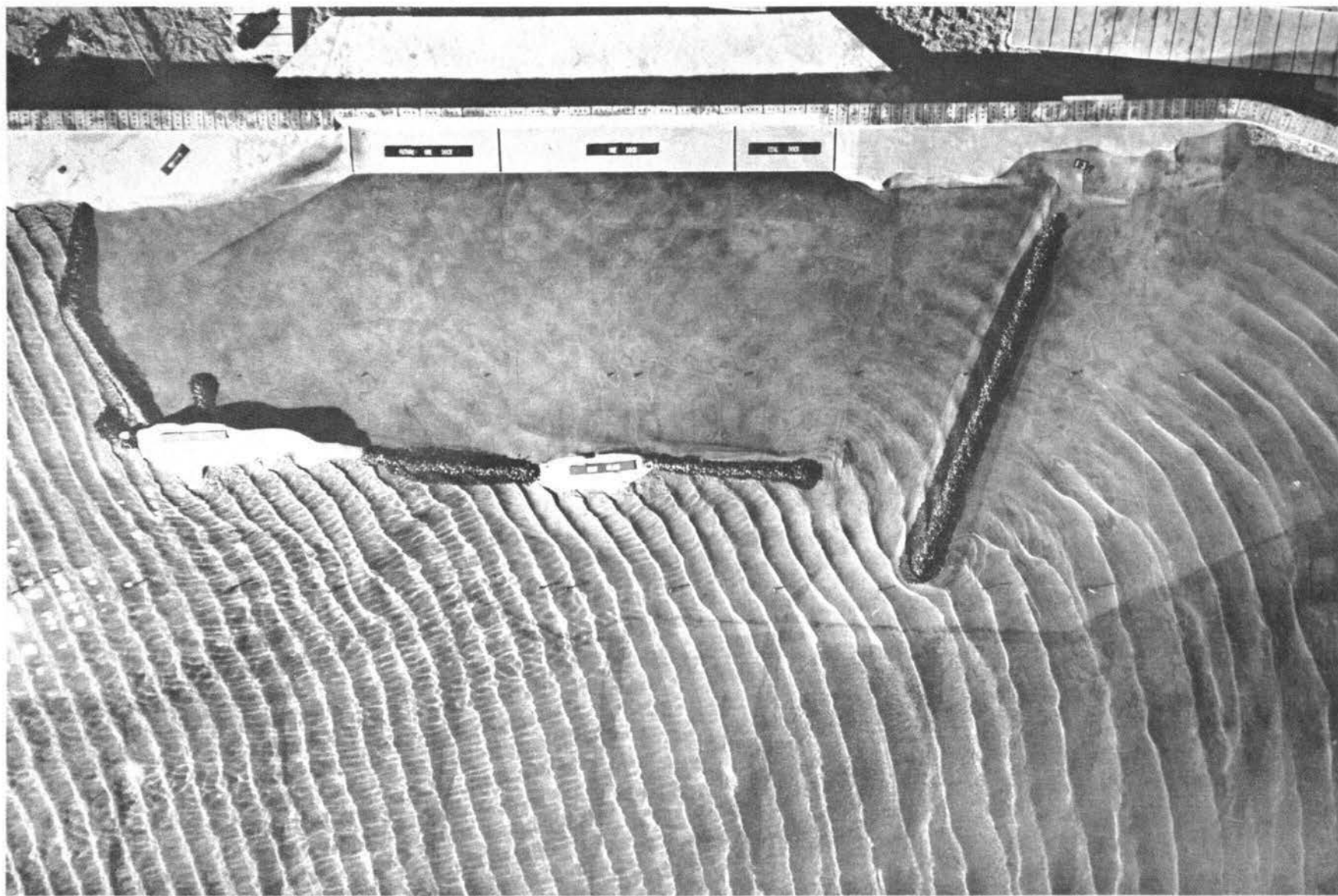
Photograph 24. Plan 13: 5.5-sec by 10-ft waves from S 22-1/2° W



Photograph 25. Plan 13-A: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



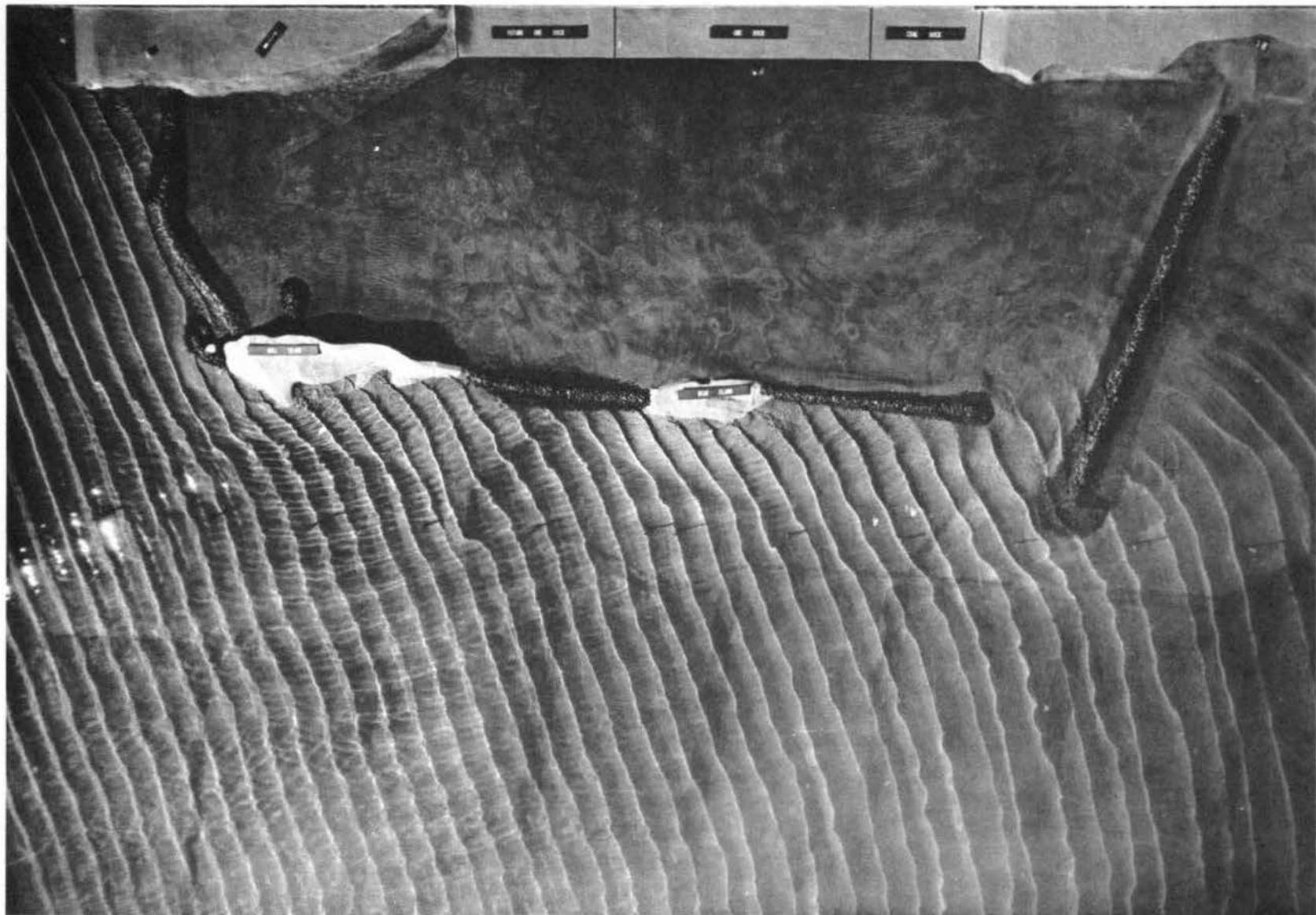
Photograph 26. Base-ER: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



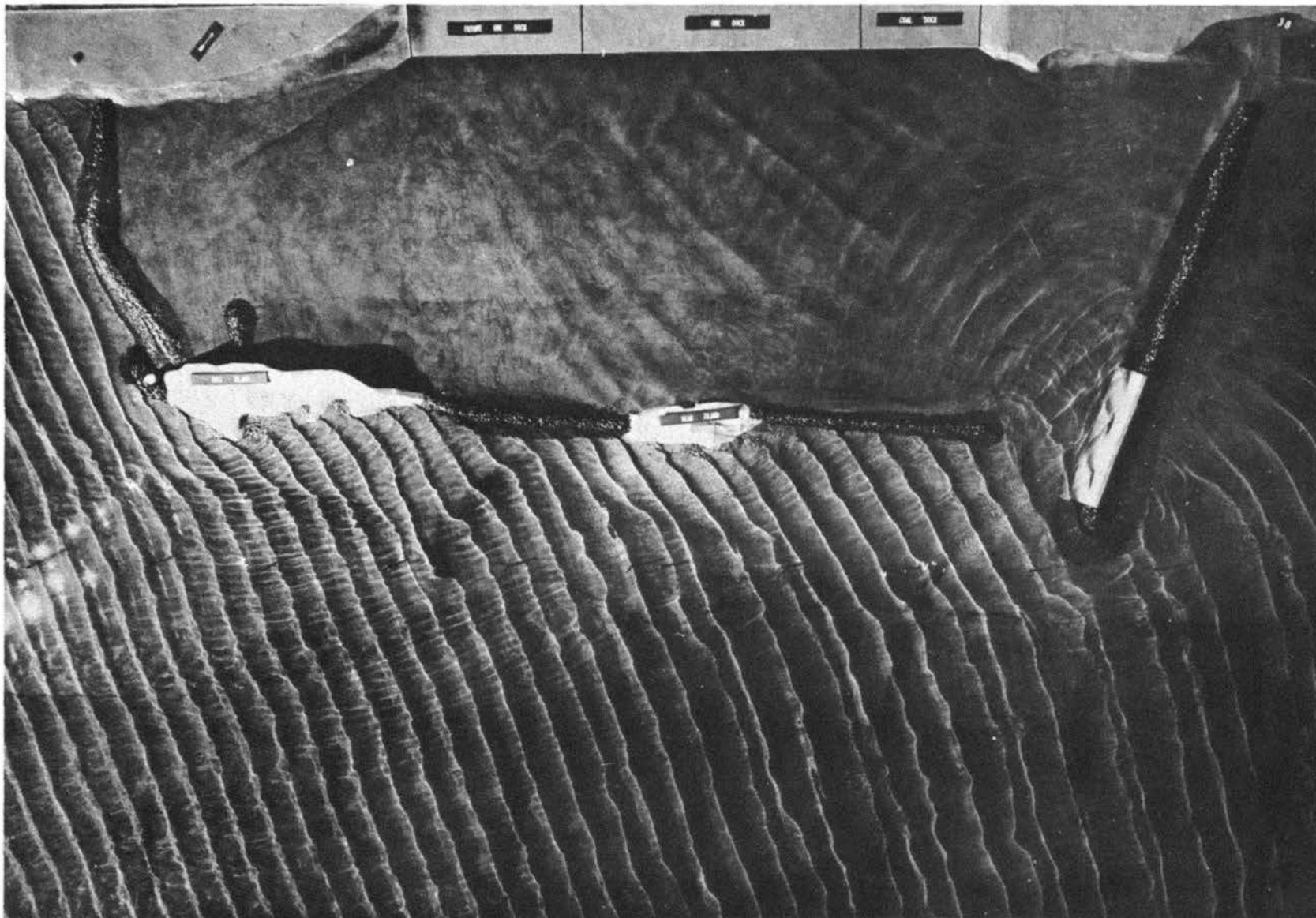
Photograph 27. Plan 1-E: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



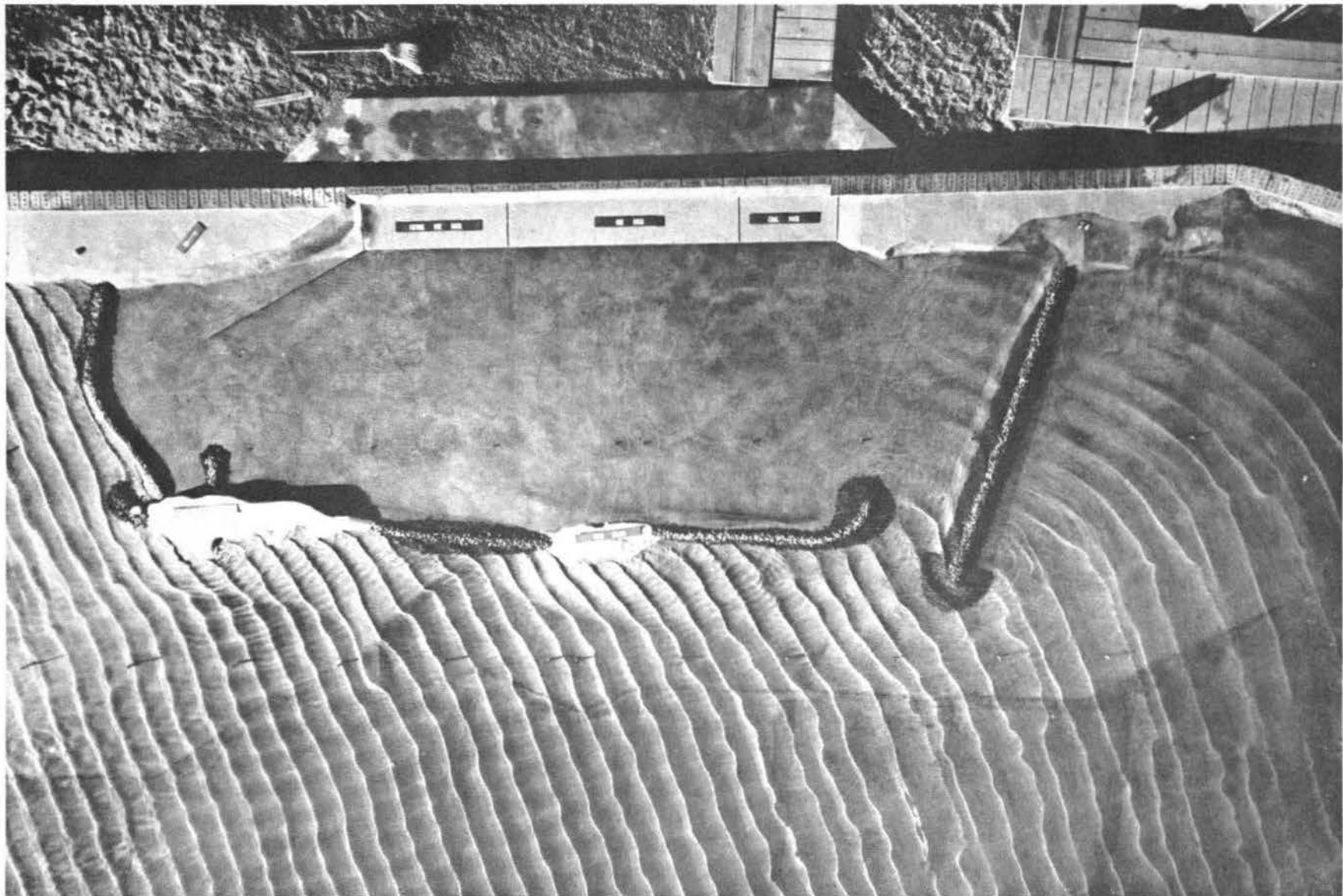
Photograph 28. Plan 1-ER: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



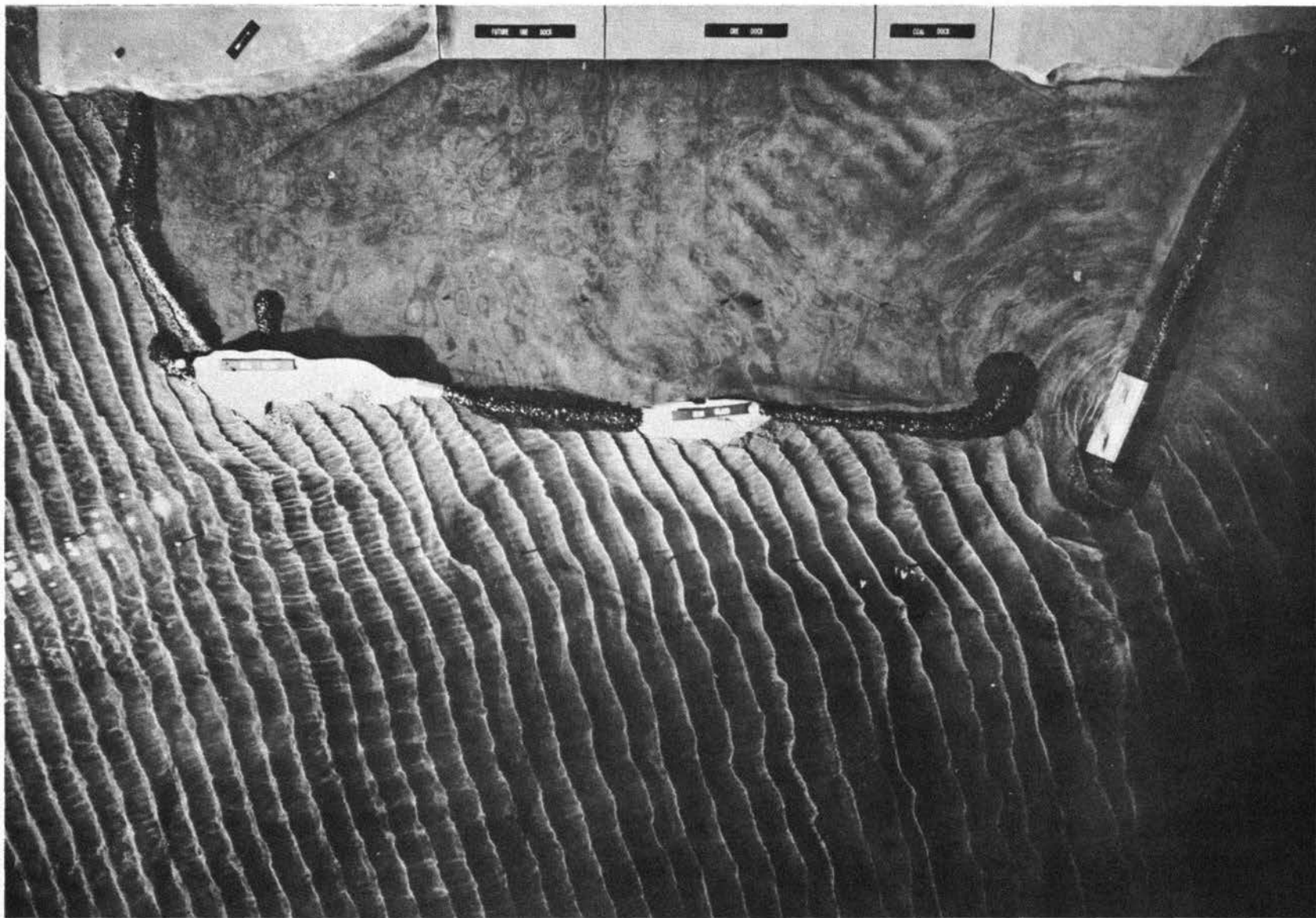
Photograph 29. Plan 2-E: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



Photograph 30. Plan 2-ER: 5.5-sec by 10-ft waves from S 22-1/2° W



Photograph 31. Plan 3-E: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W



Photograph 32. Plan 3-ER: 5.5-sec by 10-ft waves from S $22-1/2^{\circ}$ W

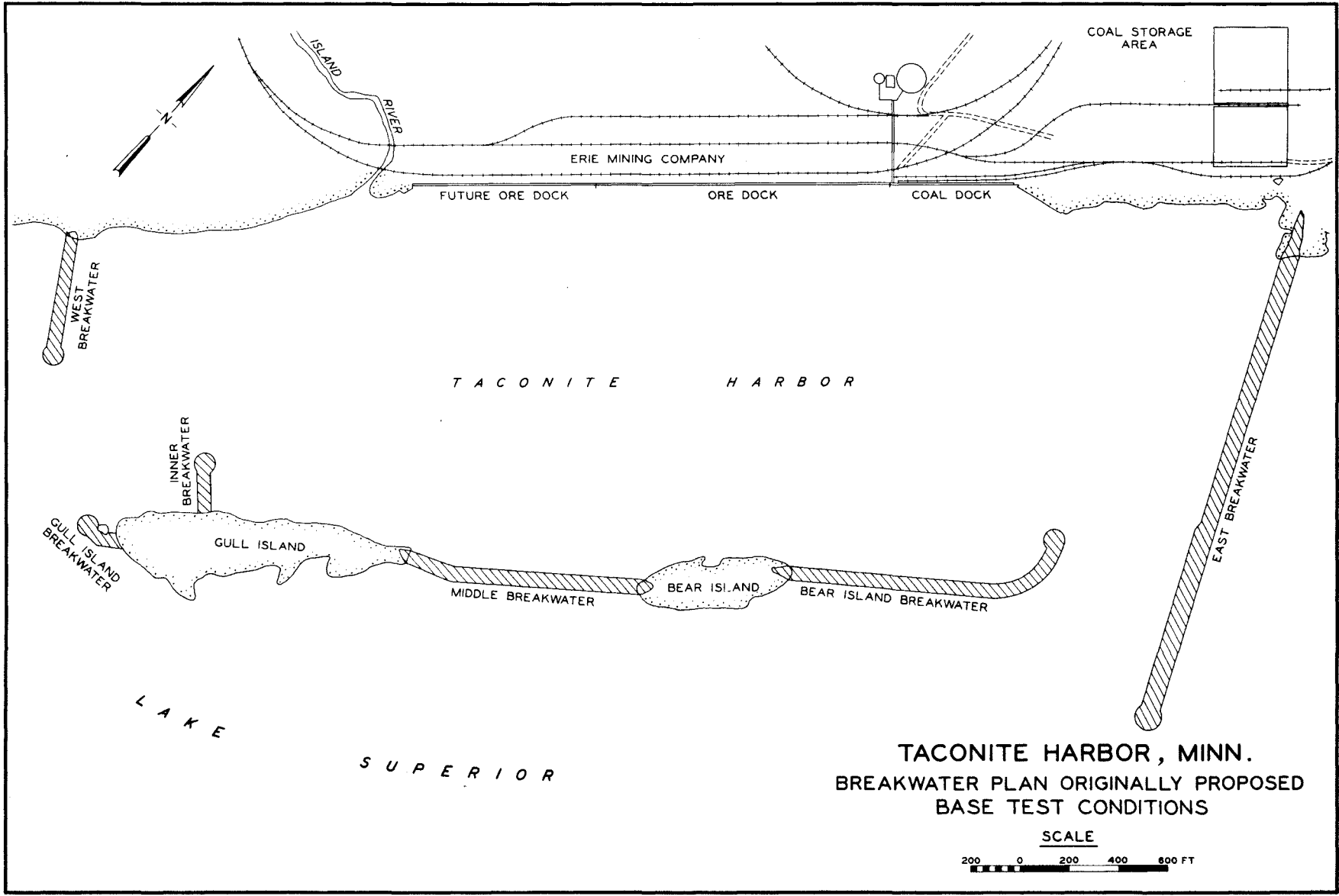
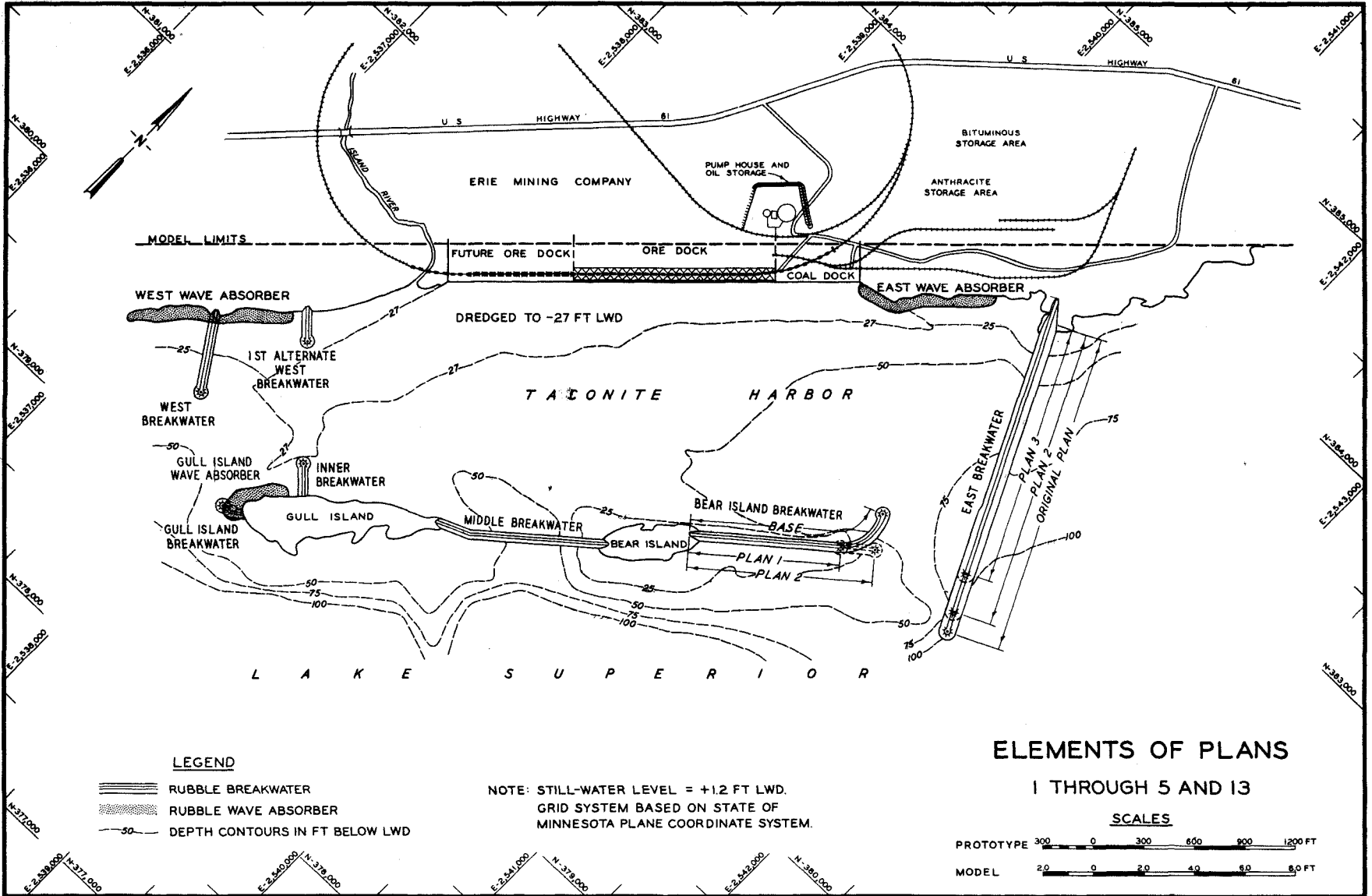
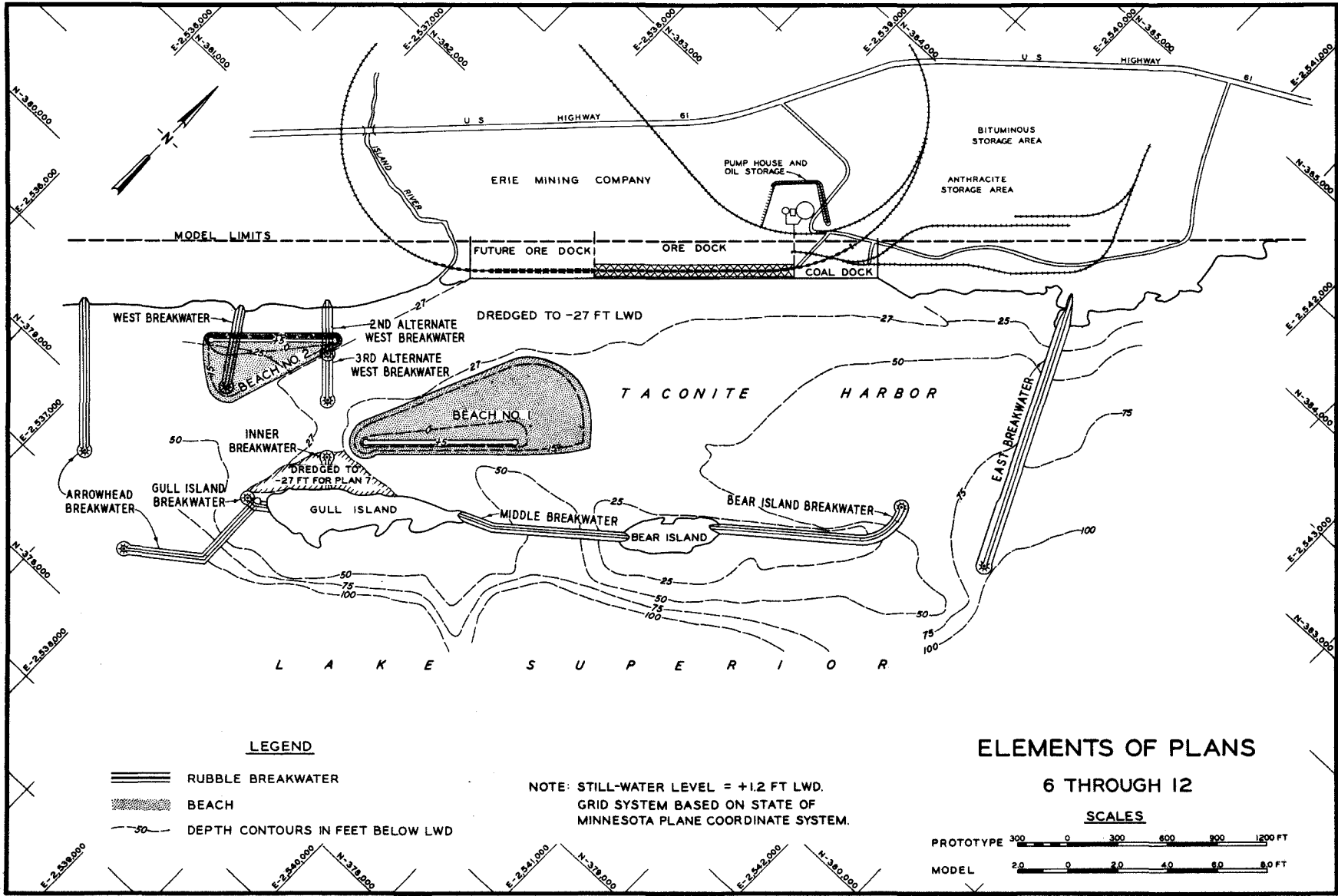


PLATE 1

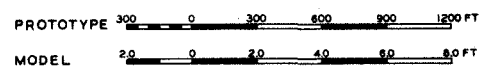


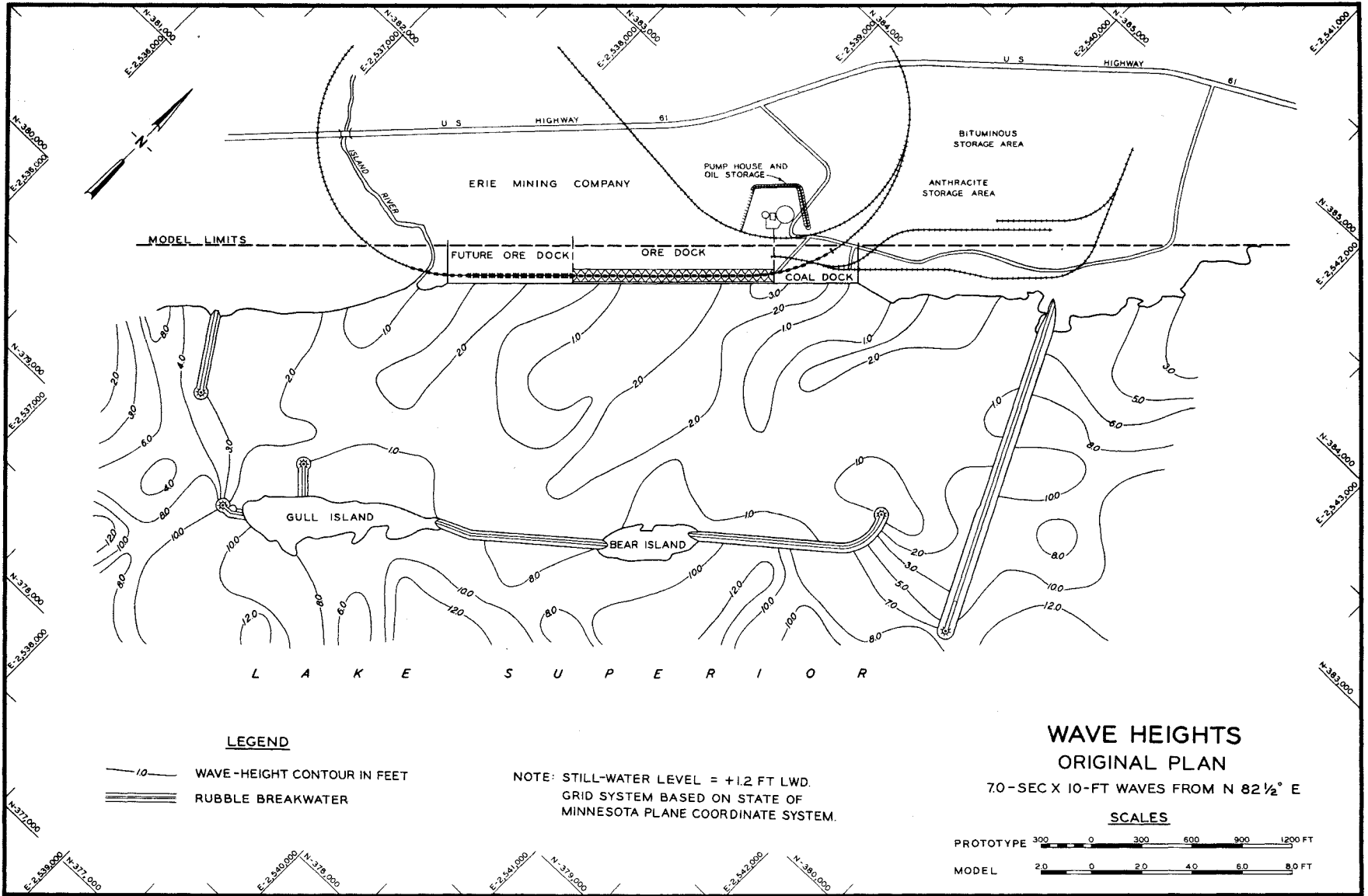


ELEMENTS OF PLANS



6 THROUGH 12

SCALES





LEGEND

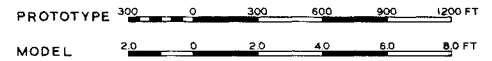
-  WAVE-HEIGHT CONTOUR IN FEET
-  RUBBLE BREAKWATER

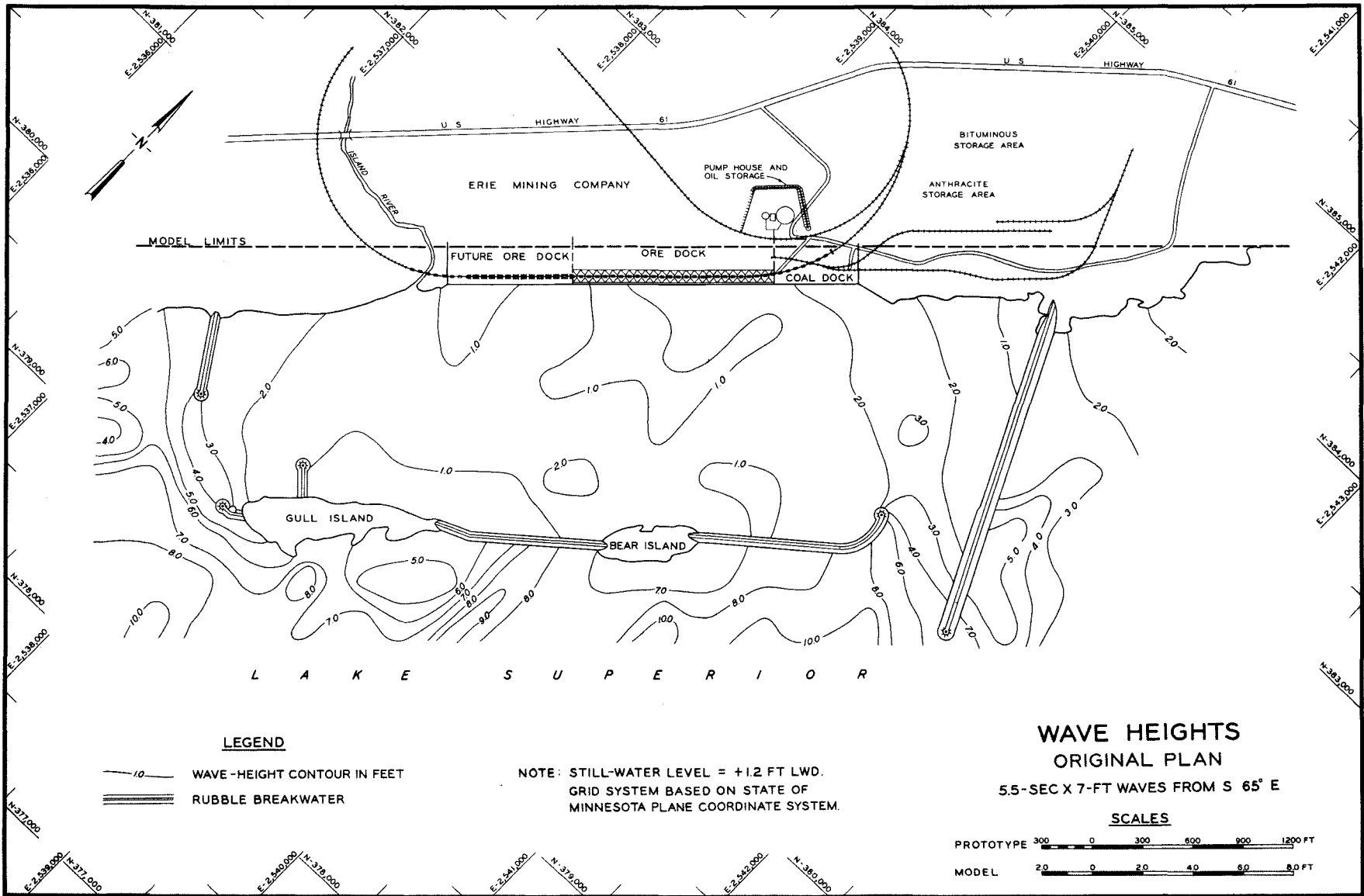
NOTE: STILL-WATER LEVEL = +1.2 FT LWD.
 GRID SYSTEM BASED ON STATE OF
 MINNESOTA PLANE COORDINATE SYSTEM.

**WAVE HEIGHTS
 ORIGINAL PLAN**

7.0-SEC X 10-FT WAVES FROM N 82 1/2° E

SCALES





MODEL LIMITS



FUTURE ORE DOCK ORE DOCK COAL DOCK

GULL ISLAND

BEAR ISLAND

L A K E S U P E R I O R

LEGEND

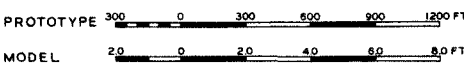
-  WAVE-HEIGHT CONTOUR IN FEET
-  RUBBLE BREAKWATER

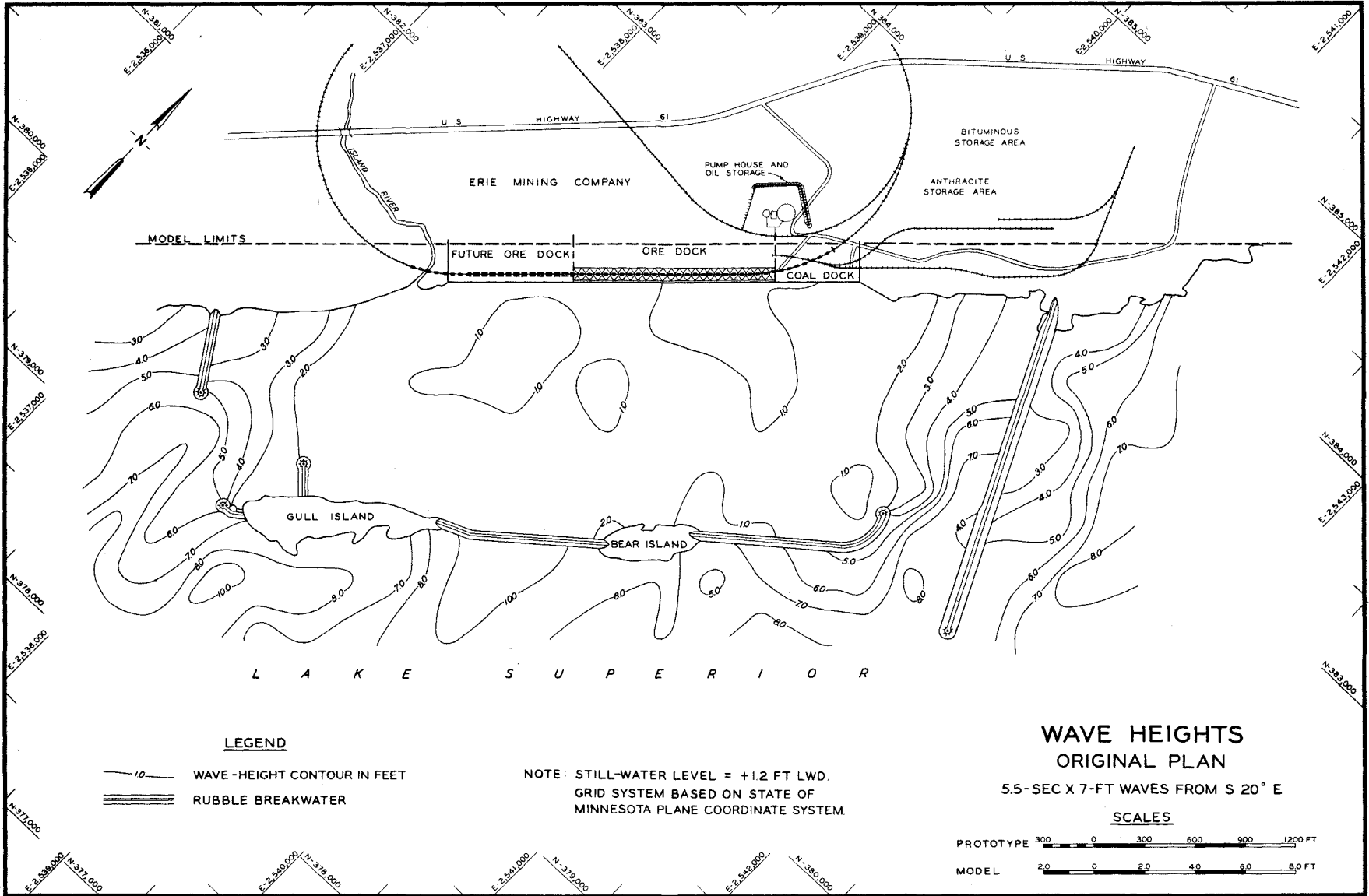
NOTE: STILL-WATER LEVEL = +1.2 FT LWD.
 GRID SYSTEM BASED ON STATE OF MINNESOTA PLANE COORDINATE SYSTEM.

WAVE HEIGHTS ORIGINAL PLAN



5.5-SEC X 7-FT WAVES FROM S 65° E

SCALES





LEGEND

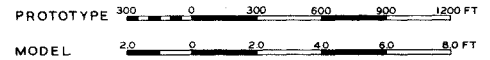
-  WAVE-HEIGHT CONTOUR IN FEET
-  RUBBLE BREAKWATER

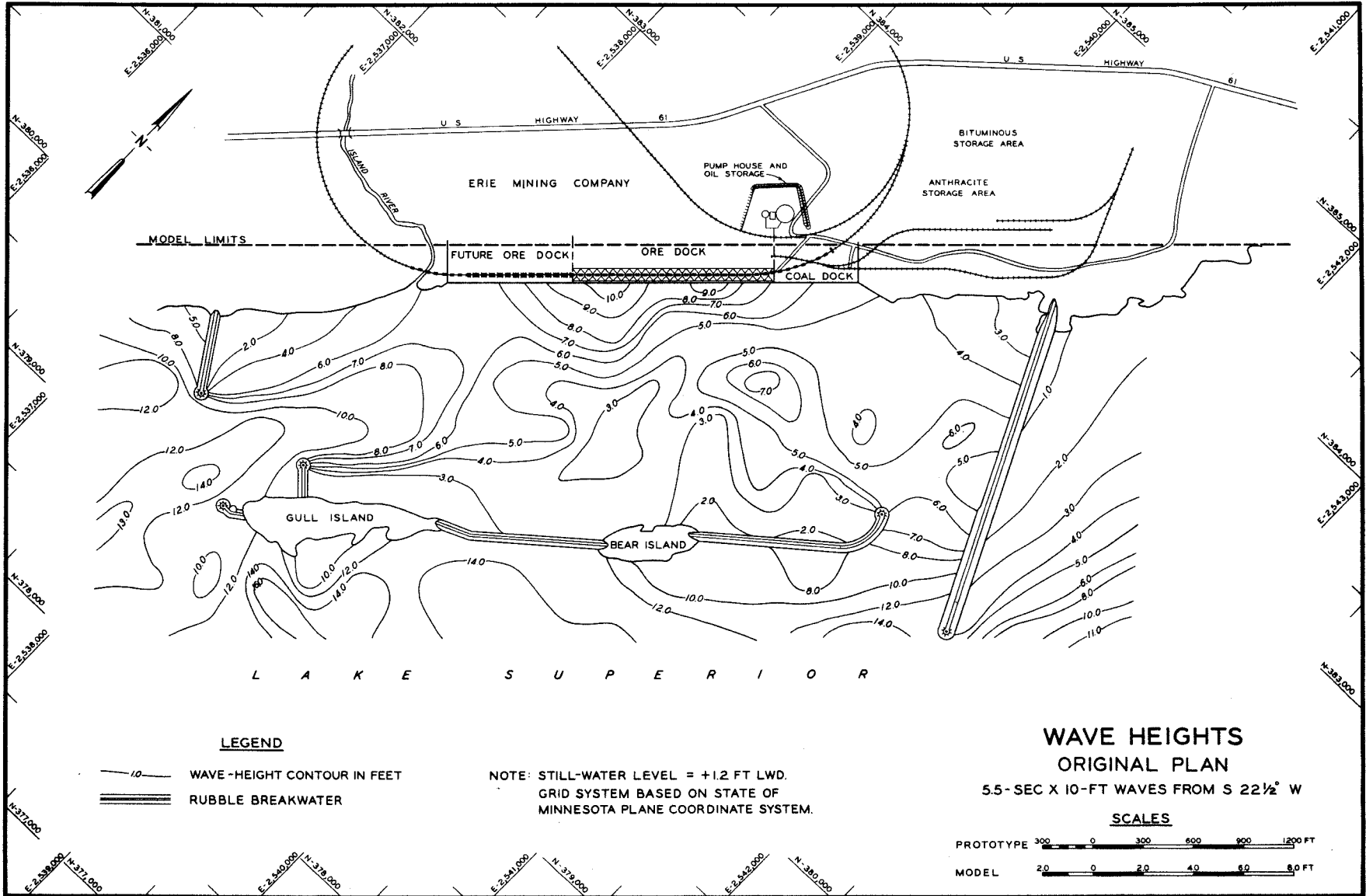
NOTE: STILL-WATER LEVEL = +12 FT LWD.
 GRID SYSTEM BASED ON STATE OF
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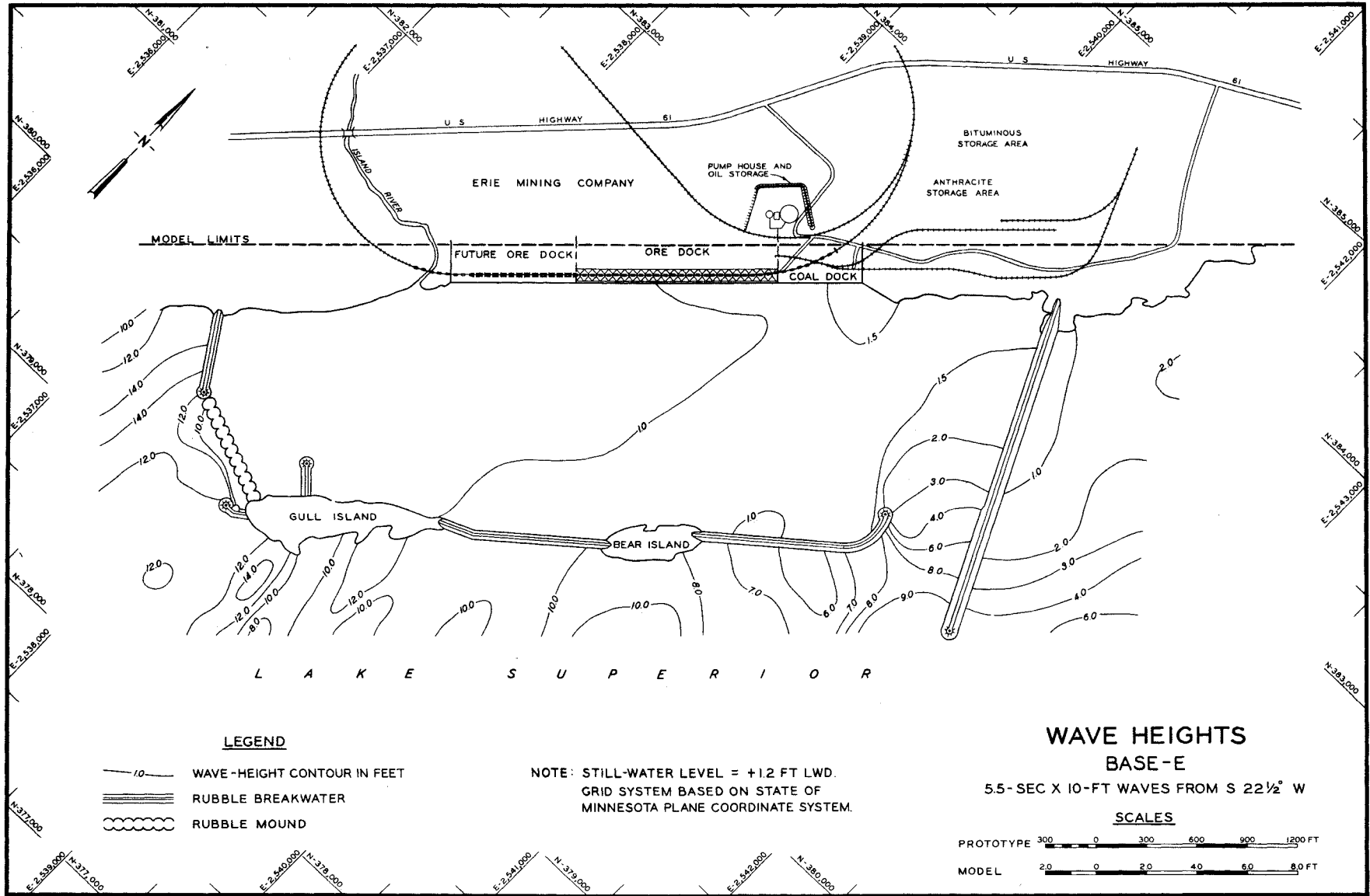
**WAVE HEIGHTS
 ORIGINAL PLAN**

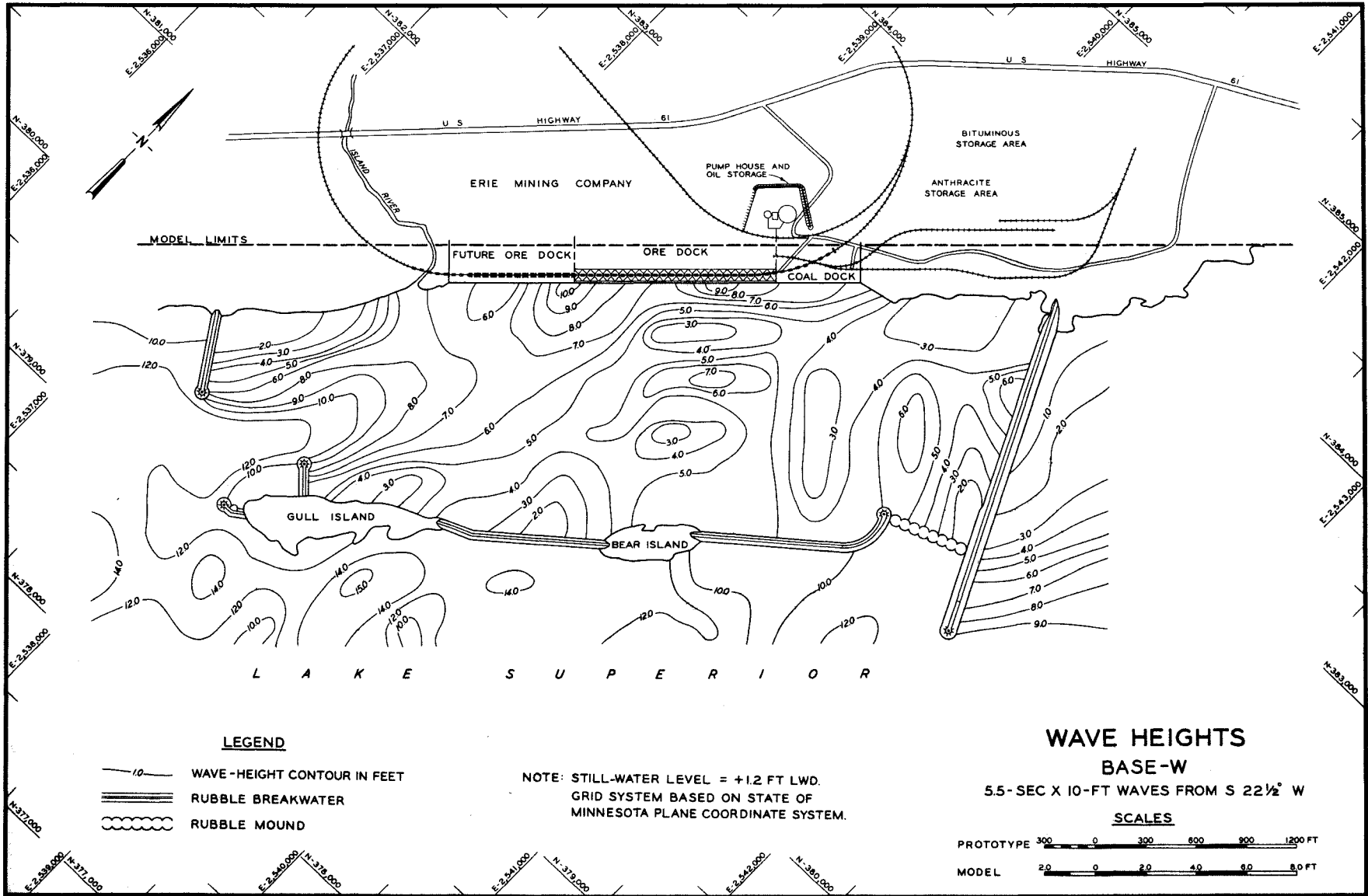
5.5-SEC X 7-FT WAVES FROM S 20° E

SCALES









MODEL LIMITS

FUTURE ORE DOCK ORE DOCK COAL DOCK

LEGEND

- WAVE-HEIGHT CONTOUR IN FEET
- RUBBLE BREAKWATER
- RUBBLE MOUND

NOTE: STILL-WATER LEVEL = +1.2 FT LWD.
 GRID SYSTEM BASED ON STATE OF
 MINNESOTA PLANE COORDINATE SYSTEM.

**WAVE HEIGHTS
 BASE-W**

5.5-SEC X 10-FT WAVES FROM S 22 1/2° W

SCALES

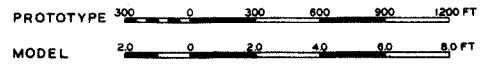
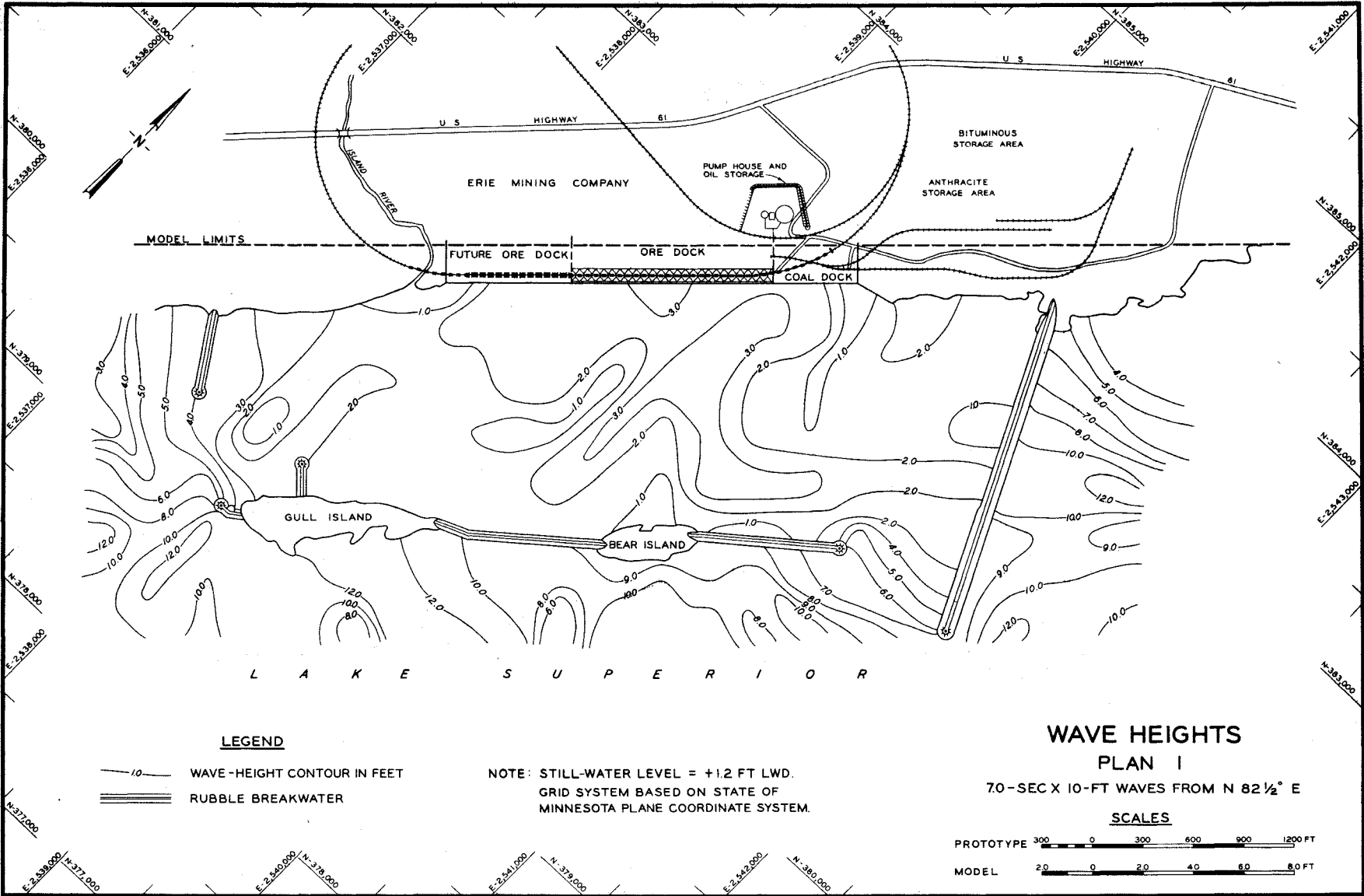


PLATE 9



LEGEND

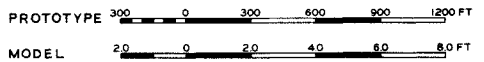
- 1.0 — WAVE-HEIGHT CONTOUR IN FEET
- ==== RUBBLE BREAKWATER

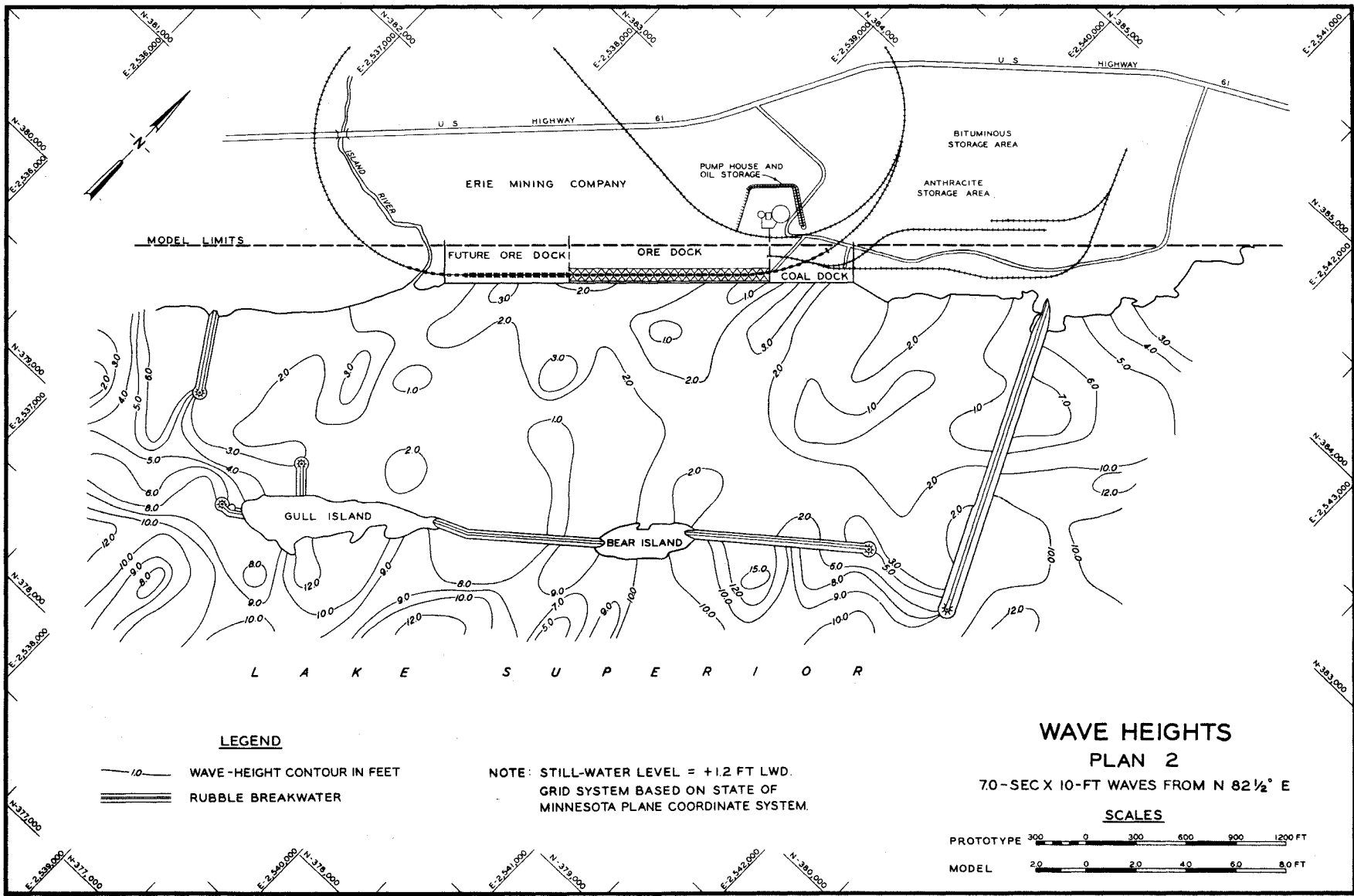
NOTE: STILL-WATER LEVEL = +1.2 FT LWD.
 GRID SYSTEM BASED ON STATE OF MINNESOTA PLANE COORDINATE SYSTEM.

**WAVE HEIGHTS
 PLAN I**

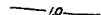

70-SEC X 10-FT WAVES FROM N 82 1/2° E

SCALES





LEGEND

-  WAVE-HEIGHT CONTOUR IN FEET
-  RUBBLE BREAKWATER

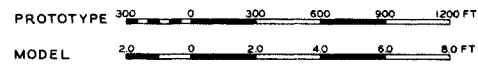
NOTE: STILL-WATER LEVEL = +1.2 FT LWD.
 GRID SYSTEM BASED ON STATE OF
 MINNESOTA PLANE COORDINATE SYSTEM.

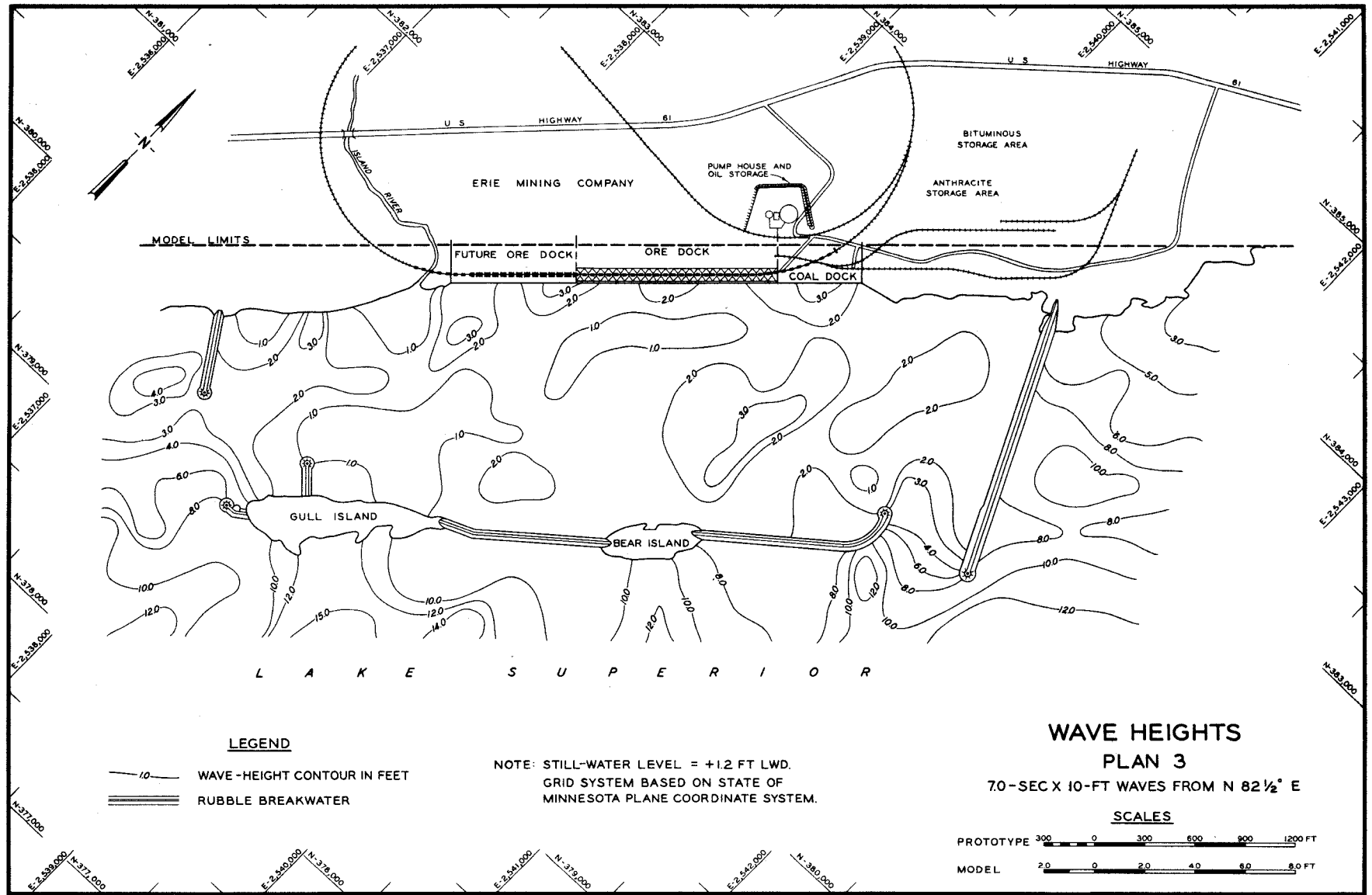
WAVE HEIGHTS

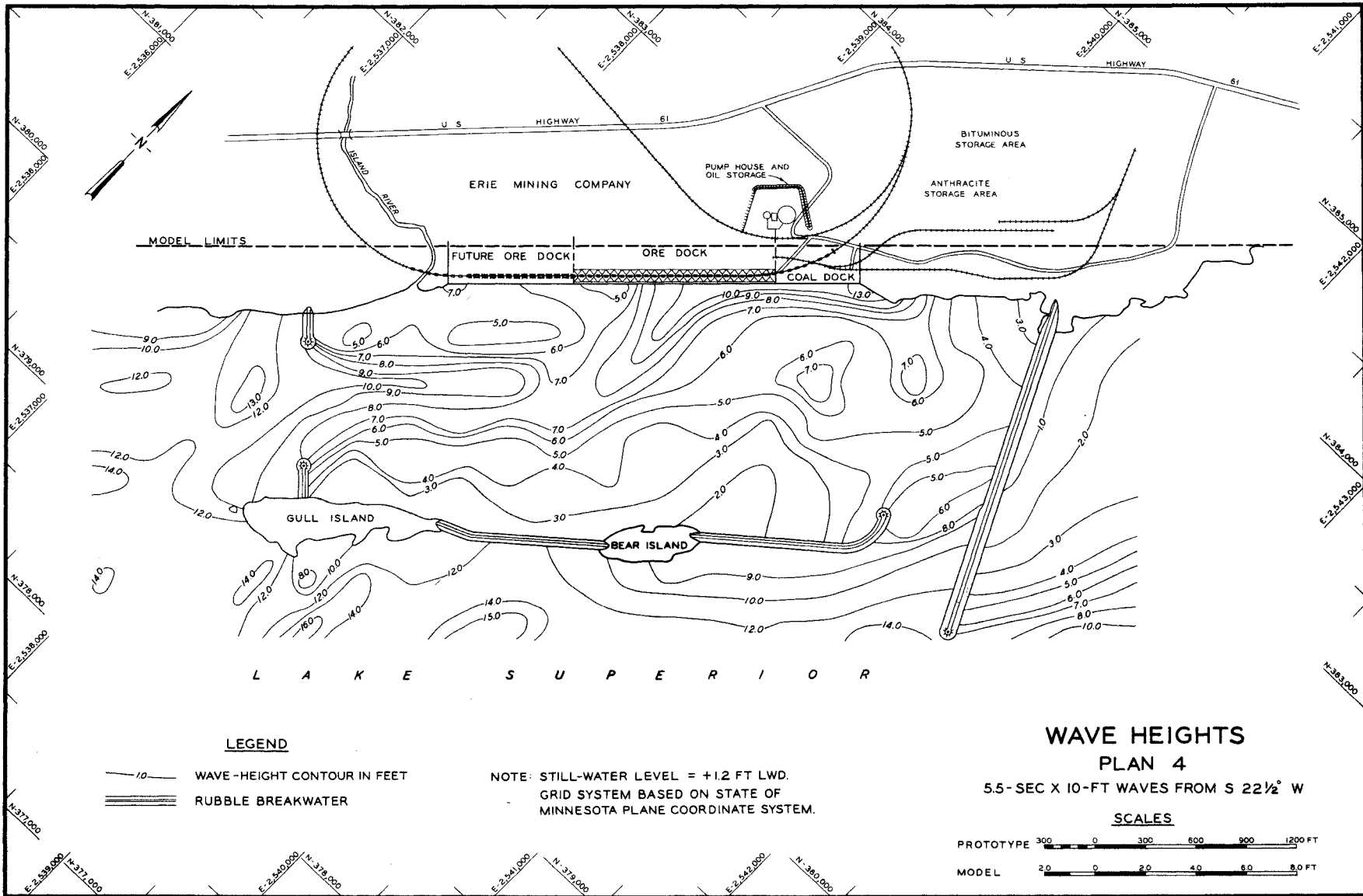
PLAN 2

70-SEC X 10-FT WAVES FROM N 82 1/2° E

SCALES







LEGEND

- WAVE-HEIGHT CONTOUR IN FEET
- RUBBLE BREAKWATER

NOTE: STILL-WATER LEVEL = +1.2 FT LWD.
 GRID SYSTEM BASED ON STATE OF MINNESOTA PLANE COORDINATE SYSTEM.

**WAVE HEIGHTS
 PLAN 4**

5.5-SEC X 10-FT WAVES FROM S 22½° W

SCALES

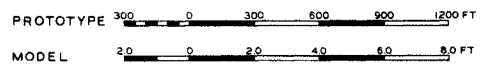


PLATE 13

