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THE HEIGHT LIMITING EFFECT OF SEA FLOOR TERRAIN FEATURES AND OF HYPOTHETICALLY EXTENSIVELY REDUCED BREAKWATERS ON WAVE ACTION AT DIABLO CANYON SEA WATER INTAKE

REPORT ON A THREE-DIMENSIONAL
PHYSICAL MODEL STUDY
FOR PACIFIC GAS AND ELECTRIC COMPANY

BY
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FREDRIC RAICHLEN
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MARCH 15, 1982

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CONTENTS

ILLUSTRATIONS

FOREWARD

After ten years of service since its construction, with no noted damage, West Breakwater at Diablo Canyon Nuclear Power Plant was damaged by a wave storm on January 28, 1981

Pacific Gas and Electric Company, the owner, adopted recommendations of its consulting engineer that a three dimensional physical model be built and used in efforts to confirm the mode or modes of wave attack that had done the damage, and as a device for developing, verifying and describing appropriate repairs or modifications to the breakwater for consideration by the owner.

Some months later, when construction and outfitting of the model was nearly finished, another inquiry was begun that would use the model first, to gain answers to another question. Paraphrased for brevity, that question was: "With West Breakwater damaged, will water levels during storms be unacceptably high at the two ventilating air intake risers for the Auxiliary Salt Water Pump chambers in the Intake Structure for Diablo Canyon Nuclear Power Plant?" PG&E was advised the question could not be answered responsibly if based on calculations. The approach by waves is across extremely irregular submerged terrain, so that waves are modified in ways that are unique to the site. It was recognized that the model, which was nearly completed, could be employed to answer the new question. Consequently the model study schedule was modified, so as to defer the investigation of damage mechanisms and of remedial schemes, to study first the question of water levels and related matters at the air intakes.

Subsequently two phases of investigation of the new question evolved. Those phases looked separately at the conditions that would prevail if there were no breakwaters in existence at all, and at conditions if breakwaters were present but extensively damaged.

Phase 1 - Wave Heights With No Breakwaters

Periodic oscillatory water waves eventually break and lose energy when their motion is impeded as they enter into shallower depths. What the critical depth may be at which breaking occurs is largely related to how high the wave is. High waves break at greater depths than low waves do. If the sea floor continues to rise and the water thereby becomes more shallow as already broken waves wash further landward, there is a persistent decrease in the energy the waves contain as they move onward toward the shoreline. On the other hand, if after breaking the broken waves move forward into water that is deeper again, or in some cases even through water of the same depth, they usually resume a wave form rather than a breaker form. Then with amplitude diminished, because of the energy lost in the breaking, they proceed onward.

In a complex way the sea floor terrain in front of the Diablo Intake Structure is of the latter type. A discontinuous but generally overlapping sill of natural rock formations exists offshore and the water deepens again along the wave path between that sill and the Intake Structure. The Phase 1 Question to be answered then was:

> "Do the natural terrain features seaward of Diablo Canyon Intake Structure limit the heights of waves that can reach that structure?"

To answer that question, Phase 1 of the model studies was carried out with only the natural sea floor modelled for the waves to cross. No breakwaters were simulated. Comprehensive tests demonstrated that wave heights at the intake locality would be limited in height by the natural sea floor terrain at Diablo Canyon Site. Data taken during the Phase 1 investigation and analyses of those data are on file and can be made available for review by interested parties. To only a limited degree do thay relate to Phase 2, however, which is the subject of this report. However, pertinent applicable data from the Phase 1 work that is also applicable to the Phase 2 matters will be extracted and displayed and discussed in the body of the report.

Phase 2 - Wave Heights With Extensively Damaged Breakwaters

Breakwaters are built in order to limit the height of waves that can reach an area in their lee. They can be viewed as if they were a local alteration of natural terrain features, producing a new composite effect on waves in concert with the effect of the remaining unaltered natural terrain.

Recognizing that breakwaters do now exist at Diablo Canyon Site, and that they cover over some of the topographic "sill" formations that contributed to the wave limiting effect before the breakwaters were built, and considering that the wave storm of January 28, 1981 had damaged part of West Breakwater, it became more pertinent and necessary to answer another question:

> "If both breakwaters at Diablo Canyon Site were to incur cumulative damage, without interim rehabilitation, until both structures were levelled by the combined effect of a seismic event and recurring

violent wave storms to as low a profile as zero tide level, would the composite effect of such levelled breakwaters and the natural submarine terrain surrounding the breakwaters continue to limit the heights of waves that can reach the Diablo Canyon Intake Structure?

"Further, whether or not limited by the composite effect of levelled breakwaters and submarine terrain, to what heights will water rise or splash at the ventilating air risers for the Auxiliary Salt Water Pumps, due to wave action, and with what force will the water strike those risers?"

The answer from the model data to the basic first part of the Phase 2 question is "yes". Under the hypothesized exceptionally damaged breakwaters condition, the composite effect of the levelled breakwaters and the terrain is to limit the wave heights that can reach the Intake Structure.

The data compiled in the Phase 2 tests also yield quantitative information on water runup, or splash, and on wave loading against the Intake Structure's ventilating air intake/exhaust risers, called "huts" in this report. They serve the Auxiliary Salt Water Pump chambers that are located within the Intake Structure.

Phase 3

The original scope of investigation for the model program has become referred to as Phase 3 of the studies that make use of the model. That is the study of how West Breakwater became damaged and the testing

of appropriate plans for its rehabilitation. The work is now under way and the results will be the subject of another report for Pacific Gas and Electric Company. That report's content will be devoted to that separate subject; it will not expand the present one on wave conditions at the Cooling Water Intake Structure.

SYNOPSIS

A three dimensional physical model of the Cooling Water Intake Basin at Diablo Canyon Nuclear Power Plant has been built and used to examine the characteristics waves would develop at the plant's Cooling Water Intake Structure under hypothetical conditions of extreme damage to the breakwaters that are seaward of the Intake. The objective was to determine the height of splash which high waves could cause at two safety-related ventilation "huts" that rise above the deck near the landward of the Intake Structure, and the magnitude of forces on the huts due to waves. In the test condition, both breakwaters have been reduced to profiles where their crests, by a combination of seismic and wave storm events, stand at zero tide level, i.e. at the elevation of Mean Lower Low Water Datum. That zero tide level at Diablo Canyon Site is 2.61 feet lower than Mean Sea Level.

Figure 1, following, is a contour map of the sea floor at and West of Diablo Intake Basin. The extremely rough relief of the submerged terrain makes detailed mathematical calculations of wave conditions in the area virtually impossible. Generally such calculations require that averaging assumptions be made in predicting the interaction of the rising sea floor, and its shape, on the wave forms that move over it. In the Diablo case it is unlikely such averagings could be depended upon. The results would at best be suspect. For that reason the physical model was used as the dependable means of solving the problem. An area of nearly 20 acres of the sea floor was surveyed in meticulous detail near and West of West Breakwater in early 1981, and mapped with 2 feet contour intervals at a scale of 1 inch to 20 feet. An additional surrounding area of 250 acres was also surveyed with nearly as densely

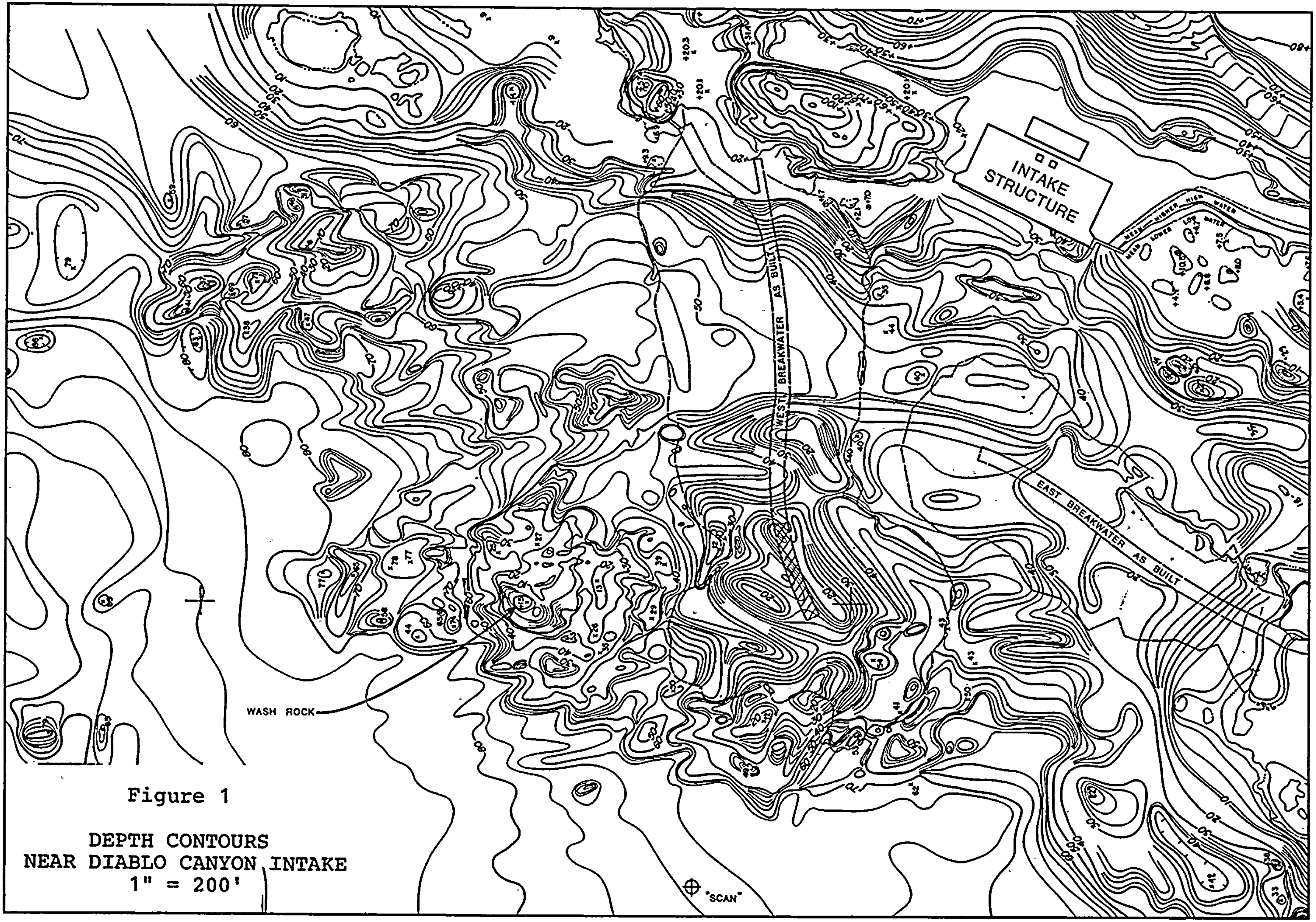

Figure 1

DEPTH CONTOURS
NEAR DIABLO CANYON INTAKE
1" = 200'

spaced soundings, and mapped from those surveys at 1 inch to 100 feet, also with 2 feet contour spacing. Figure 1 covers only part of the whole map and includes the Wash Rock just West of the end of West Breakwater. That feature's slopes proved to be so abrupt and contorted that there was room only to draw contours for each 10 feet interval of elevation. The two maps were then reproduced with care, in effect as a physical relief map, in a basin 80 feet by 120 feet at a scaled size which is one forty-fifth of nature. Wavemaking machines were positioned at various parts of the basin to drive waves of defined heights and periods and directions toward the Intake Basin. Probes were distributed strategically about the model area to record the waves. The information they sensed was delivered by telemetry to computer storage for subsequent display or processing. Load cells were mounted on the air intake "huts", and independently on tubular breathers extended up from the huts. Those cells were devised to sense forces and moments due to waves on those structural elements. The reactions of the cells were also telemetered into computer storage. Figure 2 is a photograph that illustrates how the huts with breather tube, or "snorkel," extensions would look.

The wave machines were located seaward of the 100 feet depth contour, which is the depth limit of the molded terrain in the model basin. Testing was done with two different water surface levels. Water depths at the machines were 107.5 feet and 117 feet. The former represents a tide level referred to Mean Lower Low Water Datum of +7.5 feet and the latter a water level at +17 feet. That is the combination of a 7.5 feet tide, a 1 foot storm surge, and an 8.5 feet tsunami. Three directions of wave advance were considered; southerly origin waves (203° refracted

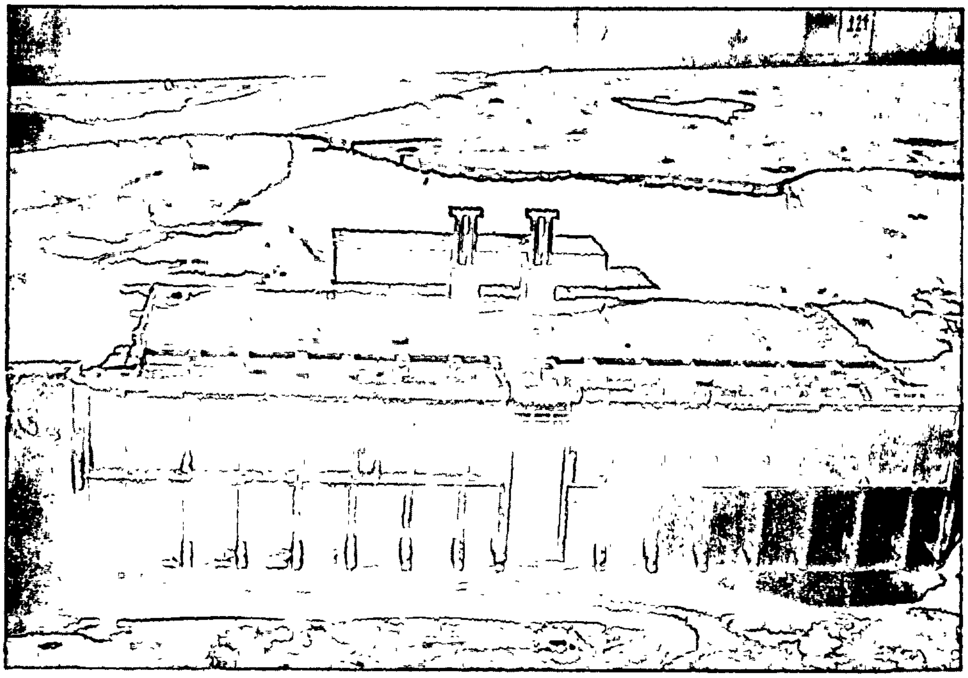

Figure 2 Intake Structure with Snorkels

azimuth at the site), southwesterly-origin waves (essentially unchanged in direction at the site) and westerly waves (258° refracted azimuth at the site). Along two of those three directions, southerly and westerly, there are narrow ravine-like paths through the terrain on their routes toward the Intake Structure. Southwest origin waves are baffled to a greater extent by a massive rock mound, the "Wash Rock", in their path toward the intake. It was concluded that southerly waves would provide more severe test conditions than the southwesterly ones would. Therefore the southerly and westerly wave directions were adopted for the test runs in which the hypothetically damaged breakwaters were incorporated.

The model studies have been carried out under the general supervision of Omar J. Lillevang, Consulting Engineer, as part of a series of on-going civil engineering assignments from Pacific Gas & Electric Company that relate to coastal engineering matters at Diablo Canyon Site.

Dr. Fredric Raichlen, functioning as staff consultant, for the Lillevang Office, is identified as the principal investigator in the model studies. He has provided invaluable advice and guidance regarding methods, scope, quality and interpretation and is the originator of several unusual and some unique techniques in the model's construction and operation.

The model was built, equipped and operated by Offshore Technology Corporation alongside its existing deep water wave laboratory at Escondido, California. Supervision of all construction, assembly of instrumentation and computer facilities, direction of tests, compilation of data and presentation of results was entrusted by Offshore Technology Corporation to Jack C. Cox.

CONCLUSIONS

Measurements, photographic and video records, observations and analyses of the waves and of their interactions with the Intake Structure in the model yield the following conclusions:

1. The heights of waves at the locality of the Cooling Water Intake Structure reach "limited" values due to the effects of offshore terrain features and of the breakwaters. Further increases in the offshore wave heights above those values do not increase the height of waves at the Intake.

2. The limited heights for the waves at the Intake Structure locality differ according to the period or frequency of the waves that are occurring and according to the direction in offshore waters from which they approach the Intake Basin.

3. The limited heights of waves at the Intake Structure locality also differ according to the profile elevations of the breakwaters that bound the Intake Basin. The limited wave heights are greater when the breakwater profiles are lowered in elevation.

4. If the profiles of both breakwaters have been levelled to elevation 0.0 feet by cumulative unrepaired damage due to storm waves and seismicity the maximum rise of splashed water (runup) observed in the model near the Air Intake Structures due to maximum limited waves indicates that some modifications to the huts are necessary to prevent ingestion of splashed water.

5. Steel tube riser stacks (snorkels) added to the present Air Intake Structures remain clear of splashed water and appear to provide means for a satisfactory solution to the splash ingestion risk.

6. With maximum limited wave heights occurring with the profiles of both breakwaters levelled to Mean Lower Low Water elevation, the structural loading on the concrete huts due to moving water impinging against and rising around those huts is substantially less than the magnitude of loads for which the huts were designed.

7. Under the same conditions of limited wave heights set forth in Number 6 above, there are no measurable loads against twin cylindrical upward extensions (snorkels) of the ventilation air intake huts due to water splashed upward after impinging against the existing ventilation air huts. It appears therefore that structural adequacy of such snorkels can readily be attained.

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March 15, 1982

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CHAPTER I

GENERAL CONSIDERATIONS

Limiting Effect Of Depth On Waves

Commonly, in technical practices, waves are said to be in "deep" water, or are referred to as deep water waves if the depth is as much or is greater than half the distance between crests of the waves that would be calculated if it were assumed the water depth were infinite. In feet, that wave length in infinitely deep water equals 5.12 times the square of the period, in seconds, between passage of two successive wave crests. For example, for waves of a 20 seconds period the conventional approach separates deep and shallow water at the 1024 feet depth contour, or if the waves occur each 10 seconds the same separation of categories occurs at the 256 feet depth location.

The wave motion that is visually evident on the surface of the sea persists throughout the water depths below. It is greatest at the surface and least at the sea floor, and varies consistently between those limits. Where the water is very deep the motion at the bottom is negligible in an engineering sense; not really discernible. Where the water is quite shallow the motion at the sea floor approaches being as great as it is at the surface. The breaking limit occurs when the bottom is too near the surface for the wave to persist as an oscillatory phenomenon. The wave then breaks and is no longer a wave. In the breaking process the energy within the wave is diminished. In the depth limiting context, breaking occurs when the still water depth approximates 1.28 times the height of the wave, measured vertically between its trough level and its crest level. That relationship is used

most reliably when the sea floor rises gradually and uniformly along a coastline, and with minimal submerged terrain features such as clefts, pinnacles, mounds, ridges or other pronounced forms.

Natural Terrain Effect At Diablo Canyon Site

The submarine terrain at Diablo Canyon Site is most emphatically not gradual or regular, and there are rocky forms between the Intake Structure and the deep ocean waters that create a discontinuous sill, which waves must cross enroute to the intake. Beyond that sill the waves traverse an area of somewhat deeper water before reaching the structure.

Because the sill is discontinuous, and irregular in profile, there was no confidence in calculating its effect on waves passing over it. The physical model was considered to be the best means for determining if there is a terrain limitation that prevents higher waves from getting to the Intake Structure unbroken. If such a limitation were found to exist, then the maximum condition for design of intake facilities insofar as wave related influences are concerned would be established, without recourse to probabilistic definitions or other derivations of maxima.

A set of experimental runs of the model was carried out in which no breakwaters were built on the sea floor, and it was found that the terrain did in fact limit the height of waves that could reach the Intake. The limit differed for each wave period and for each tide level, but the largest waves used in any of those experiments were diminished in height to limiting values before reaching the Intake Structure.

Compounded Limitations Due To Breakwaters

Many of the terrain features that limited the approaching waves have been covered over by parts of both of the Diablo Canyon breakwaters. As built, with crests standing 20 feet above Mean Lower Low Water Datum, those breakwaters intercept most of the wave action moving toward the Intake Structure, no matter how high the waves are that move toward the breakwaters from the deep sea and no matter from what direction they approach. The full height breakwaters in fact combine their effect on waves with that of the submerged terrain features they have not covered over, to limit significantly the height of the waves that can move against the Intake Structure.

Any substantial damage the breakwaters might suffer could reduce their effectiveness in limiting the height and strength of waves that move against the Intake Structure in their lee. The test program reported here was carried out to determine how much limitation on waves would remain if both breakwaters were to be extensively damaged.

Seismic Alteration Of Breakwater Cross-Sections

Pacific Gas and Electric Company asked Professor H. Bolton Seed of the University of California to consider the response of the Diablo Canyon breakwaters to a postulated seismic event. Dr. Seed reported his conclusion, that a consolidation of the core material by seismic vibration would reduce the overall height of the structure by less than 4.5 per cent and that minor slumping would occur in the upper parts of the side slope on the basin side of the trapezoidal cross-section. Figures 3 and 4 show surveyed cross-sections of the sea floor at three locations along the alignment of West Breakwater, one at the terminus where constructed slopes of the breakwater were flattened to 3:1, one where the

sea floor is relatively high and one where it is quite low. The breakwater at the latter two locations has approximately its least and its greatest structural heights. Figure 3 is the full height breakwater as it was designed and built. Figure 4 assumes that a succession of wave events had carried away all crest materials above the plane of Mean Lower Low Water, and dropped those materials on the basin side slope below Mean Lower Low Water.

When West Breakwater's seaward end was damaged during the wave storm of January 28, 1981, part of the most affected area was left at elevation zero feet, i.e. at the level of Mean Lower Low Water, and the rubble of stone and concrete fragments derived from the original construction above that level were deposited as shown on Figure 5.

On each of the basic cross-sections discussed above is shown Seed's delineation of how the cross-section would be altered by the assumed subsequent seismic episode. In the case which assumes waves had first removed the materials that were above Mean Lower Low Water, Figure 4, the subsequent seismic changes to the cross-section are so slight that it is doubtful they could be detected on the site, either visually or by conventional hydrographic surveying procedures. It was apparent that whether the seismic event preceded or followed the wave sequences was not significant in developing a hypothetically levelled cross-section. Therefore the stage of damage to both breakwaters to be tested for limiting effect on waves was selected with both breakwater crests at elevation zero feet, the seaward slopes below that level remaining as originally constructed, and the basin sides widened by as much as the materials transported there from above elevation zero could achieve while coming to rest at a slope of 1.5 horizontal to 1 vertical.

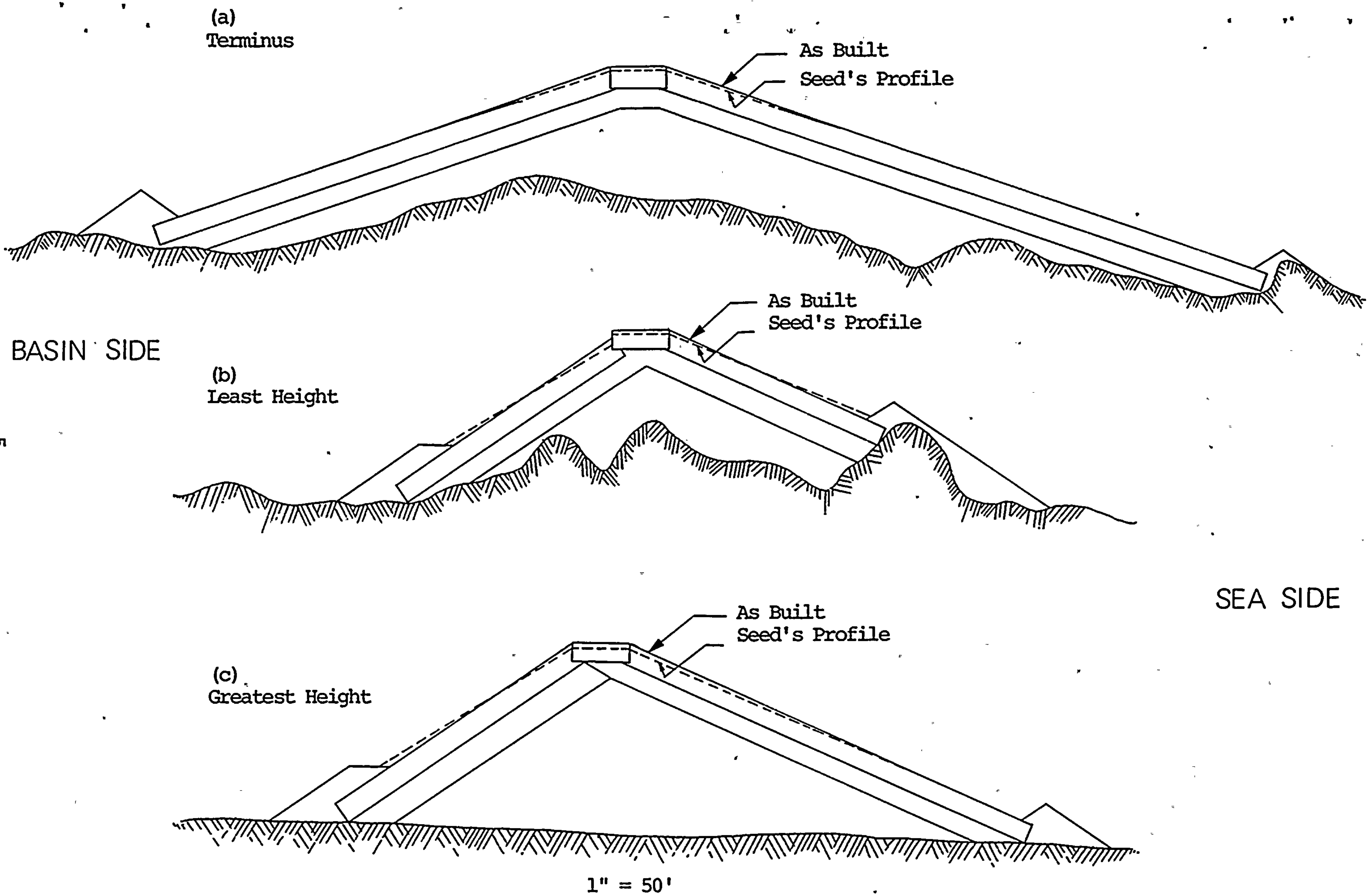


Figure 3 ORIGINAL AND SEISMICALLY DIMINISHED CROSS-SECTION PER SEED

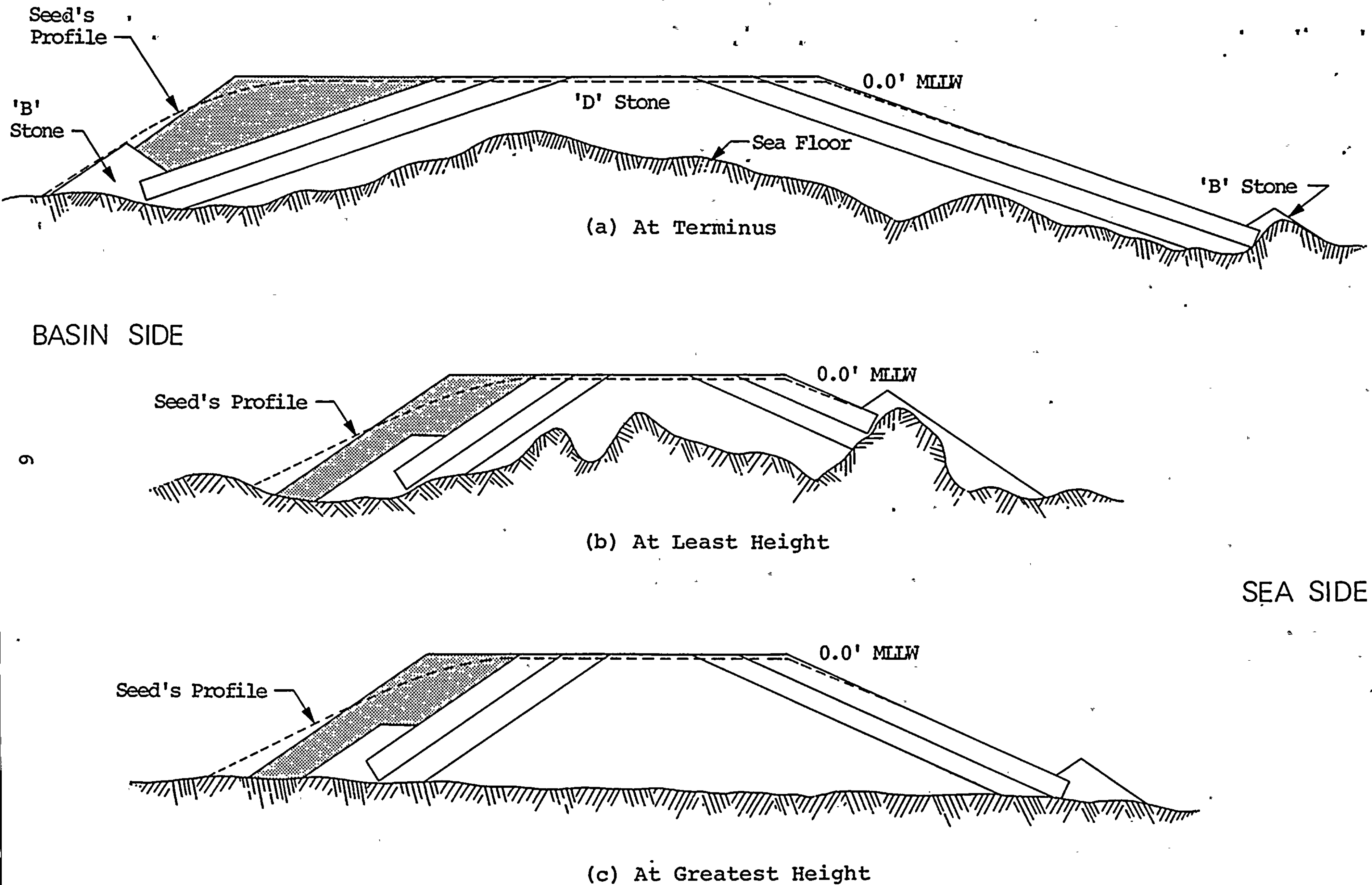


Figure 4 WAVE-LEVELLED AND SEISMICALLY DIMINISHED CROSS-SECTIONS PER SEED

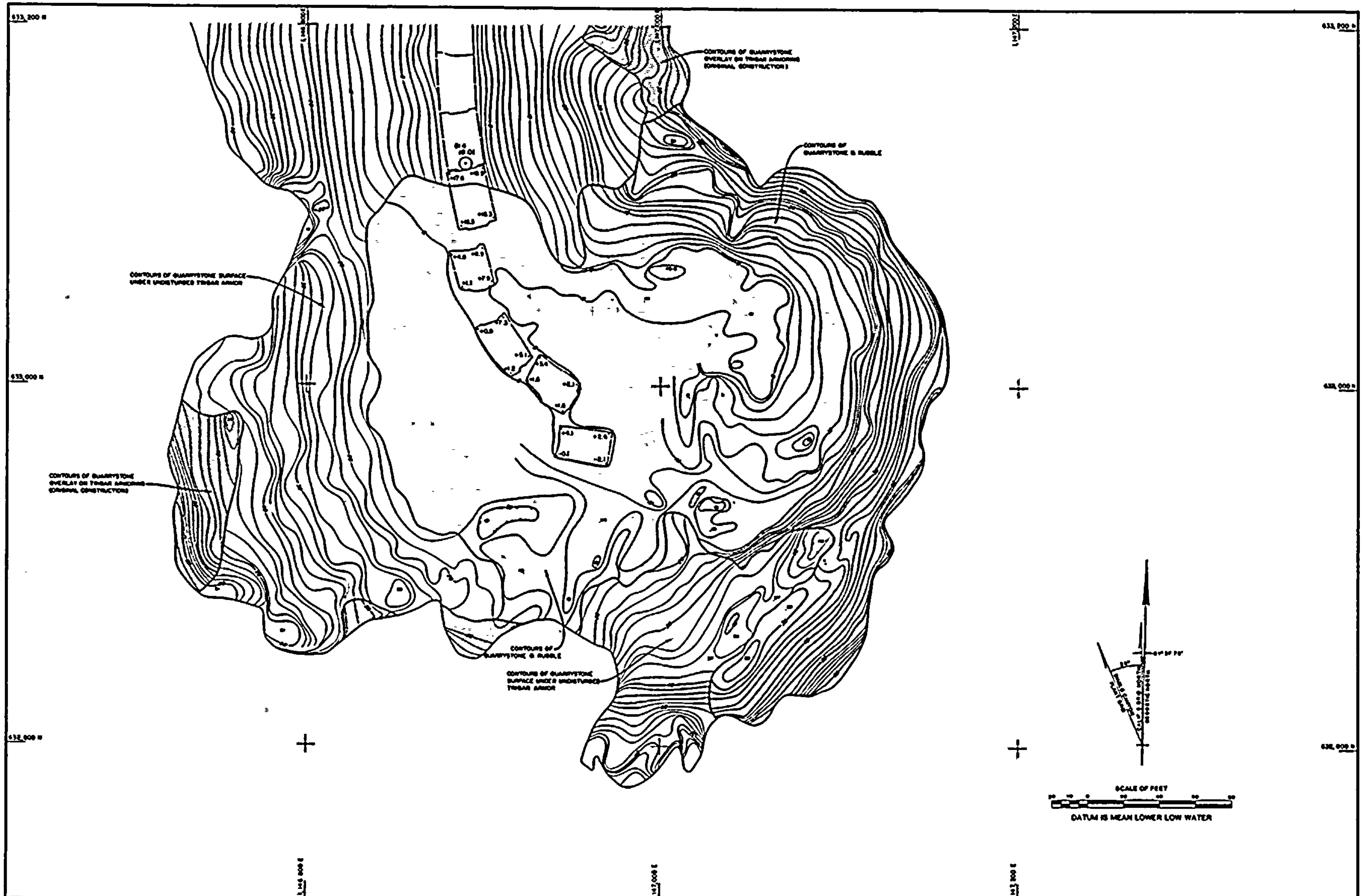


Figure 5

QUARRYSTONE & RUBBLE CONTOURS

WEST BREAKWATER AFTER JANUARY 28, 1981

DIABLO CANYON, CALIFORNIA

Construction Of Cross-Sections For Modelling

The question to be investigated can be stated as, "What is the combined effect of natural terrain features, and of the breakwaters, in limiting the wave heights at the Intake Structure, if both breakwaters are levelled to a crest elevation at the plane of Mean Lower Low Water?" To freeze that hypothetical condition for testing, the cross-section might have been made in almost any way, a solid concreted mass for example. It was judged to be a more appropriate hypothesis to use surface textures and porosities in the model assembly that would resemble prototype textures and porosities. Thus, the core and the sub-armor (B and E stone) and concrete Tribar armor zones were constructed of scaled materials. The resultant cross-section was then fixed against changing during the progress of testing by various means, the most visible being a plastic filament coarse mesh screen, stretched over the particles of material.

Numerical Model For Wave Heights/Directions

A numerical model was developed to represent the gross terrain features of the ocean floor along the paths of waves that can approach Diablo Canyon Site. The area modelled is shown by the shaded regions on Figure 6. It reaches from the coast, where it extends roughly one mile along the shore either way from Diablo Canyon, and flares out to the 206 fathoms contour line. At that depth, along the 206 fathoms contour, it is 36 miles long and the contour lies on the order of 15 miles from the coast. Between shore and about the 40 fathoms contour, elevation data were read into the model from grid points 250 feet apart. Seaward from that general depth limit, grid elevations each 500 feet were used, out to roughly 75 fathoms. The rest of the model had grid

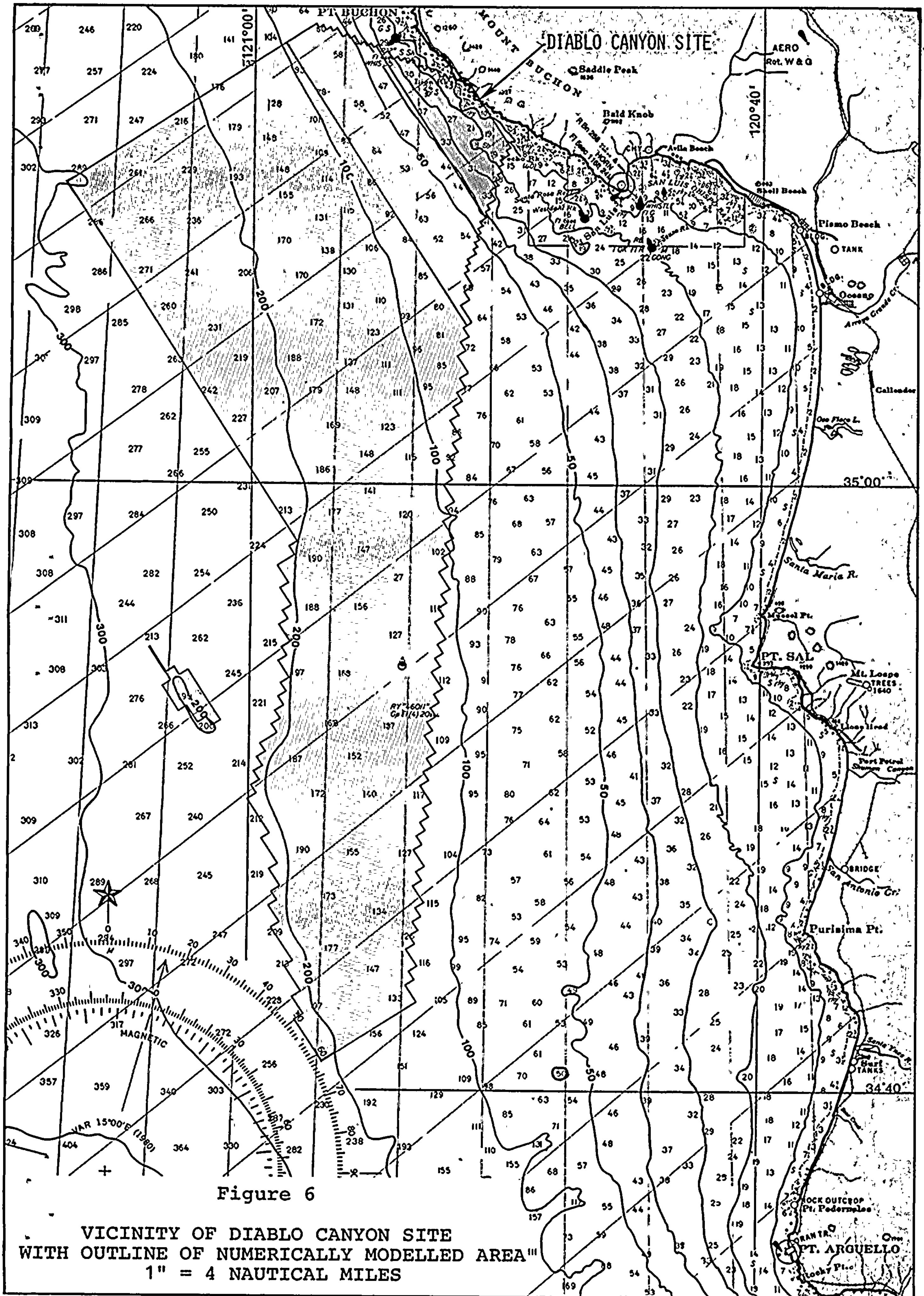


Figure 6

VICINITY OF DIABLO CANYON SITE
WITH OUTLINE OF NUMERICALLY MODELLED AREA
1" = 4 NAUTICAL MILES

data each 1,000 feet. The special hydrographic maps produced from the surveys of early 1981 were used for data at the grid points they cover. The balance of the numerical model data were taken from unpublished "smooth sheets" of field surveys made in the mid-thirties by the U.S. Coast and Geodetic Survey, predecessor of the U.S. National Ocean Survey. About 16,000 grid points comprised the model.

The numerical model was used to calculate and to display the refraction of waves of selected periods, and of selected deep water directions, as they move toward the breakwaters at Diablo Canyon Site. The program used for wave refraction calculations is an extension by Dr. R.C.Y. Koh and Professor Fredric Raichlen at California Institute of Technology of concepts and procedures described in the Journal of the Waterways and Harbors Division of the American Society of Civil Engineers by Coudert and Raichlen*.

The computer output of refracted wave characteristics can be both graphic and tabular. Both were produced in the present case. Figure 7 is an example of a tabular output, and Figure 8 of the graphic output for waves of 14 seconds period approaching in deep water from 180° azimuth, South. In the tabular example two wave rays, numbered 6 and 7, are calculated along their refracting paths from two initial points that are 200 feet apart at 97 fathoms (582 feet) depth. Referring to the column numbers over-written on the tabular data:

* Coudert, J.F. and Raichlen F., Discussion of: "Wave Refraction Near San Pedro Bay, California," JWWH, ASCE, August 1970.

WAVE REFRACTION ANALYSIS INCLUDING EFFECTS OF SHOALING 180.
DIABLO CANYON REFRACTION STUDY EXTENDED OUTER GRID 349X259
D.W.AZM = 180
WAVE PERIOD 14.000 SECONDS NORTH AZIMUTH 180.00 DEGREES DEEP WATER WAVE HEIGHT 1.000 L

REFRACTION COEFFICIENT KR APPLIES TO RAYS 11 AND 12 COEFF KS IN KRS ARE AVERAGES FOR THE TWO RAYS
KRI - REFRACT COEFF BASED ON INFINITESIMAL RAY SPACING AZM=NORTH AZIMUTH, AWFL=ANGLE RAY TO FALL LINE(ANTICLOCKWISE+)
LENGTH UNIT L IS THE FOOT (1.400 0.0 6)

TIME (SEC)	RAY 11 (OK) X (L)	Y (L)	DEPTH (L)	AZM (DEGS*10)	AWFL	KS	KRI	HT (L)	KR	KRS	RAY 12 (OK) X (L)	Y (L)	DEPTH (L)	AZM (DEGS*10)	AWFL	KS	KRI	HT (L)
0.0	88233	86168	526.6	1800	-658	0.99	1.00	1.0	1.000	0.993	88129	85997	528.0	1800	-683	0.99	1.00	1.0
7.0	87806	86429	525.4	1800	-764	0.99	1.00	1.0	1.000	0.993	87702	86258	527.3	1800	-779	0.99	1.00	1.0
14.0	87379	86689	524.6	1800	-785	0.99	1.00	1.0	1.000	0.992	87275	86518	526.7	1800	-803	0.99	1.00	1.0
21.0	86952	86950	523.3	1800	-731	0.99	1.00	1.0	1.000	0.992	86848	86779	525.5	1800	-750	0.99	1.00	1.0
28.0	86525	87211	521.3	1800	-686	0.99	1.00	1.0	1.000	0.992	86421	87040	523.7	1800	-717	0.99	1.00	1.0
35.0	86098	87471	518.8	1801	-715	0.99	1.00	1.0	1.000	0.992	85994	87301	521.3	1801	-745	0.99	1.00	1.0
42.0	85671	87732	517.1	1801	-763	0.99	1.00	1.0	1.000	0.992	85567	87562	520.0	1801	-782	0.99	1.00	1.0
49.0	85244	87993	515.3	1801	-773	0.99	1.00	1.0	1.000	0.992	85140	87823	518.3	1801	-775	0.99	1.00	1.0
56.0	84818	88254	513.9	1801	-750	0.99	1.00	1.0	1.001	0.992	84713	88084	516.5	1801	-756	0.99	1.00	1.0
63.0	84391	88516	512.1	1801	-735	0.99	1.00	1.0	1.001	0.992	84287	88345	514.8	1801	-749	0.99	1.00	1.0
70.0	83964	88777	509.8	1801	-754	0.99	1.00	1.0	1.001	0.992	83860	88606	512.9	1801	-771	0.99	1.00	1.0
77.0	83538	89038	508.5	1801	-794	0.99	1.00	1.0	1.001	0.992	83434	88868	511.6	1801	-800	0.99	1.00	1.0
84.0	83112	89300	507.1	1802	-794	0.99	1.00	1.0	1.001	0.992	83007	89130	510.2	1802	-795	0.99	1.00	1.0
91.0	82686	89561	505.6	1802	-797	0.99	1.00	1.0	1.001	0.992	82581	89391	508.7	1802	-791	0.99	1.00	1.0
98.0	82260	89823	504.0	1802	-829	0.99	1.00	1.0	1.001	0.992	82155	89653	507.1	1802	-809	0.99	1.00	1.0
105.0	81834	90085	503.1	1802	-854	0.99	1.00	1.0	1.001	0.992	81729	89915	505.7	1802	-840	0.99	1.00	1.0
112.0	81408	90347	503.1	1802	-844	0.99	1.00	1.0	1.001	0.992	81303	90177	505.3	1802	-841	0.99	1.00	1.0
119.0	80982	90609	502.5	1802	-800	0.99	1.00	1.0	1.001	0.992	80877	90439	504.8	1803	-812	0.99	1.00	1.0
126.0	80556	90871	501.2	1803	-743	0.99	1.00	1.0	1.001	0.992	80452	90701	503.6	1803	-767	0.99	1.00	1.0
133.0	80131	91134	499.2	1803	-756	0.99	1.00	1.0	1.002	0.992	80026	90964	501.7	1803	-779	0.99	1.00	1.0
140.0	79705	91396	497.9	1803	-809	0.99	1.00	1.0	1.002	0.992	79601	91226	500.9	1803	-829	0.99	1.00	1.0
147.0	79280	91659	497.2	1803	-861	0.99	1.00	1.0	1.002	0.992	79175	91489	500.1	1803	-844	0.99	1.00	1.0
154.0	78854	91921	496.4	1803	-880	0.99	1.00	1.0	1.002	0.992	78750	91752	499.4	1803	-863	0.99	1.00	1.0
161.0	78429	92184	496.3	1804	-858	0.99	1.00	1.0	1.002	0.992	78325	92015	498.7	1804	-835	0.99	1.00	1.0
168.0	78004	92447	495.8	1804	-808	0.99	1.00	1.0	1.003	0.993	77900	92278	498.2	1804	-808	0.99	1.00	1.0
175.0	77579	92710	494.7	1804	-802	0.99	1.00	1.0	1.003	0.993	77475	92541	497.1	1804	-802	0.99	1.00	1.0
182.0	77154	92973	493.7	1804	-809	0.99	1.00	1.0	1.003	0.993	77050	92804	496.1	1804	-808	0.99	1.00	1.0
189.0	76729	93236	492.7	1804	-815	0.99	1.00	1.0	1.003	0.993	76625	93067	495.1	1804	-813	0.99	1.00	1.0
196.0	76305	93500	491.8	1804	-815	0.99	1.00	1.0	1.003	0.993	76200	93331	494.2	1804	-811	0.99	1.00	1.0
203.0	75880	93763	491.0	1805	-801	0.99	1.00	1.0	1.003	0.993	75775	93594	493.3	1805	-802	0.99	1.00	1.0
210.0	75456	94027	489.9	1805	-786	0.99	1.00	1.0	1.004	0.993	75351	93858	492.3	1805	-790	0.99	1.00	1.0
217.0	75031	94290	488.3	1805	-773	0.99	1.00	1.0	1.004	0.993	74926	94122	491.0	1805	-781	0.99	1.00	1.0
224.0	74607	94554	486.7	1805	-761	0.99	1.00	1.0	1.004	0.993	74502	94386	489.4	1805	-767	0.99	1.00	1.0
231.0	74183	94818	485.0	1805	-749	0.99	1.00	1.0	1.004	0.993	74078	94650	487.7	1805	-745	0.99	1.00	1.0
238.0	73759	95082	483.1	1806	-744	0.99	1.00	1.0	1.004	0.993	73654	94914	485.7	1806	-740	0.99	1.00	1.0
245.0	73335	95347	481.3	1806	-752	0.99	1.00	1.0	1.004	0.992	73230	95178	483.9	1806	-748	0.99	1.00	1.0
252.0	72911	95611	479.6	1806	-763	0.99	1.00	1.0	1.004	0.992	72806	95443	482.2	1806	-760	0.99	1.00	1.0
259.0	72488	95875	478.1	1806	-772	0.99	1.00	1.0	1.004	0.992	72383	95707	480.7	1806	-769	0.99	1.00	1.0
266.0	72064	96140	476.7	1806	-779	0.99	1.00	1.0	1.004	0.992	71959	95972	479.3	1806	-778	0.99	1.00	1.0
273.0	71641	96405	475.3	1807	-788	0.99	1.00	1.0	1.004	0.992	71536	96237	477.9	1807	-788	0.99	1.00	1.0
280.0	71218	96670	474.1	1807	-800	0.99	1.00	1.0	1.004	0.991	71113	96502	476.7	1807	-797	0.99	1.00	1.0
287.0	70795	96935	473.0	1807	-814	0.99	1.00	1.0	1.004	0.991	70689	96767	475.6	1807	-810	0.99	1.00	1.0
294.0	70372	97200	472.1	1807	-817	0.99	1.00	1.0	1.003	0.991	70266	97032	474.6	1807	-804	0.99	1.00	1.0
301.0	69949	97466	471.3	1808	-804	0.99	1.00	1.0	1.003	0.991	69844	97297	473.6	1808	-787	0.99	1.00	1.0
308.0	69527	97731	469.8	1808	-752	0.99	1.00	1.0	1.003	0.990	69421	97563	472.3	1808	-768	0.99	1.00	1.0
315.0	69104	97997	467.7	1808	-718	0.99	1.00	1.0	1.003	0.990	68998	97829	470.3	1808	-736	0.99	1.00	1.0
322.0	68682	98263	466.2	1808	-740	0.99	1.00	1.0	1.003	0.989	68576	98094	468.3	1808	-723	0.99	1.00	1.0
329.0	68260	98529	465.0	1808	-797	0.99	1.00	1.0	1.003	0.989	68154	98360	467.0	1808	-785	0.99	1.00	1.0
336.0	67838	98795	464.1	1809	-821	0.99	1.00	1.0	1.002	0.989	67732	98626	466.4	1809	-839	0.99	1.00	1.0
343.0	67416	99061	463.3	1809	-803	0.99	1.00	1.0	1.002	0.988	67310	98893	465.5	1809	-814	0.99	1.00	1.0
350.0	66994	99327	462.6	1809	-804	0.99	1.00	1.0	1.002	0.988	66888	99159	464.6	1809	-797	0.99	1.00	1.0
357.0	66572	99594	461.8	1809	-791	0.99	1.00	1.0	1.002	0.988	66466	99425	464.0	1809	-801	0.99	1.00	1.0
364.0	66151	99861	460.2	1810	-742	0.99	1.00	1.0	1.002	0.988	66044	99692	462.8	1809	-765	0.99	1.00	1.0
371.0	65730	100128	458.1	1810	-711	0.99	1.00	1.0	1.001	0.987	65623	99959	460.7	1810	-711	0.99	1.00	1.0
378.0	65308	100395	456.0	1810	-717	0.99	1.00	1.0	1.001	0.986	65202	100226	458.5	1810	-708	0.99	1.00	1.0
385.0	64888	100662	454.0	1810	-730	0.98	1.00	1.0	1.001	0.986	64781	100493	456.5	1810	-726	0.99	1.00	1.0
392.0	64467	100929	452.1	1811	-740	0.98	1.00	1.0	1.000	0.985	64360	100760	454.6	1811	-731	0.99	1.00	1.0
399.0	64046	101197	450.5	1811	-710	0.98	1.00	1.0	1.000	0.985	63939	101028	452.8	1811	-710	0.98	1.00	1.0
406.0	63626	101464	447.9	1811	-643	0.98	1.00	1.0	0.999	0.984	63518	101295	450.3	1811	-639	0.98	1.00	1.0
413.0	63206	101732	444.6	1812	-631	0.98	1.00	1.0	0.999	0.983	63098	101563	447.2	1811	-641	0.98	1.00	1.0
420.0	62786	102000	441.3	1812	-611	0.98	1.00	1.0	0.999	0.982	62678	101831	443.9	1812	-624	0.98	1.00	1.0
427.0	62367	102268	437.8	1812	-627	0.98	1.00	1.0	0.998	0.981	62259	102099	440.2	1812	-633	0.98	1.00	1.0
434.0	61947	102537	434.7	1813	-675	0.98	1.00	1.0	0.998	0.980	61839	102367	437.4	1812	-684	0.98	1.00	1.0
441.0	61528	102805	432.0	1813	-693	0.98	1.00	1.0	0.997	0.979	61420	102636	435.0	1813	-702	0.98	1.00	1.0
448.0	61110	103074	429.3	1814	-685	0.98	1.00	1.0	0.997	0.979	61001	102905	432.3	1813	-687	0.98	1.00	1.0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
469.0	59856	103882	421.0	1815	-707	0.98	1.00	1.0	0.996	0.976	59747	103712	424.1	1815	-712	0.98	0.99	1.0
476.0	59439	104152	418.5	1815	-721	0.98	1.00	1.0	0.995	0.975	59329	103982	421.5	1815	-733	0.98	0.99	1.0
483.0	59022	104422	416.8	1816	-658	0.98	1.00	1.0	0.995	0.974	58912	104252	419.5	1816	-686	0.98	0.99	1.0
490.0	58605	104692	413.3	1816	-645	0.98	1.00	1.0	0.995	0.973	58495	104522	415.5	1816	-620	0.98	0.99	1.0
497.0	58189	104963	411.0	1817	-650	0.98	1.00	1.0	0.994	0.973	58079	104793	413.3	1817	-651	0.98	0.99	1.0
504.0	57773	105233	407.6	1817	-624	0.98	0.99	1.0	0.994	0.972	57663	105064	410.1	1817	-618	0.98	0.99	1.0
511.0	57358	105504	404.1	1818	-640	0.98	0.99	1.0	0.994	0.971	57248	105335	406.8	1818	-645	0.98	0.99	1.0
518.0	56943	105776	401.2	1818	-663	0.98	0.99	1.0	0.993	0.970	56832	105606	404.0	1818	-702	0.98	0.99	1.0
525.0	56529	106047	398.5	1819	-746	0.98	0.99	1.0	0.993	0.969	56418	105878	401.4	1819	-753	0.98	0.99	1.0
532.0	56115	106319	397.7	1819	-732	0.98	0.99	1.0	0.993	0.969	56003	106149	400.2	1819	-743	0.98	0.99	1.0
539.0	55701	106591	395.4	1820	-657	0.97	0.99	1.0	0.993	0.968	55589	106422	398.0	1820	-660	0.98	0.99	1.0
546.0	55287	106864	392.2	1820	-600	0.97	0.99	1.0	0.992	0.967	55176	106694	394.8	1820	-598	0.97	0.99	1.0
553.0	54875	107137	388.8	1821	-577	0.97	0.99	1.0	0.992	0.966	54763	106967	390.8	1821	-563	0.97	0.99	1.0
560.0	54462	107410	386.0	1822	-544	0.97	0.99	1.0	0.992	0.965	54350	107240	387.4	1821	-508	0.97	0.99	1.0
567.0	54050	107683	381.5	1822	-430	0.97	0.99	1.0	0.992	0.964	53938	107513	383.5	1822	-407	0.97	0.99	1.0
574.0	53639	107956	376.1	1823	-415	0.97	0.99	1.0	0.991	0.962	53527	107786	377.9	1822	-469	0.97	0.99	1.0
581.0	53229	108229	371.3	1823	-423	0.97	0.99	1.0	0.990	0.960	53116	108059	372.9	1823	-428	0.97	0.99	1.0
588.0	52819	108503	366.7	1824	-452	0.97	0.99	1.0	0.990	0.959	52705	108333	368.5	1823	-472	0.97	0.99	1.0
595.0	52409	108776	362.7	1824	-534	0.97	0.99	1.0	0.990	0.957	52296	108606	364.8	1824	-537	0.97	0.99	1.0
602.0	52001	109050	359.9	1825	-604	0.97	0.99	1.0	0.989	0.956	51887	108880	362.0	1825	-593	0.97	0.99	1.0
609.0	51593	109324	355.8	1826	-546	0.97	0.99	1.0	0.988	0.954	51478	109154	358.6	1825	-551	0.97	0.99	1.0
616.0	51185	109599	351.3	1826	-520	0.96	0.98	0.9	0.988	0.953	51071	109429	353.9	1826	-516	0.96	0.99	1.0
623.0	50779	109873	346.4	1827	-480	0.96	0.98	0.9	0.987	0.951	50664	109703	348.8	1827	-479	0.96	0.99	1.0
630.0	50374	110148	341.7	1828	-452	0.96	0.98	0.9	0.986	0.948	50258	109978	343.6	1828	-461	0.96	0.99	0.9
637.0	49969	110423	336.9	1829	-431	0.96	0.98	0.9	0.986	0.947	49853	110253	338.9	1829	-446	0.96	0.99	0.9
644.0	49566	110699	332.8	1830	-431	0.96	0.98	0.9	0.985	0.945	49450	110528	334.4	1829	-451	0.96	0.99	0.9
651.0	49163	110974	328.1	1830	-412	0.96	0.98	0.9	0.985	0.943	49047	110804	329.8	1830	-456	0.96	0.98	0.9
658.0	48762	111249	326.3	1831	-461	0.96	0.98	0.9	0.984	0.941	48645	111079	325.8	1831	-491	0.96	0.98	0.9
665.0	48361	111525	321.2	1832	-506	0.96	0.98	0.9	0.984	0.940	48244	111355	322.8	1832	-534	0.96	0.98	0.9
672.0	47961	111801	317.4	1833	-541	0.95	0.98	0.9	0.984	0.939	47843	111631	319.6	1833	-567	0.95	0.98	0.9
679.0	47562	112077	314.7	1834	-594	0.95	0.98	0.9	0.984	0.938	47444	111908	316.8	1834	-603	0.95	0.98	0.9
686.0	47164	112354	311.9	1835	-551	0.95	0.98	0.9	0.984	0.937	47046	112184	314.0	1835	-538	0.95	0.98	0.9
693.0	46767	112631	308.6	1836	-498	0.95	0.98	0.9	0.984	0.936	46648	112462	310.6	1836	-462	0.95	0.98	0.9
700.0	46371	112909	304.5	1837	-385	0.95	0.98	0.9	0.983	0.934	46252	112739	306.0	1837	-370	0.95	0.98	0.9
707.0	45976	113186	299.1	1838	-318	0.95	0.98	0.9	0.983	0.932	45857	113017	300.5	1838	-339	0.95	0.98	0.9
714.0	45583	113464	293.8	1839	-326	0.95	0.98	0.9	0.983	0.930	45463	113294	295.4	1838	-349	0.95	0.98	0.9
721.0	45191	113741	288.9	1840	-398	0.94	0.98	0.9	0.983	0.929	45071	113572	290.4	1840	-416	0.95	0.98	0.9
728.0	44800	114018	284.5	1841	-431	0.94	0.98	0.9	0.982	0.927	44680	113849	286.4	1841	-448	0.94	0.98	0.9
735.0	44411	114296	280.8	1842	-491	0.94	0.98	0.9	0.982	0.925	44291	114127	282.5	1842	-463	0.94	0.98	0.9
742.0	44024	114574	277.5	1844	-518	0.94	0.98	0.9	0.981	0.924	43903	114405	279.2	1843	-492	0.94	0.98	0.9
749.0	43638	114853	273.7	1845	-474	0.94	0.97	0.9	0.980	0.922	43516	114684	275.6	1844	-463	0.94	0.98	0.9
756.0	43253	115131	269.1	1847	-457	0.94	0.97	0.9	0.979	0.919	43131	114963	271.0	1846	-403	0.94	0.98	0.9
763.0	42871	115411	264.7	1848	-457	0.94	0.97	0.9	0.978	0.916	42747	115242	266.5	1848	-460	0.94	0.98	0.9
770.0	42490	115690	259.4	1850	-443	0.94	0.97	0.9	0.976	0.913	42366	115521	261.7	1849	-462	0.94	0.98	0.9
777.0	42112	115970	254.5	1852	-494	0.93	0.97	0.9	0.975	0.911	41987	115801	256.9	1852	-513	0.93	0.98	0.9
784.0	41736	116250	250.3	1854	-510	0.93	0.96	0.9	0.974	0.908	41610	116081	253.0	1854	-550	0.93	0.98	0.9
791.0	41363	116531	245.6	1857	-517	0.93	0.96	0.9	0.973	0.906	41236	116362	248.4	1856	-560	0.93	0.98	0.9
798.0	40992	116812	242.6	1859	-590	0.93	0.96	0.9	0.972	0.904	40864	116644	244.8	1859	-598	0.93	0.98	0.9
805.0	40623	117095	239.9	1862	-577	0.93	0.96	0.9	0.972	0.903	40494	116927	242.2	1862	-585	0.93	0.98	0.9
812.0	40256	117378	236.7	1864	-533	0.93	0.96	0.9	0.972	0.902	40126	117210	238.9	1864	-539	0.93	0.98	0.9
819.0	39891	117662	231.7	1868	-445	0.93	0.96	0.9	0.971	0.900	39761	117495	234.7	1867	-478	0.93	0.98	0.9
826.0	39531	117947	222.4	1872	-457	0.92	0.95	0.9	0.970	0.897	39399	117781	227.1	1871	-481	0.92	0.98	0.9
833.0	39177	118232	216.1	1876	-465	0.92	0.95	0.9	0.970	0.896	39043	118067	218.6	1876	-471	0.92	0.98	0.9
840.0	38826	118518	209.7	1880	-505	0.92	0.95	0.9	0.970	0.893	38692	118353	212.8	1880	-489	0.92	0.98	0.9
847.0	38480	118805	204.6	1885	-502	0.92	0.94	0.9	0.970	0.891	38344	118641	207.6	1885	-512	0.92	0.98	0.9
854.0	38139	119092	199.2	1889	-523	0.92	0.94	0.9	0.969	0.890	38001	118929	202.4	1889	-525	0.92	0.98	0.9
861.0	37801	119381	194.7	1893	-448	0.92	0.94	0.9	0.969	0.888	37663	119219	197.3	1893	-481	0.92	0.98	0.9
868.0	37468	119669	188.7	1898	-385	0.92	0.93	0.9	0.969	0.888	37329	119508	191.8	1898	-407	0.92	0.98	0.9
875.0	37142	119957	178.8	1904	-412	0.91	0.93	0.9	0.969	0.886	37000	119798	183.8	1904	-436	0.91	0.98	0.9
882.0	36823	120245	172.3	1910	-450	0.91	0.93	0.9	0.969	0.886	36679	120088	175.3	1911	-509	0.91	0.98	0.9
889.0	36508	120534	170.1	1914	-746	0.91	0.94	0.9	0.972	0.888	36364	120379	171.3	1916	-615	0.91	0.98	0.9
896.0	36196	120824	169.7	1917	-818	0.91	0.94	0.9	0.976	0.891	36052	120671	171.2	1919	-731	0.91	0.98	0.9
903.0	35886	121115	168.1	1920	-483	0.91	0.95	0.9	0.978	0.893	35742	120963	169.5	1921	-477	0.91	0.98	0.9
910.0	35580	121408	163.3	1926	-533	0.91	0.95	0.9	0.978	0.893	35435	121257	166.1	1925	-431	0.91	0.98	0.9
917.0	35280	121701	157.6	1934	-677	0.91	0.94	0.9	0.974	0.889	35132	121550	161.9	1930	-560	0.91	0.98	0.9
924.0	34987	121995	156.2	1941	-789	0.91	0.94	0.9	0.967	0.883	34835	121844	159.0	1937	-816	0.91	0.97	0.9
931.0	34697	122293	154.0	1946	-805	0.91	0.94	0.9	0.961	0.878	34542	122142	158.8	1943	-790	0.91	0.97	0.9
938.0	34410	122592	153.9	1952	-616	0.91	0.93	0.9	0.955	0.872	34252	122441	156.2	1948	-657	0.91	0.96	0.9
945.0	34128	122893	151.2	1958	-627	0.91	0.93	0.9	0.951	0.868	33966	122742	154.6	1955	-669	0.91	0.95	0.9
952.0	33851	123195	148.6	1963	-556	0.91	0.93	0.9	0.947	0.865	33686	123045	151.3	1962	-574	0.91	0.94	0.9
959.0	33578	123498	145.6	1969	-533	0.91	0.94	0.9	0.945	0.864	33411	123349	148.2	1968	-560	0.91	0.94	0.9
966.0	33310	123801	143.3	1975	-734	0.91	0.94	0.9	0.943	0.862	33141	123654	146.0	1973	-636	0.91	0.93	0.8
973.0	33047	124107	139.8	1982	-407	0.91	0.94	0.9	0.938	0.855	32874	123959	142.2	1978	-336	0.91	0.91	0.8
980.0	32791	124411	135.3	1987	-399	0.92	0.95	0.9	0.932	0.853	32614	124263	136.7	1983	-373	0.92	0.90	0.8
987.0	32538	124715	132.3	1991	-192	0.92	0.95	0.9	0.925	0.848	32358	124566	132.8	1986	-134	0.92	0.89	0.8
994.0	32291	125016	124.0	1992	-8	0.92	0.95	0.9	0.919	0.846	32108	124865	124.6	1988	-114	0.92	0.88	0.8
1001.0	32049	125311	117.1	1993	-48	0.92	0.95	0.9	0.916	0.846	31865	125159	118.8	1993	-193	0.92	0.87	0.8
1008.0	31813	125600	110.1	1995	-100	0.93	0.95	0.9	0.919	0.858	31630	125450	111.1	1999	-138	0.93	0.87	0.8
1015.0	31584	125883	103.5	1997	-129	0.93	0.95	0.9	0.924	0.859	31401	125736	104.2	2002	-191	0.93	0.87	0.8
1022.0	31362	126160	96.6	2001	-166	0.94	0.95	0.9	0.930	0.870	31181	126017	98.3	2007	-187	0.93	0.87	0.8
1029.0	31148	126432	89.2	2007	-230	0.94	0.94	0.9	0.937	0.884	30968	126292	90.3	2012	-146	0.94	0.87	0.8
1036.0	30944	126697	82.9	2015	-234	0.95	0.94	0.9	0.942	0.895	30765	126560	84.2	2018	-213	0.95	0.87	0.8
1043.0	30750	126958	76.4	2023	-231	0.96	0.93	0.9	0.945	0.906	30570	126824	78.6	2026	-312	0.96	0.83	0.8
1050.0	30564	127212	71.5	2027	101	0.97	0.92	0.9	0.947	0.919	30384	127081	69.9	2023	201	0.97	0.83	0.9
1057.0	30393	127452	55.0	2020	49	1.01	0.88	0.9	0.935	0.954	30212	127305	47.1	2004	100	1.03	0.87	0.9
1064.0	30236	127631	34.7	2012	-164	1.09	0.80	0.9	0.916	1.032	30065	127486	26.0	1984	154	1.16	0.83	1.0
1071.0	30104	127831	34.2	2031	0	1.10	0.71	0.8	0.830	0.978	29937	127635	30.2	1972	188	1.12	1.06	1.2
1078.0	29983	128000	21.6	2027	-11	1.21	0.62	0.7	0.832	1.074	29810	127769	12.2	1918	113	1.37	1.45	2.0
1085.0	29902	128111	5.7	2020	26	1.64	0.56	0.9										

Figure 7

Column 1 identifies for each line the accumulated time of wave travel from the initial point to the point for which that line displays calculated refracted wave conditions.

Columns 2, 3, 12 and 13 give the coordinate position that each of the rays reaches at that time. The coordinate units are feet. The coordinate system is rotated 58° 37' 30" clockwise from California State Coordinate System (Zone V) orientation. At Diablo Canyon Site that is a clockwise rotation of 57 degrees from True North. The grid origin is at California Zone V coordinates N 592,492.4 feet; E 1,022,451.1 feet.

Columns 4 and 14 display the water depths, in feet rather than fathoms, at the coordinate locations.

Columns 5 and 15 show the azimuth angle from which the wave ray is moving at each time represented by each line, azimuths being turned clockwise from Zone V North, in degrees times 10.

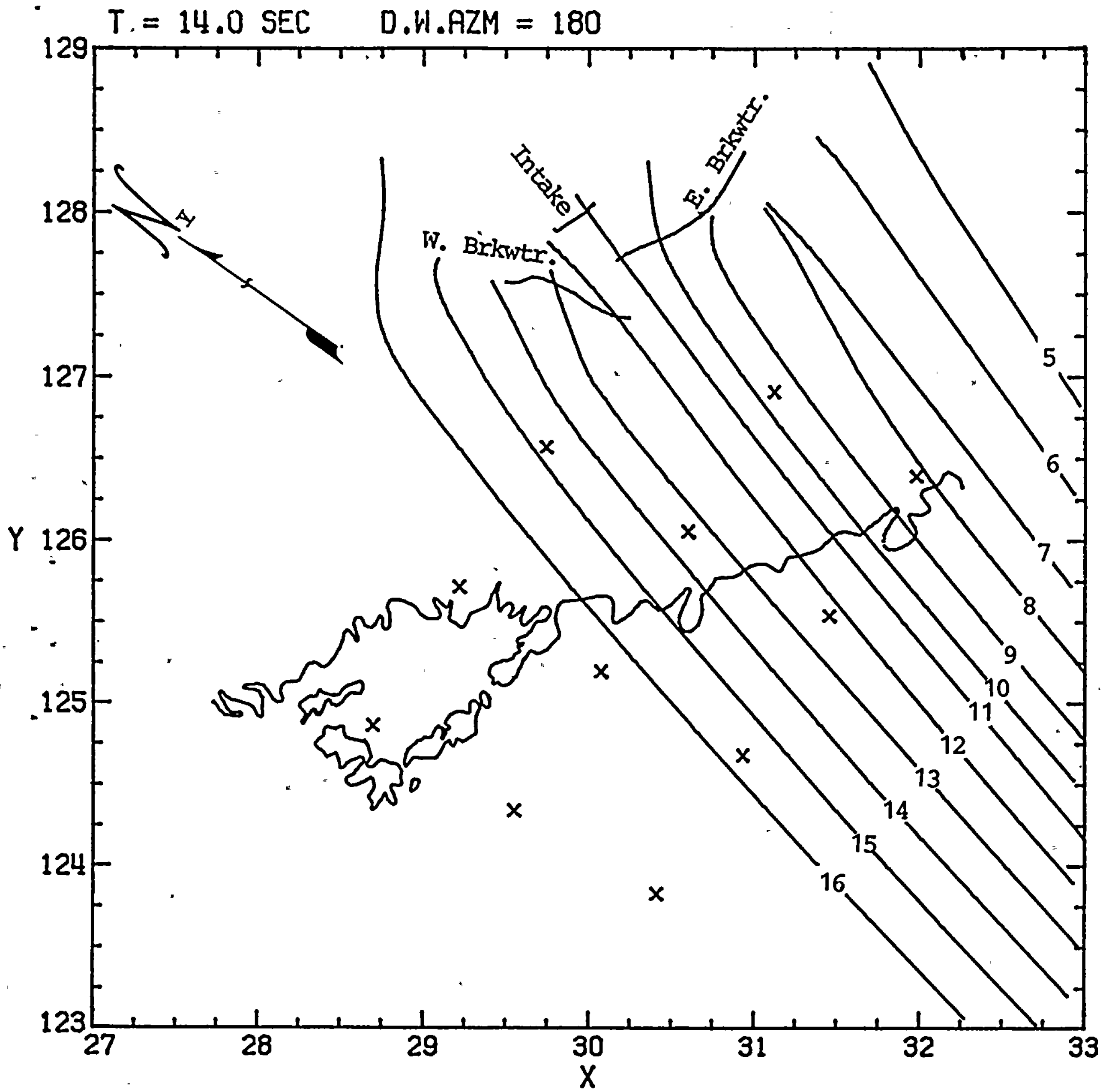
Columns 6 and 16 show, in degrees times 10, the obliquity of wave incidence with the contours being crossed.

Columns 7 and 17 are Shoaling Factors, the relative changed wave height due only to changed depth.

Columns 8 and 18 display KRI, the wave height at the calculation point due only to refraction, expressed as a fraction of the height in deep water before the effects of refraction, as determined along each ray for each incremental advance of that single ray.

Columns 9 and 19 display the combined effects of shoaling and refraction along Rays 6 and 7 that a deep water wave of unit height would display at the location represented by each line of the table. The values are the product of Shoaling Factor times KRI, i.e., Column 7 times Column 8 for Ray Number 6 and Column 17 times Column 18 for Ray Number 7.

Column 10 is derived from the spread or convergence, at each accumulated time value, of Rays 6 and 7. It is the usually calculated Coefficient of Refraction and gives the average height of the refracted wave between two adjoining rays if the deep water wave height were unity. If there have not been important localized terrain influences along the individual rays, to affect wave heights along a narrow path of advance, one can expect a fairly smooth variation of refraction coefficient from $KRI_{Ray\ 6}$ to KR to $KRI_{Ray\ 7}$. If in any case the variation appears to be less than systematic, one examines the terrain features that have been crossed to assess what effects they may have had and judgements can be made to gain sensible appreciation of wave conditions along the route of rays that are under study.



FEET x 10^{-3}

Figure 8 REFRACTION OF 16 SECOND WAVES FROM SOUTH
(Deep Water Ray Spacing Of 200 Feet)

The information compiled for the tabular display also is used to plot graphic displays. Selectively, the diagrams can plot the path of any wave ray all the way from deep water to shoal water near the shoreline, or the plots can be limited to specific areas of interest as required. Figure 8 is an example of the latter type of display. It shows twelve refracted rays during the last mile of advance toward Diablo Canyon Intake Basin. In this example the 100 feet depth contour and the two breakwaters and the face of the Intake Structure have been added to aid visualizing the local effects of the waves, but the rays are plotted as if the breakwaters were not present. The wave rays were uniformly spaced 200 feet apart in deep water and the plots show how much each pair of rays has diverged or converged. The ratio of their spacing at deep water to the spacing at any shallow location is the Refraction Coefficient tabulated by Column 10 of Figure 7.

CHAPTER II

THE PHYSICAL MODEL: CONSTRUCTION, INSTRUMENTATION, OPERATION

Creating The "Relief Map"

A model of the Diablo Canyon Sea Water Intake Structure and of hypothetically damaged breakwaters was constructed in the outdoor test basin. It is 120 feet long by 80 feet wide, with walls 4 feet high. At a model scale of 1:45 this represents an area 3600 feet by 5400 feet, 446 acres. The walls of the basin were assigned North-South and East-West map limits bounded by California Zone V grid coordinates N 630,400 feet, N 634,000 feet, E 1,143,000 feet; and E 1,148,400 feet.

Figure 9 is a contour map that illustrates the complex sea floor topography that then was modeled in the basin. Its borders represent the walls surrounding the model basin. The model was constructed so as to represent all apparent features above the contour at 100 feet below Mean Lower Low Water Datum. The detail of the contours shown in Figure 9 suggests the density of the field surveying done at Diablo Canyon Site. The parts of the map modelled West and South of West Breakwater were done in Spring 1981.

The areas closest to West Breakwater were sounded more densely than elsewhere, to permit mapping at 1:240 (1" = 20'). The balance of the area was mapped at 1:1200 (1" = 100'). Contours were interpolated and drawn for each 2 feet change in elevation, from digital values of soundings recorded during the field surveys. The resulting maps at those two scales were enlarged 5.33 times and 26.67 times, respectively,

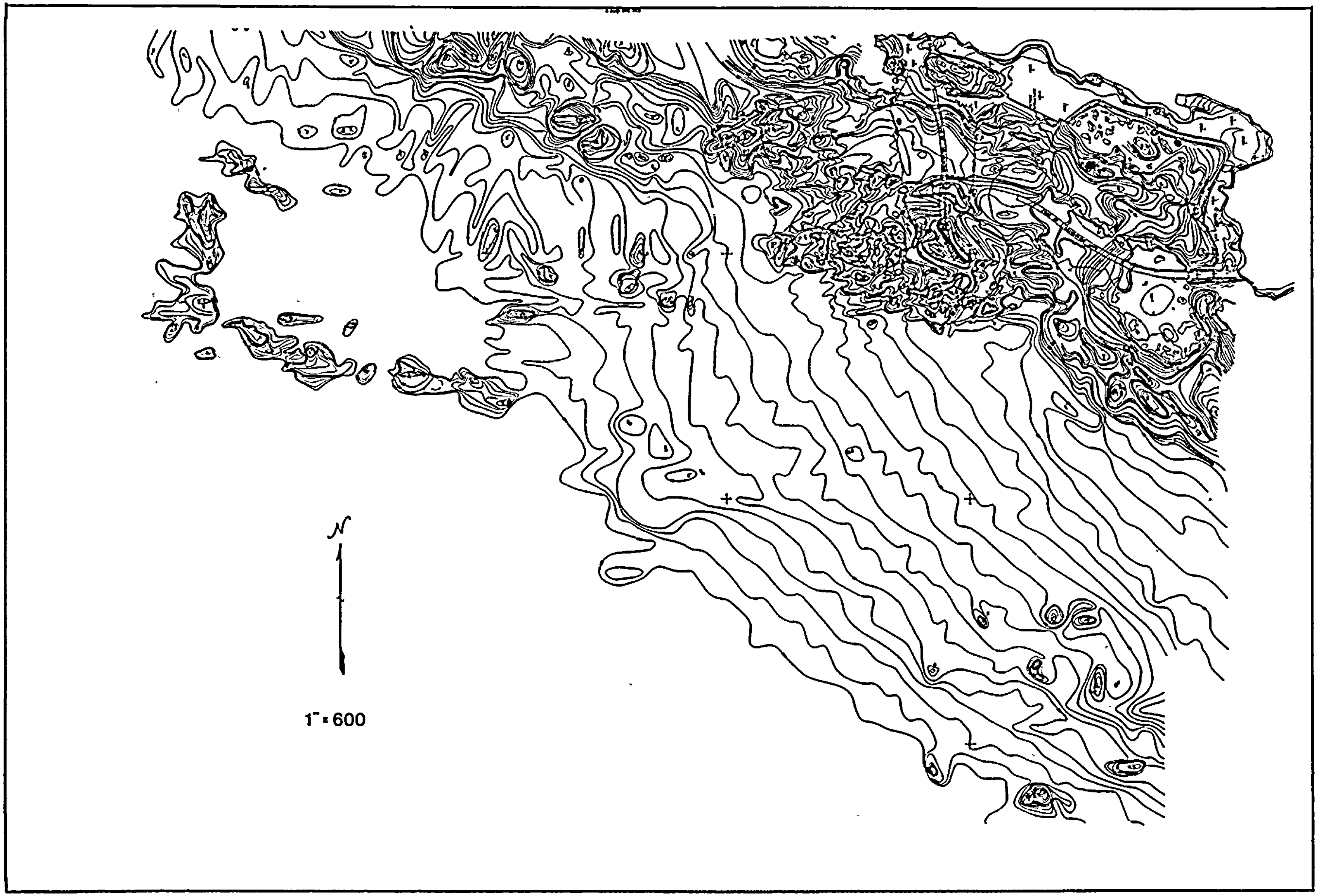


Figure 9 BASIN BOUNDARIES AND TERRAIN MODEL CONTOURS

to attain map sheets at the adopted scale for the model, 1:45 or 1" = 3.75'. The enlargements were printed in sections on a heavy photographic paper. Each of these 4' x 4.5' separate scale-controlled sheets depicted an area in nature 150 by 200 feet. The sheets were placed on the floor of the model basin in a carefully fitted mosaic, under direction of a licensed surveyor, and were firmly glued to the floor. The use of these map sheets is shown in Figure 10. With the contours delineated by the map being thus "drawn" to scale on the basin floor, a detailed guide was available for molding the model terrain.

The approach for reproducing the "relief map" to scale in the model was first to follow each of the contour lines with a 16 gage galvanized ribbon, bent to follow the shape of the contour. The ribbons were fixed in place by spot welding to small angle iron clips that had first been anchored to the concrete floor with nails driven by a 22-caliber cartridge stud driver. Figure 11 shows close-up details of the shaping of the ribbons and the method of anchoring. The upper edge of each contour ribbon was set to its appropriate elevation at each of the anchoring clips, which were typically spaced 4 to 6 inches apart along the contour length. Optical levels were used in standard surveyor procedures to confirm that the elevation of each ribbon's upper edge was accurately represented. If any was found to be more than .005 feet different than the desired contour elevation it was corrected. This corresponds to a tolerance in prototype elevation of 2.7 inches or less. Horizontal accuracy in the model was controlled by survey methods to within a quarter of an inch, which is to say less than 1 foot in full scale. The ribbons were not welded to the clip angles until the surveyor concluded they were clamped to the angles with the intended elevation

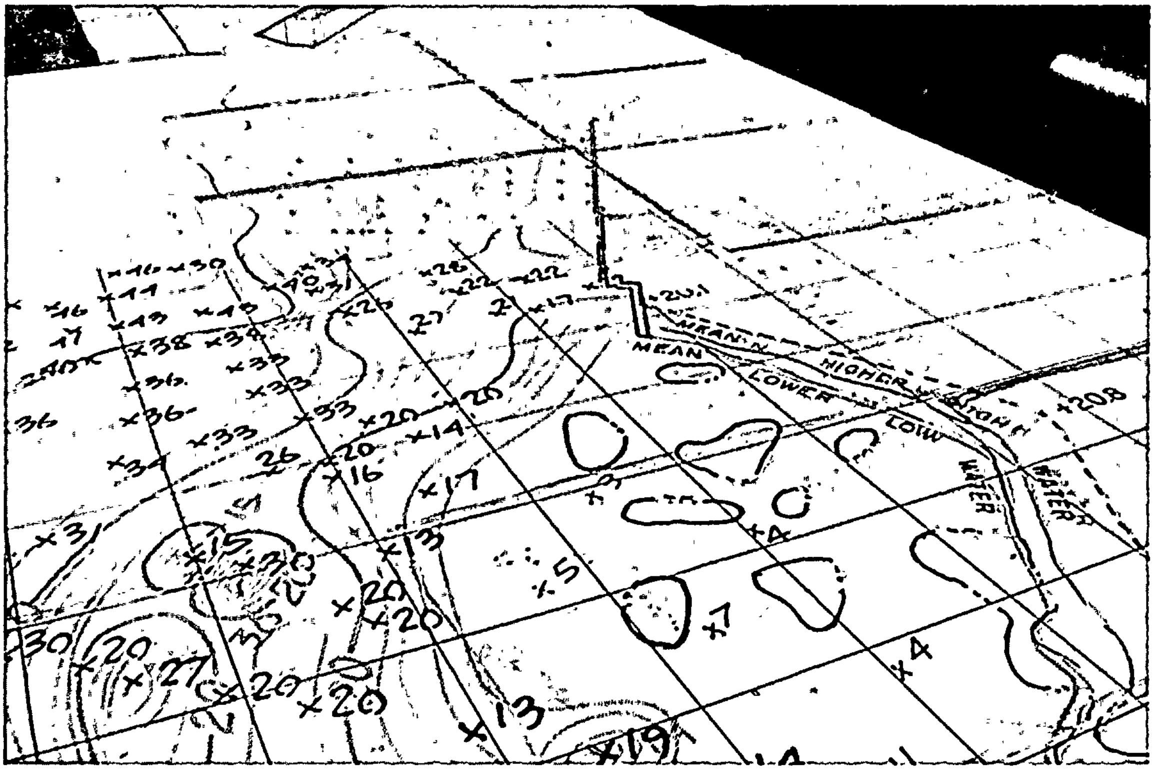


Figure 10 Floor of Model Basin with Map Sheets in Place

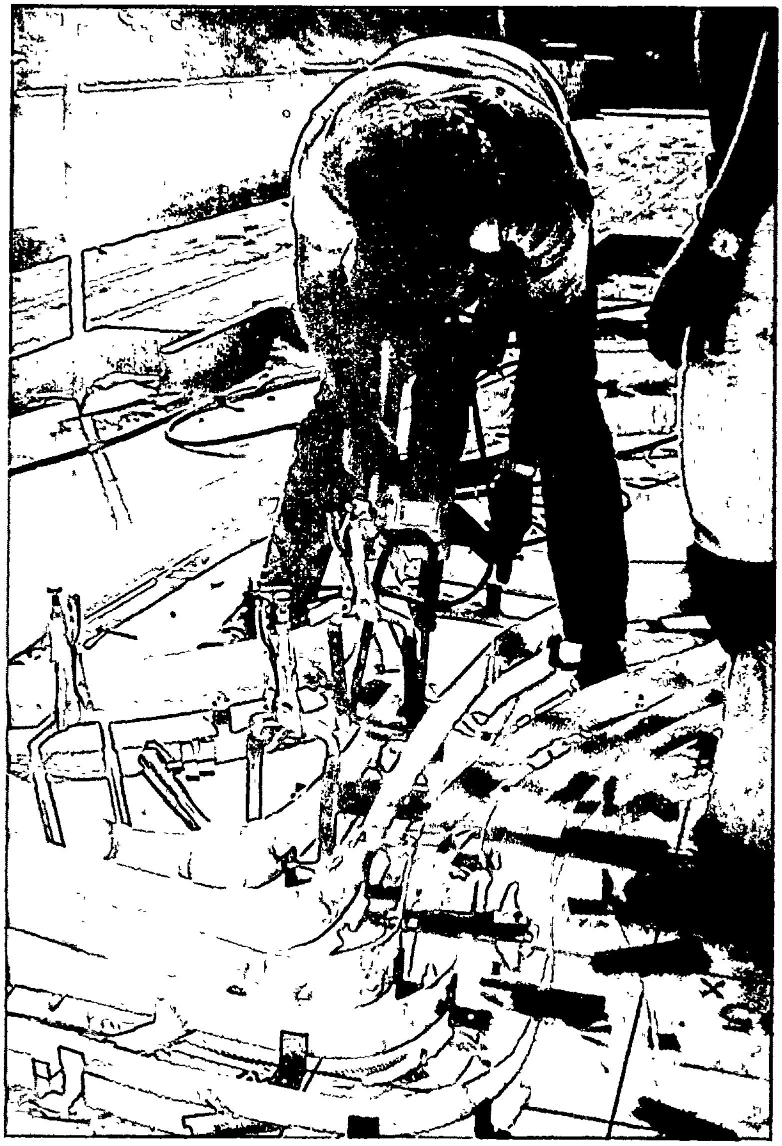


Figure 11 Spot Welding Clamped Contour Ribbons

and position. Where the contour lines became so closely spaced as to leave no room for the angle iron clips, the use of ribbons became impractical. In such locations 10 inch long eaves gutter spikes were used like grade stakes. They were driven along each contour line on nominal spacings of 2 inches or less. These "stakes" were individually surveyed for correct height. Figure 12 illustrates the techniques of ribbons and stakes used to form the three dimensional shapes and shows the detail involved in constructing the required terrain forms. Once the ribbons and stakes were installed, the model was filled with sand to about 2 inches below the ribbon edges. Then a sand/cement mixture was spread to fill that 2 inches and was trowelled to produce the finished three dimensional terrain. Figure 13 shows the finished molding of some of the same terrain features that are in the area viewed by Figure 12. By utilizing this contour ribbon approach, rather than relying on the more traditional straight profile-line templates, greater and more faithful detail could be achieved in the model than could otherwise have been accomplished with such contorted terrain.

The Intake Structure

A 1:45 scaled model of the wave influencing elements of the Sea Water Intake Structure was also built and was installed in the test basin. As shown in Figure 14, all below-deck compartments in the first 38 feet and apertures between those compartments and through the structure's upper deck, were modeled. Beyond the 38 foot distance there are no openings through the deck. Except for the front parapet wall, the above-deck region seaward of the huts was left flush. The control building behind the huts was included in the model, for its effect on the movement of water from waves that passes across the Intake Structure.

Figure 12 NORTHEASTERLY AREA OF MODEL BEFORE FILLING WITH SAND AND MORTAR
Intake Structure Model at Upper Right, Ready for Lowering Into Position.

Figure 13 Part of Finished Terrain Model Viewed Along Axis of West Breakwater

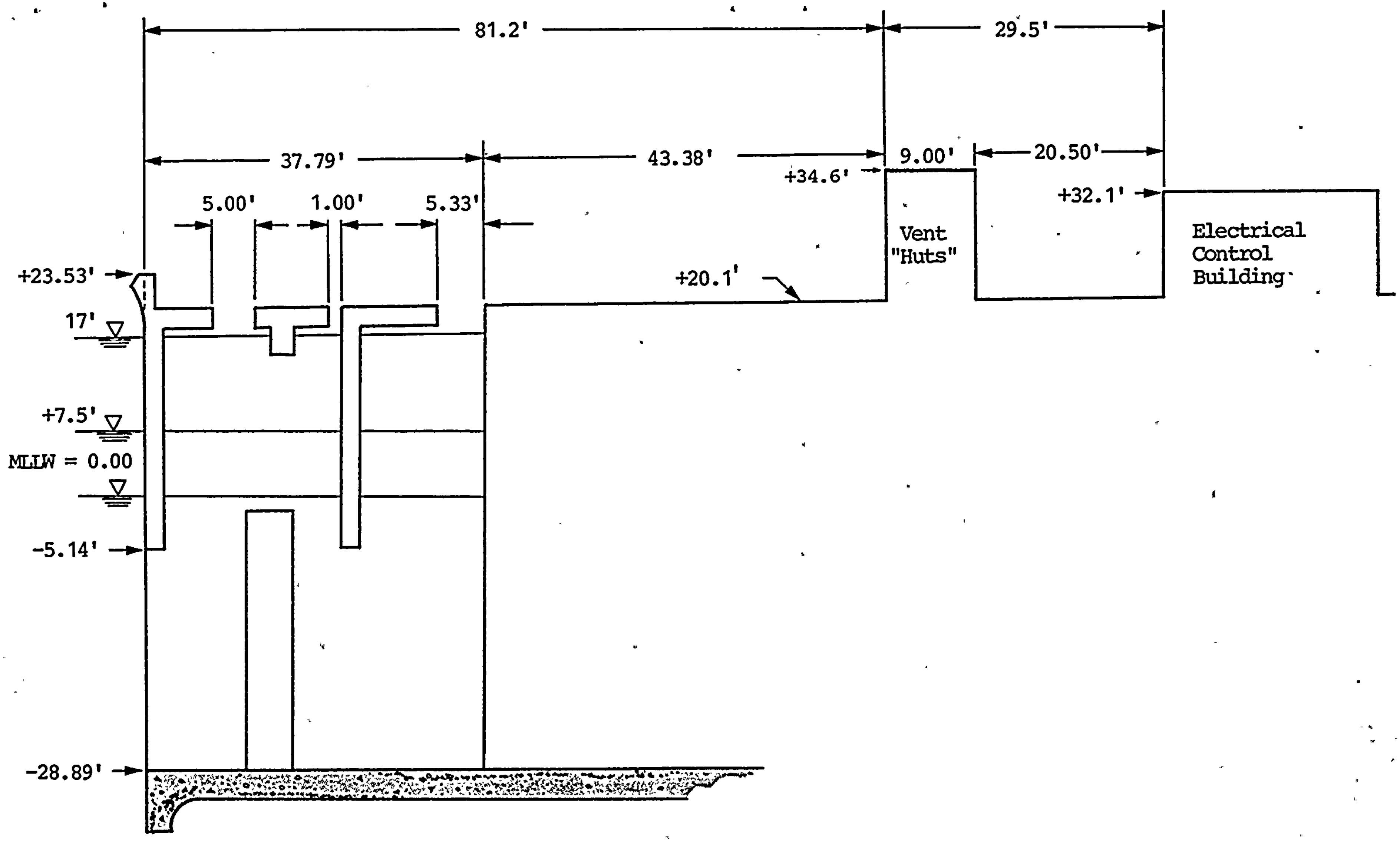


Figure 14

CROSS-SECTION OF INTAKE STRUCTURE MODEL
(All Elevations Refer to Mean Lower Low Water Datum)

The ventilation huts were isolated structurally from the rest of the intake model and were fitted with instruments installed to sense and record any forces and point of application of forces against the huts due to the moving water. Above each of the huts vertical twin cylindrical extensions, referred to as "snorkels", were built to permit ventilating air to be taken from higher elevations. The snorkels in the model were totally separated from the huts so that the huts and snorkels were free to move relative to each other. Thus, any loads sustained by the snorkels were independently sensed and measured, in the same fashion as the hut loads were independently sensed and measured. Details of modeling these snorkels are shown in Figure 15.

The Levelled Breakwaters

A major phase of investigation during the test program was to establish, with a hypothetical case of damaged breakwaters, the extent to which waves overtop the Sea Water Intake Structure and wash against the ventilation huts and splash upward at the snorkels. For the hypothetical case the condition of the breakwater was assumed to be the cumulative affect of a seismic event which would consolidate the breakwaters and also cause them to slump, and to a succession of severe wave storms that would remove all of the breakwater materials that originally were in place above the zero tide level and deposit them against the basinward slopes. The central core and the seaward portions of the sub-armor and of the armored zones of both breakwaters were built from the sea floor up to elevation zero in the manner of the original design. Carefully scaled materials, both in size and in shape were used. The levelled mounds were completed to a broadened trapezoidal shape by adding sufficient amounts of core material of armor sub-layer stones (B

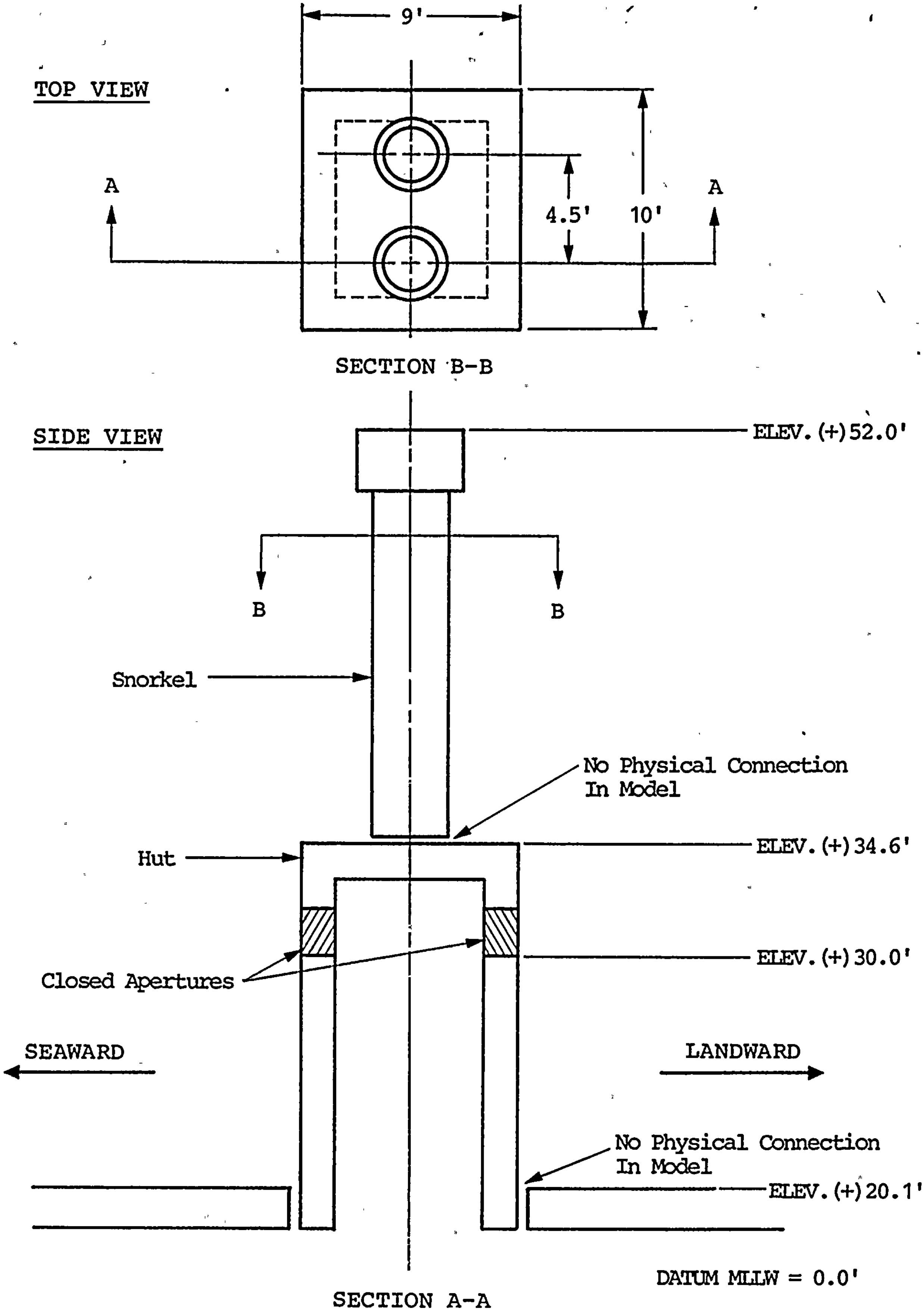


Figure 15 SCHEMATIC PLAN AND SECTION OF AIR INTAKE STACKS (HUTS) AND SNORKELS

and E rock) and of broken armor elements to the basin side of the breakwaters, so that the resultant cross-sectional area would be the same in the levelled condition as it had been in the original undamaged geometry. Cross-sections of this hypothetical levelled condition are illustrated by Figure 16. Since it was the objective of the tests to observe the influence of the terrain and of this levelled cross-section on the waves at that stage of damage, rather than the effect of waves on the cross-section, a coarse netting was placed over the breakwaters to hold the test configuration through the duration of the data taking.

Generation Of Waves

Generation of waves in the model basin was done with a wave machine which operates on a swinging parallelogram principle, producing waves by nearly a piston type of motion. The articulation of the wavemaker is shown in Figure 17. The wavemaker blade is moved back and forth in the water by reciprocating hydraulic rams that respond to variable voltage signals for control of blade movement, both rate of motion and amplitude of stroke. The available ram stroke is 18 inches. The complete wavemaker is an assembly of modules, each designed to be movable about the basin so that waves may be directed on the model from various angles. In the present tests five modular units were joined to make up the wavemaker. Each unit is 11 feet in length and can be individually driven. However, all five were driven synchronously, as if one moving wall, to produce waves of long continuous crests.

The motion of the wavemaker blade is always started and stopped from the fully retracted position, where the wave trough occurs and at which time the horizontal velocity of the blade is zero. This produces smooth starts and stops, by avoiding an instantaneous mismatch, between

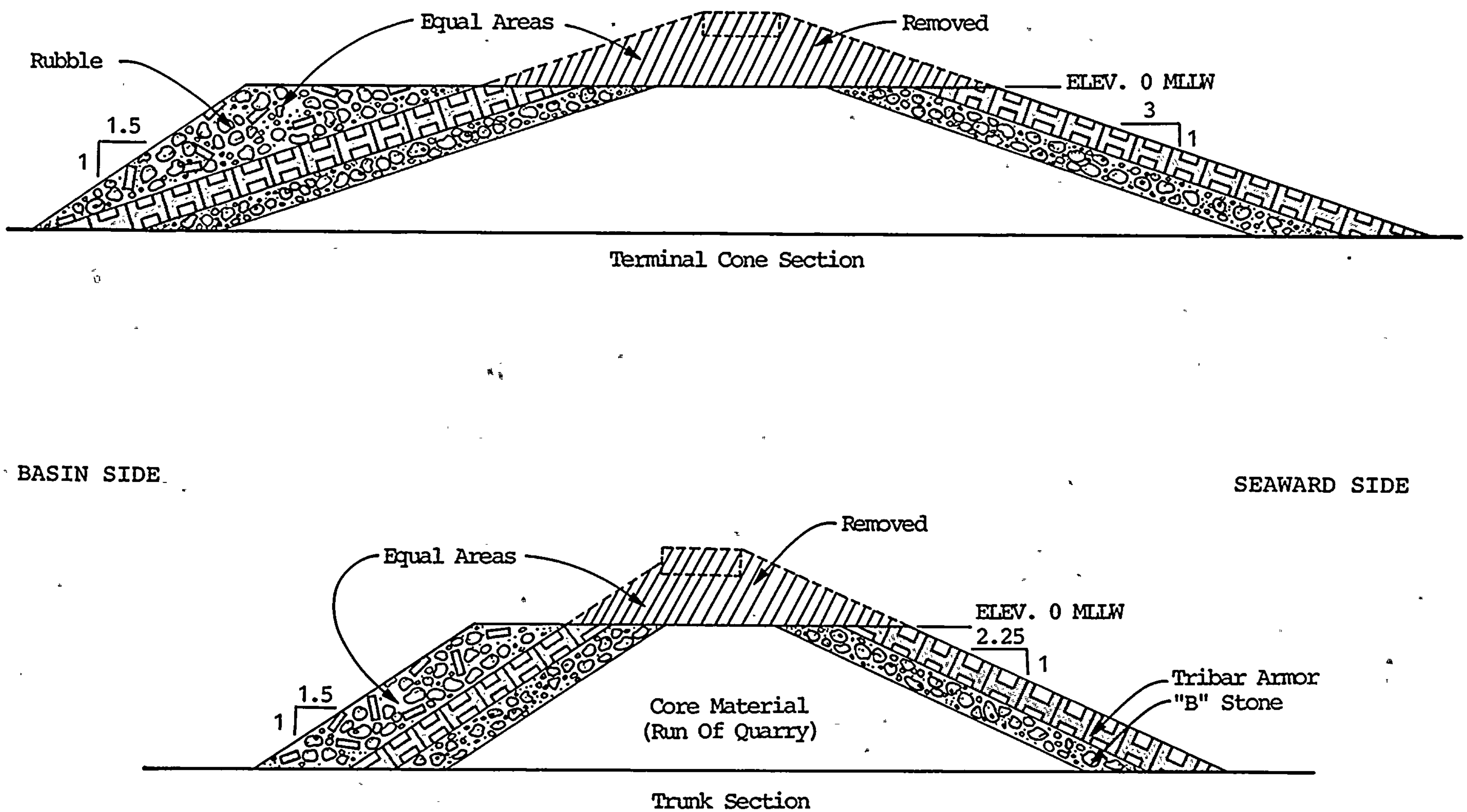


Figure 16 TYPICAL MODEL CROSS-SECTIONS OF BREAKWATERS HYPOTHETICALLY LEVELLED TO ZERO CREST ELEVATIONS

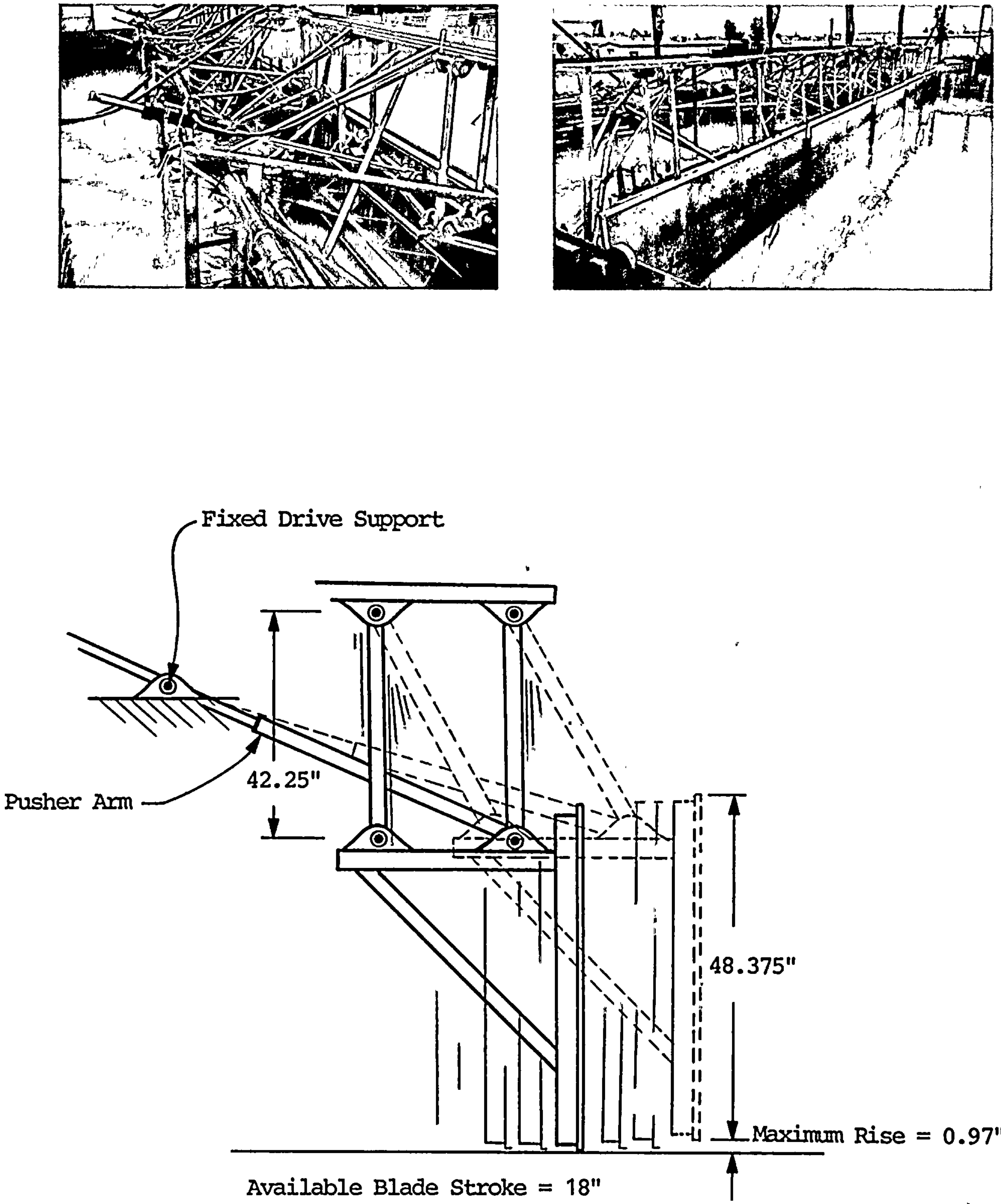
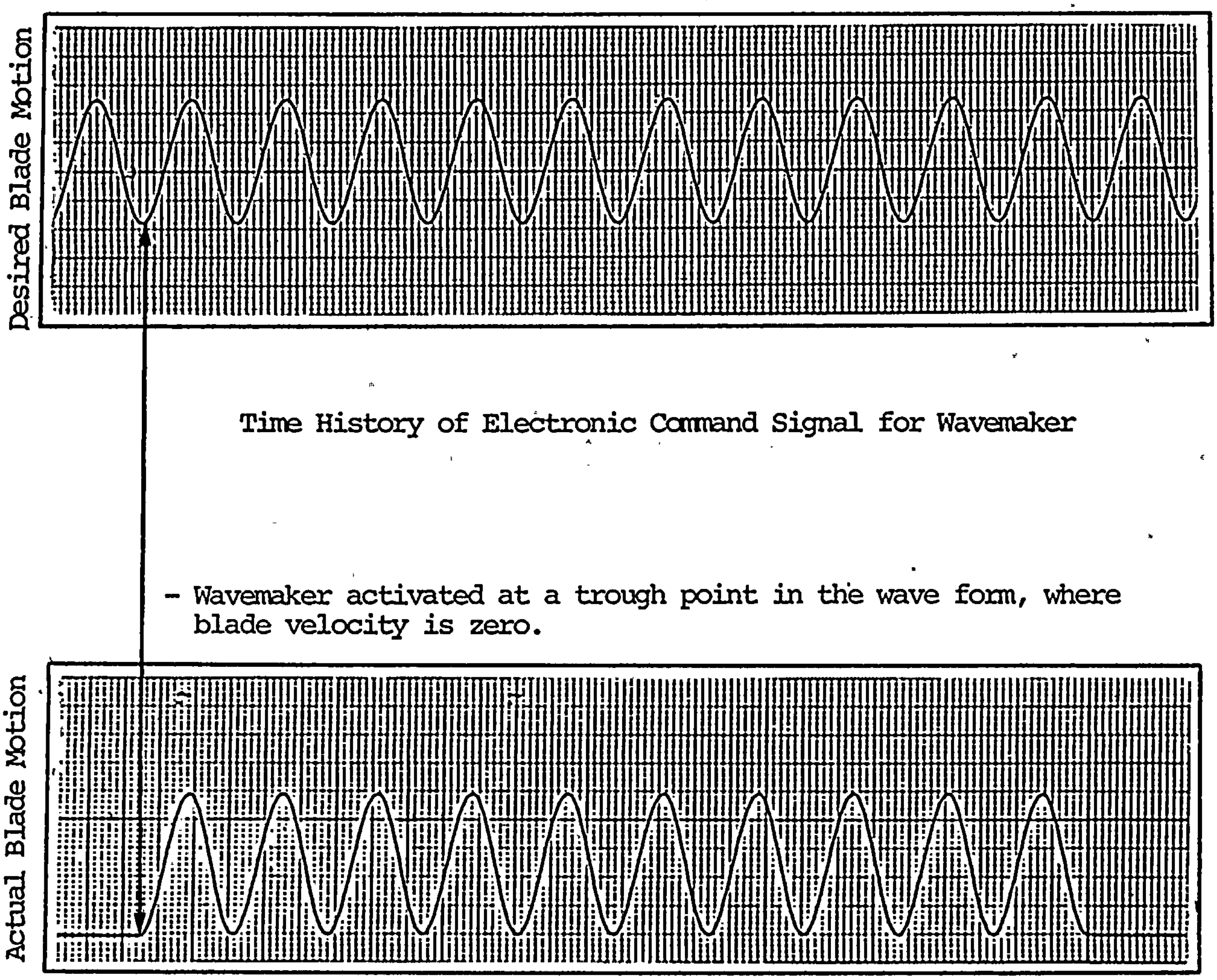


Figure 17 Swinging Parallelogram Piston Wavemaker

the zero start-up velocity of the wavemaker and a non-zero blade trajectory requirement at that moment which could cause the blade to lurch. Perhaps more important to the testing, this quite effectively avoids the transient form waves that usually lead and terminate model wave trains at the start and at the end of an experiment. Those transients often distort model results. Figure 18 shows an example of the wavemaker being activated at a trough point in the blade displacement control signal. The resulting clean form of the initial wave in the train is apparent in Figure 18.

Wave guides were extended from each end of the composite 55 feet long wavemaker, aligned perpendicular to the blade in the initial direction of wave motion to prevent "spilling" of wave energy laterally from the ends of the waves as they moved toward the areas of interest in the model. The guides are an assembly of vertically adjustable boards which can be independently shifted up or down to conform to terrain features along the length of the guide.

Movable wave absorbers were placed along some of the side walls of the basin and in areas where inappropriate side reflections of the waves could develop. The absorbers are wooden cribs containing stainless steel shavings, a machine shop waste. The curled shavings tend to act as giant springs, dissipating much of the unwanted wave motion that otherwise would be reflected. Wave reflection from the model coast and from structures is allowed to occur undamped, as it does in nature. However, once these reflected waves travel back to the wavemaker and are recombined with newly generated waves, the resultant combination of newly generated waves and re-reflected waves greatly complicates analysis. Therefore testing is usually done in bursts of waves that continue only



Time History of Wavemaker Blade Motion

Figure 1-8 Synchronization of Wavemaker Control Signal with Zero Velocity Position of Blade

long enough to avoid re-reflections from the wavemaker. Typically this represents a set of fourteen waves.

Instrumentation

Instrumentation for the model consisted of:

1) A field of sixteen wave probes that sense water level;

2) Load cells and bending moment gages to monitor wave or runup forces sustained by the air intake huts and their snorkels;

3) Visual recordings, which included making of videotapes, high speed 16 mm movies and 35 mm still photography.

The wave probes that were used are a capacitance type, capable of measuring changes in water surface displacement of up to 24 inches in model scale, i.e., 90 feet in nature. As the water level shifts at the probe, a change in the electrical capacitance of the probe is sensed. By calibrations the capacitance is converted into the change in water surface elevation. The sixteen probes were deployed in the model basin at various selected locations, mounted on adjustable tripod stands to facilitate placement in various water depths. The legs of the tripods were made of 3/4 inch all-thread rod, causing minimal disruption to the passing wave motion while still providing complete flexibility in locating the wave probe over any sort of rough bottom topography. To relate wave probe signals to the change in water level, the probes are calibrated remotely by driving the probe up and down in the water, triggering a micro-switch at one inch increments of movement of the probe. The capacitance reading of the probe and the trigger signal are sensed by a Tektronix 4052 computer. A calibration relationship is automatically

computed for each wave probe. An example of the linearity of the calibration is shown in Figure 19. Each of the wave probes is sampled by the computer during testing at a rate of 10 Hz. The sampled record is then stored on floppy disk in digital format and a hard copy time history of the water surface elevation at each probe location can be printed immediately, or at any later time, from the disk.

Runup loads on the air intake huts and snorkels were measured by utilizing I-beam style load cells installed inside the hut structures. Separate load cells were mounted to sense force components perpendicular to each face of each hut, representing the onshore (x) and the longshore (y) components of loading. Bending moment gages were linked to the load cells to measure bending moments, also in the same component directions. The acquired information was resolved to give resultant force values and resultant directions of forces against each hut. From the recorded and resolved forces, and the separately recorded moment values, the points of application of the resultants also are determined. The load cells are statically calibrated in 1 ounce increments, model scale, from zero to 32 ounces, the equivalent of zero to 91 tons at full scale. As is demonstrated in Figures 20 and 21, the load cells are also strongly linear in this range. The analog output of the load cells was monitored on a high speed oscillograph, in order to detect any peak loadings of impulse type which might be sustained by the structure. The dynamic response of the load cells was examined to determine if their sensitivity was sufficient so that typical impact loads would be sensed. The dynamic response of the load cells to an impulsively applied test load showed that measured forces sensed by using these load cells are at least as great as the actual applied force. It is probable that the reported measured force in some cases is larger than the actual applied force.

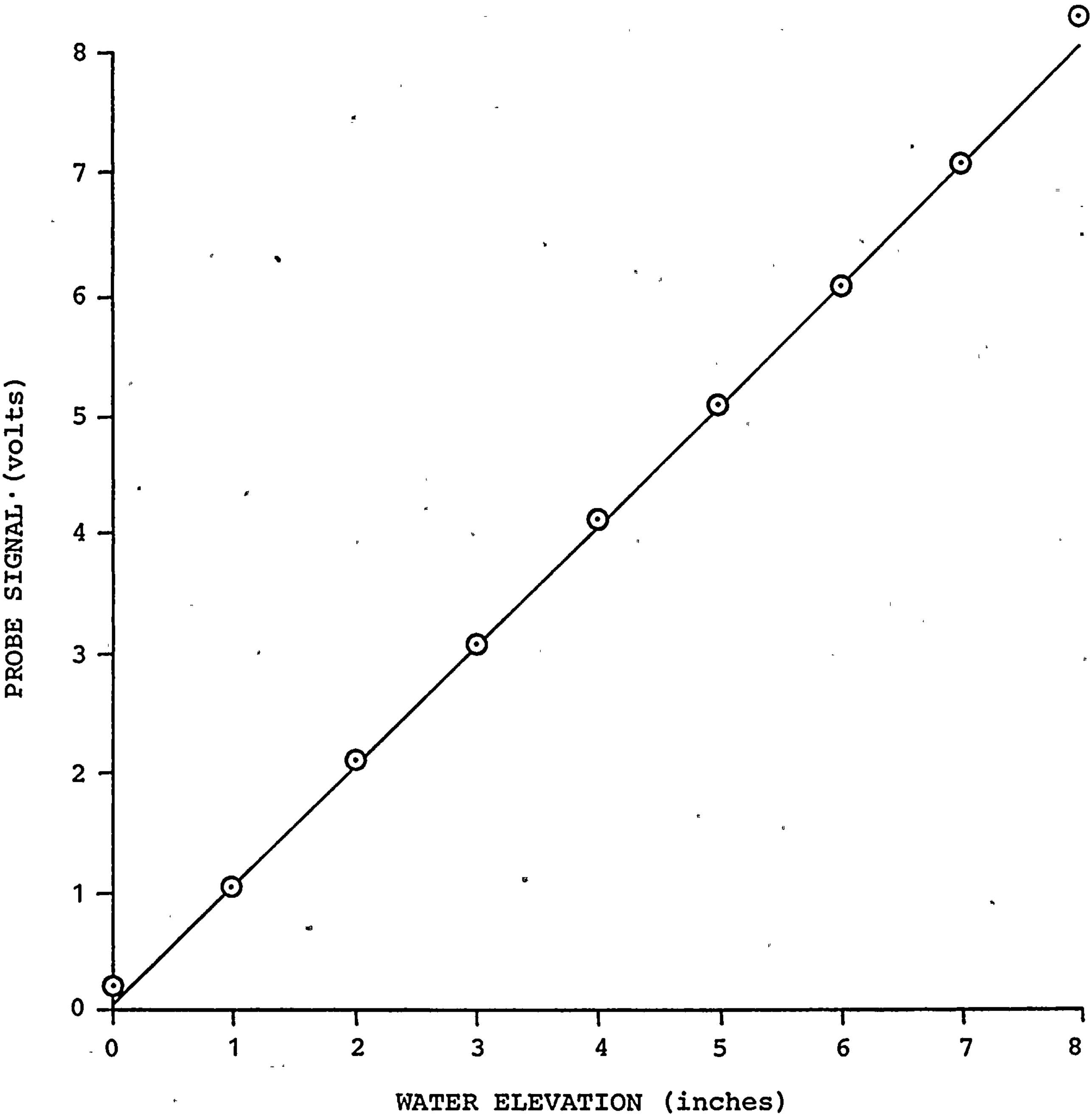


Figure 19 LINEAR CALIBRATION EXAMPLE
Capacitance Wave Probes

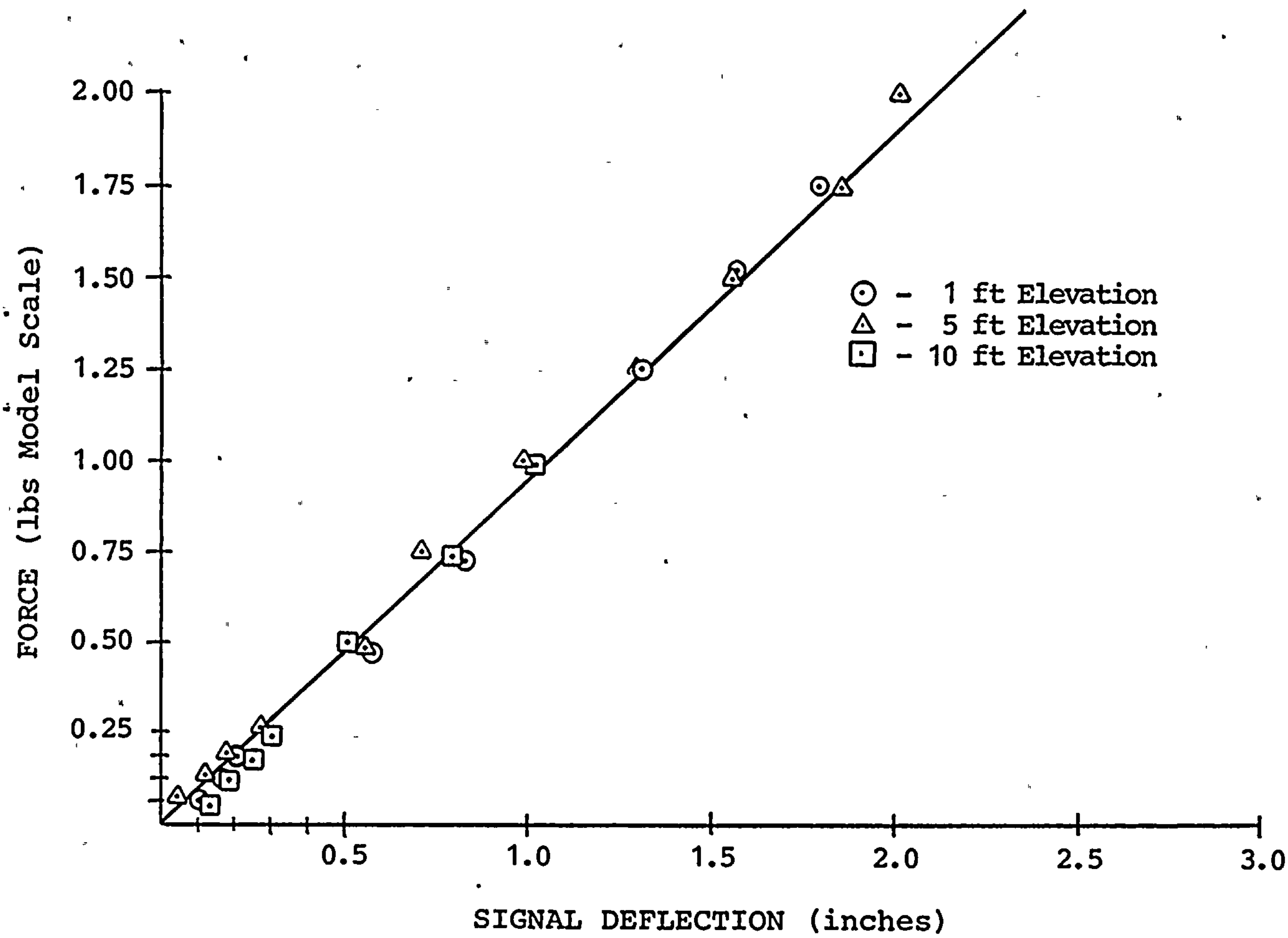


Figure 20 LINEAR CALIBRATION EXAMPLE
I-Beam Type Load Cells

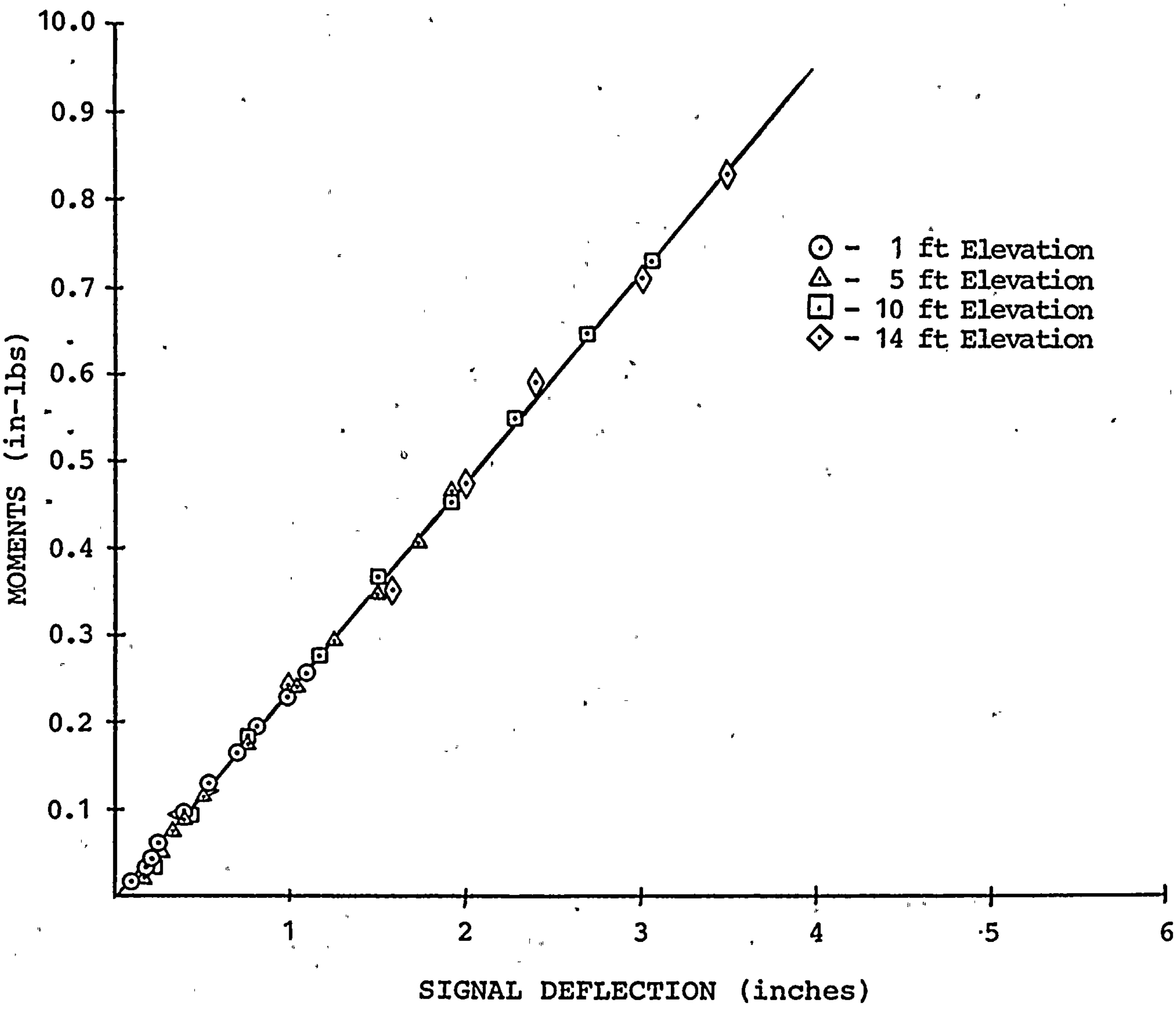


Figure 21 LINEAR CALIBRATION EXAMPLE
Bending Moment Gage

Therefore, the reported forces are conservative statements of the actual applied loads.

Visual Records

Photographic records of the wave transformations in the basin and of their impingements on the Intake Structure played an important role in the data taking. Three video cameras, a high speed motion picture camera and still photography were employed in various configurations at one time or another to document the tests.

Video cameras were used to monitor runup behavior on the air intake huts, and for observation of wave diffraction/refraction patterns as the waves moved across changing depths toward the Intake. The diffraction recordings were accomplished by suspending a video camera 70 feet in the air above the tank. Runup on the air intake huts was observed by utilizing two video cameras aimed slightly obliquely toward opposite sides of the two huts. That permits a clear view of the side face of the nearest hut and the back faces of both huts in one view and the opposite side face and the front faces in the other. The two views can be displayed separately on a video monitor or in split-screen form on the one monitor so that the runup and overtopping of the structures can be seen on each side of each hut simultaneously. The monitor image can also be switched to the overhead video camera, to observe behavior in the basin at any time during progress of a test. The various images on the monitor were recorded on videotape for play back and review.

When working with models which involve phenomena responding to gravity, such as waves, physical behavior follows Froude Number scaling. In this type of modelling, the time scale is the square root of the model's linear scale. With a model scale of 1:45, motion in the model

occurs 6.71 times faster than at full size. Many details of wave motion, and associated phenomena, happen so quickly in the model that it becomes useful to photograph them at selected times with a high speed camera. When such high speed photography is projected at standard rates, the behavior of the model is seen at a more familiar speed. In these tests, high speed photography was shot at 128 frames per second. When projected at 24 frames per second the action appears to occur at a speed of only 1.26 times the speed in nature at full size, rather than at 6.71 times as fast as real time for the prototype. This proved to be of great value in appreciating the effect of wave action at the intake site. The high speed movie camera was used to photograph overall wave behavior in a wide field of view on the model. These shots, taken from eye level, provided a record of the transformation process of the waves as they would refract over the rough bottom topography and impact three dimensionally on the structure. Both the high speed film and the video were supplemented by 35 mm photographs taken both overhead and at model level.

CHAPTER III

TEST PROCEDURES

Configurations Of Test Conditions

Two basic conditions were investigated in the model: A condition without the breakwaters constructed and one with the breakwaters constructed but with crests levelled to the elevation of Mean Lower Low Water. The latter is referred to as the levelled breakwaters condition. For the case without the breakwaters only a few data are presented, later in this report, in explanation of bases for choices of wave attack directions. The measurements with the levelled breakwaters condition will be presented and discussed in detail.

Experiments were conducted at two different water levels in the model basin: First, at a level with the maximum astronomical tide of 7.5 feet above Mean Lower Low Water, and second with a level 17 feet above Mean Lower Low Water, derived by adding to the 7.5 feet astronomical tide a 1 foot meteorological surge and an 8.5 feet tsunami. For both these water level stages the model was exposed to periodic waves with various heights at each of several wave periods and for several wave directions. Layouts of the wavemaker and the guide walls in the model basin are presented in Figures 22 and 23. They show the orientation of the wave machines located in the areas where the basin floor is at a depth of 100 feet below Mean Lower Low Water Datum and is not molded to represent terrain. Figure 22 is the layout for waves approaching from South in deep water (180 degrees Azimuth) and Figure 23 shows it for waves from West in deep water (270 degrees Azimuth).

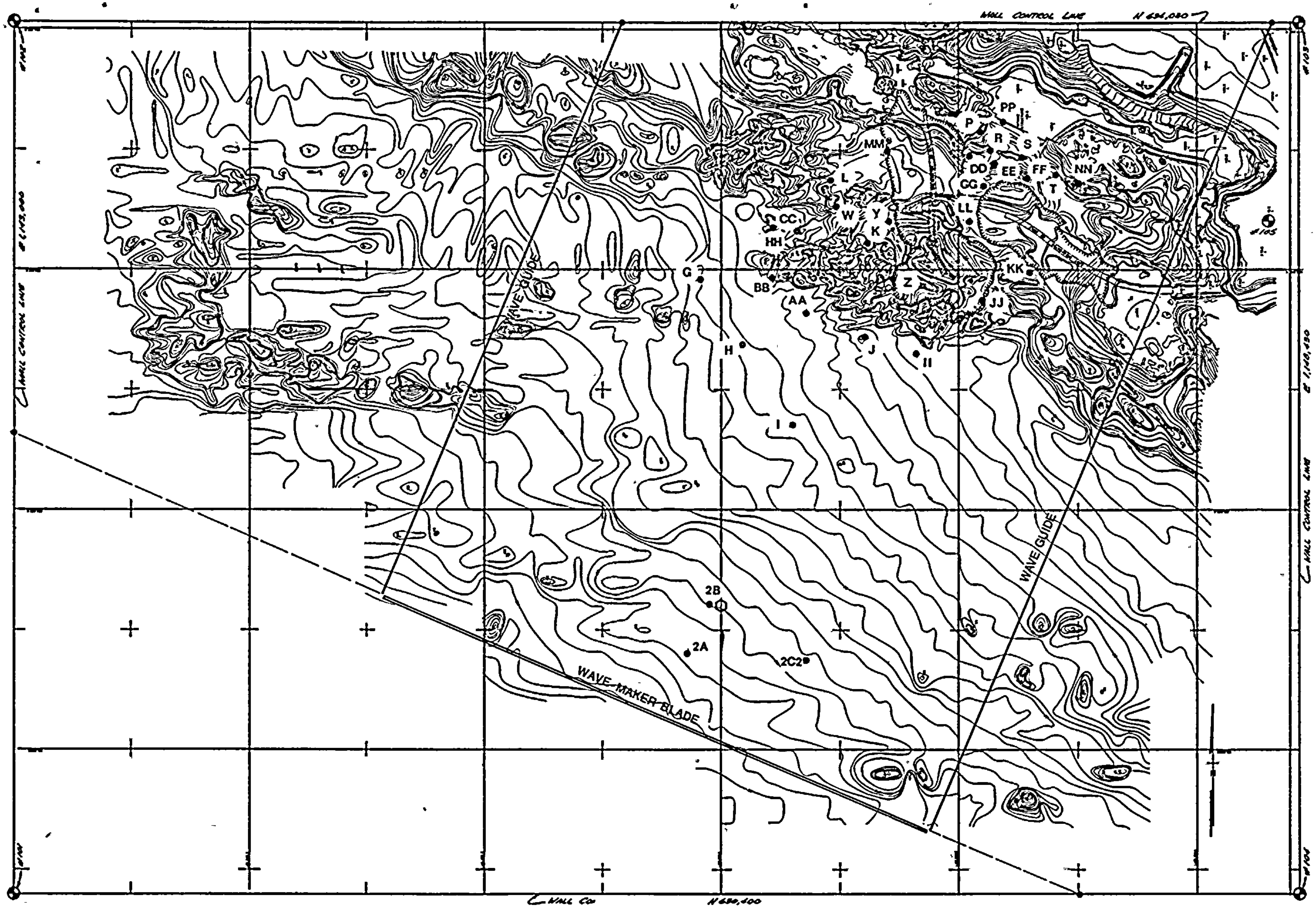


Figure 22 WAVEMAKER PLACEMENT IN THE BASIN AND LOCATION FOR PROBES, WAVES FROM SOUTH

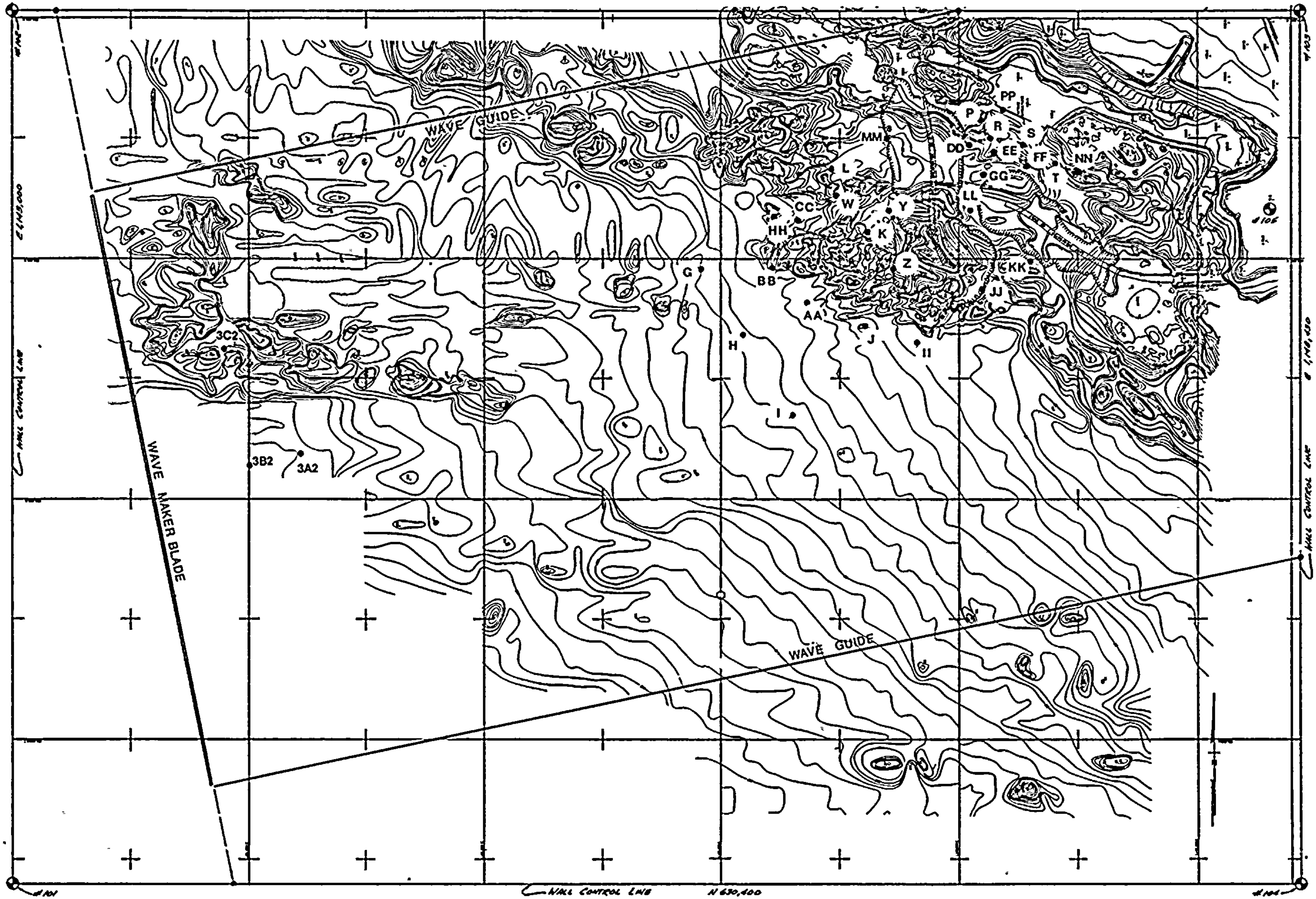


Figure 23 WAVEMAKER PLACEMENT IN THE BASIN AND LOCATION FOR PROBES, WAVES FROM WEST

As can be seen in Figures 22 and 23, this left room in the constant depth areas of the model basin for flexibility in arranging the wave machines, to allow them to be oriented in desired directions. Figures 22 and 23 also show the locations, marked by lettered disks, where wave gages were placed. Prototype coordinates for each location were determined by the surveyor and recorded for future reference. Each location was paint marked on the floor of the model.

Orienting The Wave Machines

The orientations of the wave machines were selected with the help of refraction diagrams for waves from the deep water directions of interest. Refraction diagrams describe the change in direction of periodic waves due to variations in the depth and in the form of such variations. With change in depth there is change in wave speed. When such changes differ along the crest of an advancing wave it results in concentrating or in diminishing of wave energy at a given location. It is a refraction phenomenon analogous to lens effects on light. Since the change in direction is a function of wave speed, refraction is a function of wave period and of depth variation for waves. These are well described by a linear wave theory. For this study a numerical refraction program was used that is based on the work of Coudert and Raichlen*, which applies the numerical method for simultaneously solving the differential equation of wave ray curvature and the equations which describe the coordinate transformations. Examples of graphical output for such calculations appear in Figures 24 and 25 which display, for the given wave directions and for equal spacing (or equal energy flux) between

* Coudert, J.F. and Raichlen, F., Discussion of: "Wave Refraction Near San Pedro Bay, California", JWWH, ASCE, August 1970

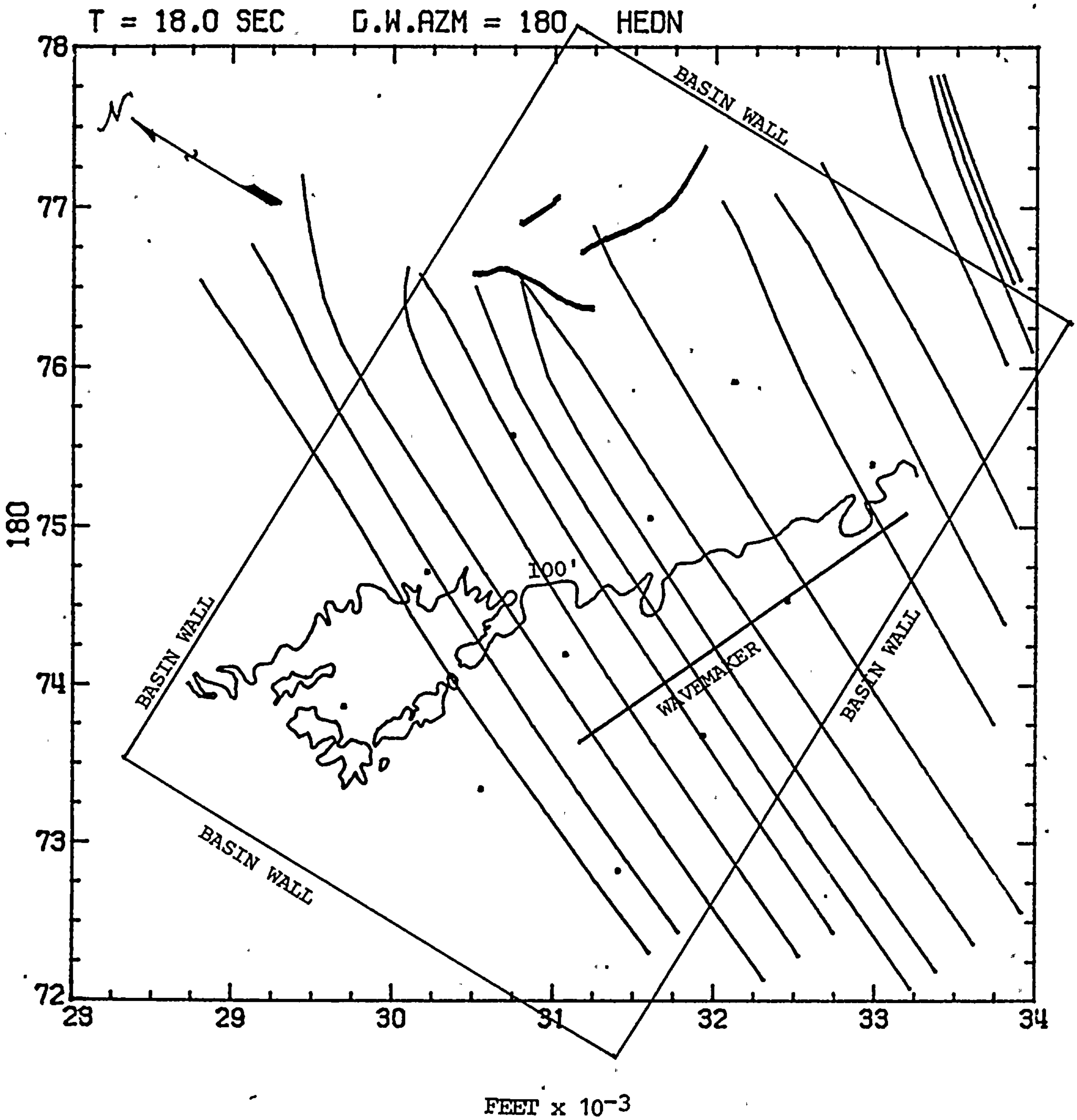


Figure 24 WAVEMAKER ALIGNMENT RELATIONSHIP TO REFRACTED DIRECTION OF 18 SECONDS WAVES FROM SOUTH

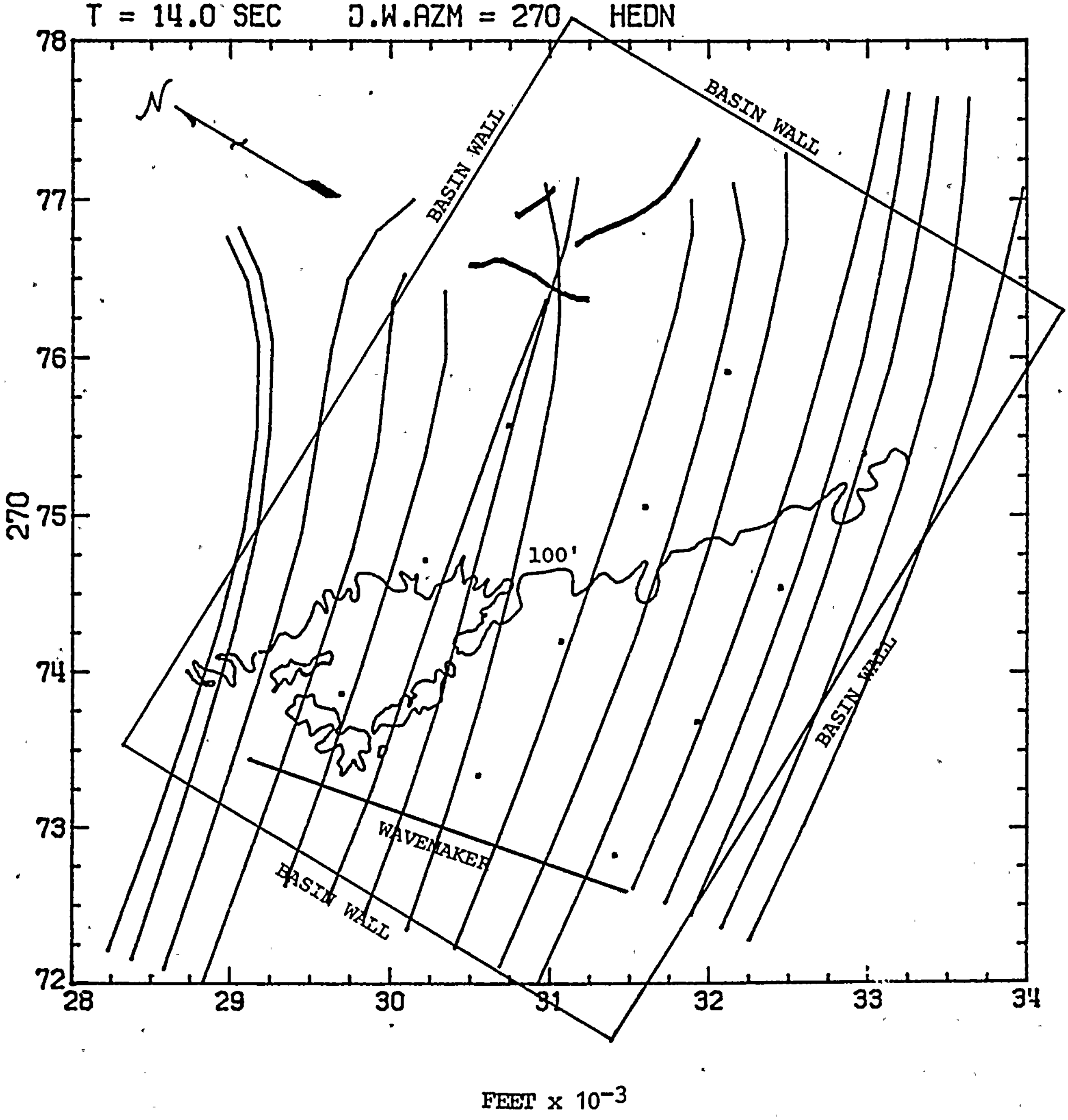


Figure 25 WAVEMAKER ALIGNMENT RELATIONSHIP TO REFRACTED DIRECTION OF 14 SECONDS WAVES FROM WEST

wave rays in deep water, where and how and in what degree there would be changes in those waves at shallow water locations. These diagrams also show the wave direction at the beginning of the molded contours in the model basin, thus providing the required information to locate the wave machines. In Figures 24 and 25, the refracted wave rays are shown for waves of two different periods and from two different original directions in deep water. An 18 seconds wave with a direction of 180 degrees (South), and a 14 seconds wave with a deep water direction of 270 degrees (West). With these wave rays plotted and the outline of the wave basin and the 100 feet contour superimposed on the map, the direction of the wave machine for the wave periods which are considered most important could be decided. In general, the wave machines were oriented so that the wave plate was perpendicular to the average directions of the rays at the 100 feet contour line for wave periods between 14 seconds and 18 seconds; the rays given most attention were those that proceeded toward the Cooling Water Intake. This approach was quite satisfactory and allowed the wave machines to be placed as far as possible from the 100 feet contour in the model, in the unmolded region of constant depth, and thus to allow for proper wave profile development.

Generating Of Cnoidal Waves

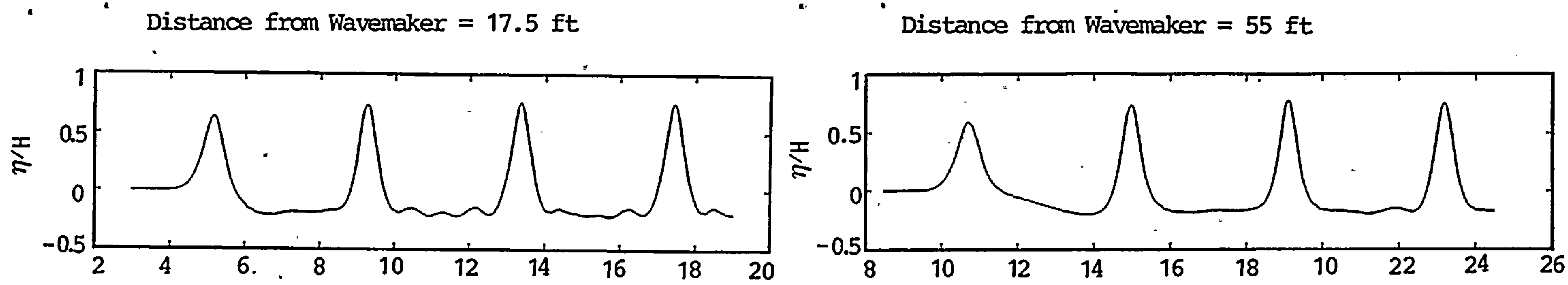
In general, the wavemaker should be located at a sufficient distance from the molded contours to allow for the wave to develop a natural shape before it begins to pass over the contoured areas. Since for some directions in this model it was necessary to place portions of the wave machine at distances which were less than normally considered to be desirable, means were applied to offset that disadvantage. It was accomplished by programming the stroke of the wavemaker to move with

varying rates of motion, rather than in uniform periodic motion. By that means a wave profile was produced immediately that is very comparable with shallow water forms which occur in nature. These waves, referred to as "cnoidal"* waves, differ in shape from a sinusoidal wave. Characteristically the crests are more peaked and the troughs are flattened.

Goring and Raichlen** recognized the problem of using an incorrect wave form for testing in shallow water conditions. Figure 26 shows the impact of using a sinusoidal wave form for shallow water studies versus a cnoidal wave form. The two wave traces shown on the left hand side of the figure respectively represent a cnoidal and a regular sinusoidal wave, shortly after being generated in "shallow" water. Both are fairly clean and uniformly shaped. On the right hand side are the same waves after their forms have moved down a tank of constant water depth. It is easy to see that the cnoidal wave has retained its shape to a notable extent while the sinusoidal wave has broken down into a crest with several frequency components that are evidenced by its changing more jagged profile. These aberrations are the result of artificially generating a sinusoidal wave form, which is not really stable in shallow water. Following the aforementioned method developed by Goring and Raichlen, a cnoidal wave plate trajectory was incorporated into the wave generation command signal, to create waves in the model which were very close to cnoidal in shape and therefore closely approximated the desired wave characteristics. Model waves were thus achieved that would be

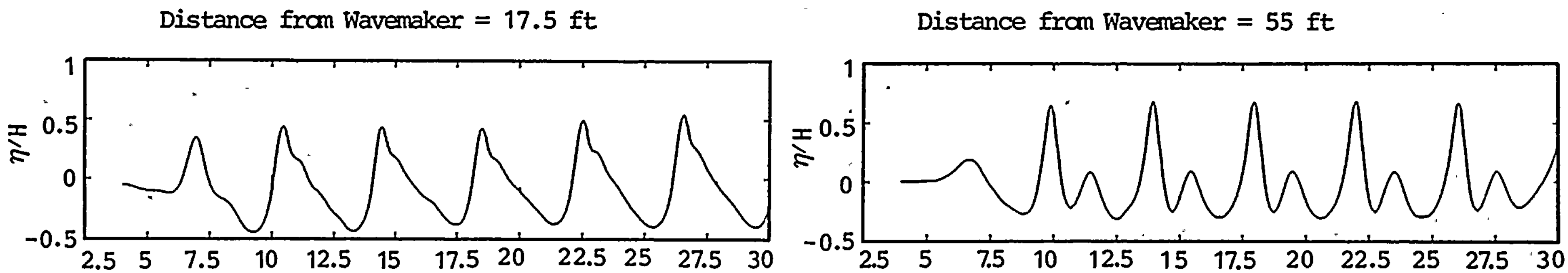
* The term <u>cnoidal</u> is used since the wave profile is given by the Jacobian elliptical cosine function, usually designated by the symbol cn.

** Goring, D. and Raichlen F., "The Generation of Long Waves in the Laboratory," Proceedings of the 17th International Coastal Engineering Conference, March 1980, Sydney Australia



CNOIDAL WAVES

h = 1 ft   T = 4.08 sec   Stroke = 12.13 in



SINUSOIDAL TRAJECTORY

h = 1 ft   T = 4.08 sec   Stroke = 12.13 in

Figure 26   BREAKDOWN OF A SINUSOIDAL WAVE IN A SHALLOW WATER FLUME VERSUS THE NON-CHANGING CHARACTER OF A CNOIDAL WAVE IN OTHERWISE IDENTICAL CIRCUMSTANCES

permanent in profile character except for changes in form due only to changing depths. It also meant that because the correct wave form was immediately generated, less distance was required for the wave form to adapt to its natural shape. Figure 27 gives an example of the water surface time history measured in the model at a distance from the wavemaker equal to about four times the water depth in front of the machine. The wave form modelled is of a prototype 16 seconds wave with a height of 35.73 feet. Note that the wave does possess peaked crests and flattened troughs. The uniformity of the wave demonstrates the success with generating close approximations of cnoidal wave forms in the model.

Data Sampling

Sea surface elevations that were measured by the sixteen wave probes, and stored by the computer, were processed and analyzed to extract desired wave data for any given test. The typical test length, utilizing periodic wave forms, required 45 seconds of model time to run. Typically, fourteen waves could generate at the wavemaker before the initial wave reflected from the model and returned to the wavemaker. By limiting the sample time period to 45 seconds, wave probes in the vicinity of the intake structure would see only the waves which do not contain components of a re-reflected wave system. For analysis purposes, only the second through sixth waves in the wave train were considered. These were analyzed for both wave height and relative position of both wave crest and trough relative to still water level.

Similar to the analysis of wave heights, forces on the air intake huts were also examined for loading only by waves two through six. The force components were measured separately in the directions perpendicular to the walls of the huts. They then were combined in a vector concept

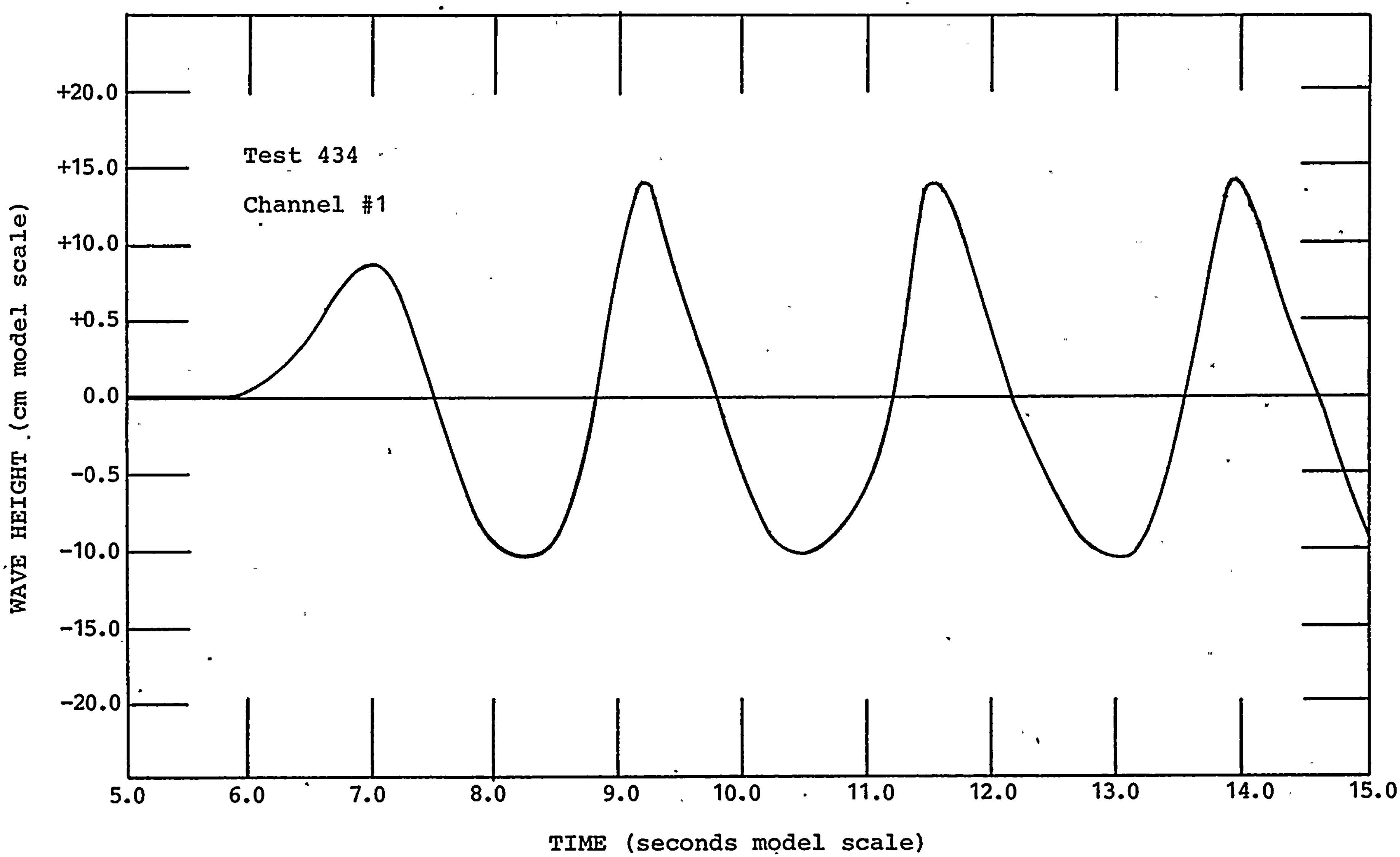


Figure 27 WAVE FORM EXAMPLE RECORDED IN THE DIABLO MODEL TANK NEAR THE WAVEMAKER

in order to get both magnitude and direction of the resultant force. The extended ventilating air snorkels, suspended over the top of the air intake huts with no physical interconnection, were instrumented independently of the huts to measure force and bending moment on the snorkels only. Thus, they could sense any noticeable forces on the snorkels, should water splashed upward at the air intake huts strike the snorkels. Simultaneous measurement of bending moment components in the same planes as used for force measurement allowed the resolution of forces into point of application of the resultant force separately on the huts and separately on the snorkels. All loads were recorded as individual traces, concurrently on a single continuous analog high speed oscillograph record, in order to identify peak impact occurrences and to monitor the time relationships between the different components. The component forces, the magnitude and the direction of the resultant force, and the point of application of the force could then be extracted in terms of average values, and of maximum and minimum observed values, during the several waves that were examined.

As a complement to force measurement on the hut structures, stop action video was utilized to determine green water runup on the huts. Accuracy in estimating runup in this manner was about 1 foot in the prototype. Overhead video records were helpful in considering how the actual wave refraction and diffraction patterns evolved as the waves moved across the complex topography of the Intake Basin area. They were further used to identify locations of focused wave energy on the breakwaters.

CHAPTER IV

RESULTS AND COMMENTARY

Limited Wave Heights

In discussing limit waves near the intake structure it is best to look first at the model without the breakwaters present. In this case, referring to Figures 1 or 22 or 23 it is seen that the intake is protected in a sense by the underwater "ridges" upon which the breakwaters were built. These features, and others offshore, trigger wave breaking to produce a depth limiting condition for incident waves. In order to define these waves, measurements were made at two positions in the Intake Basin in front of the Cooling Water Intake Structure. Simultaneous wave measurements were made at other locations in the model, but these do not necessarily define limiting wave conditions in front of the intake and are generally not described in this report.

Certain of these results are presented in Figure 28 for waves approaching the Cooling Water Intake Basin from a deep water direction of 180° (a refracted direction of 203° at the 100 feet contour region of the model) and for waves from a deep water direction of 225° (about 225° in the constant depth region in the model). In the three parts of Figure 28, graphical plots are presented for the variation of the wave height at two positions in front of the Intake Structure, denoted as Positions R and S, for wave periods of 12, 16 and 20 seconds. These locations can be seen in the inset map of each figure. In each portion of the figure, the abscissa is the wave height measured at a point distant from the wave machine equal to four times the water depth at the machine. That depth of water is 100 feet plus a 7.5 feet tide above

HEIGHTS OF WAVES FROM SOUTH AT INTAKE STRUCTURE VERSUS HEIGHTS OFFSHORE IN 107.5 FEET DEPTH

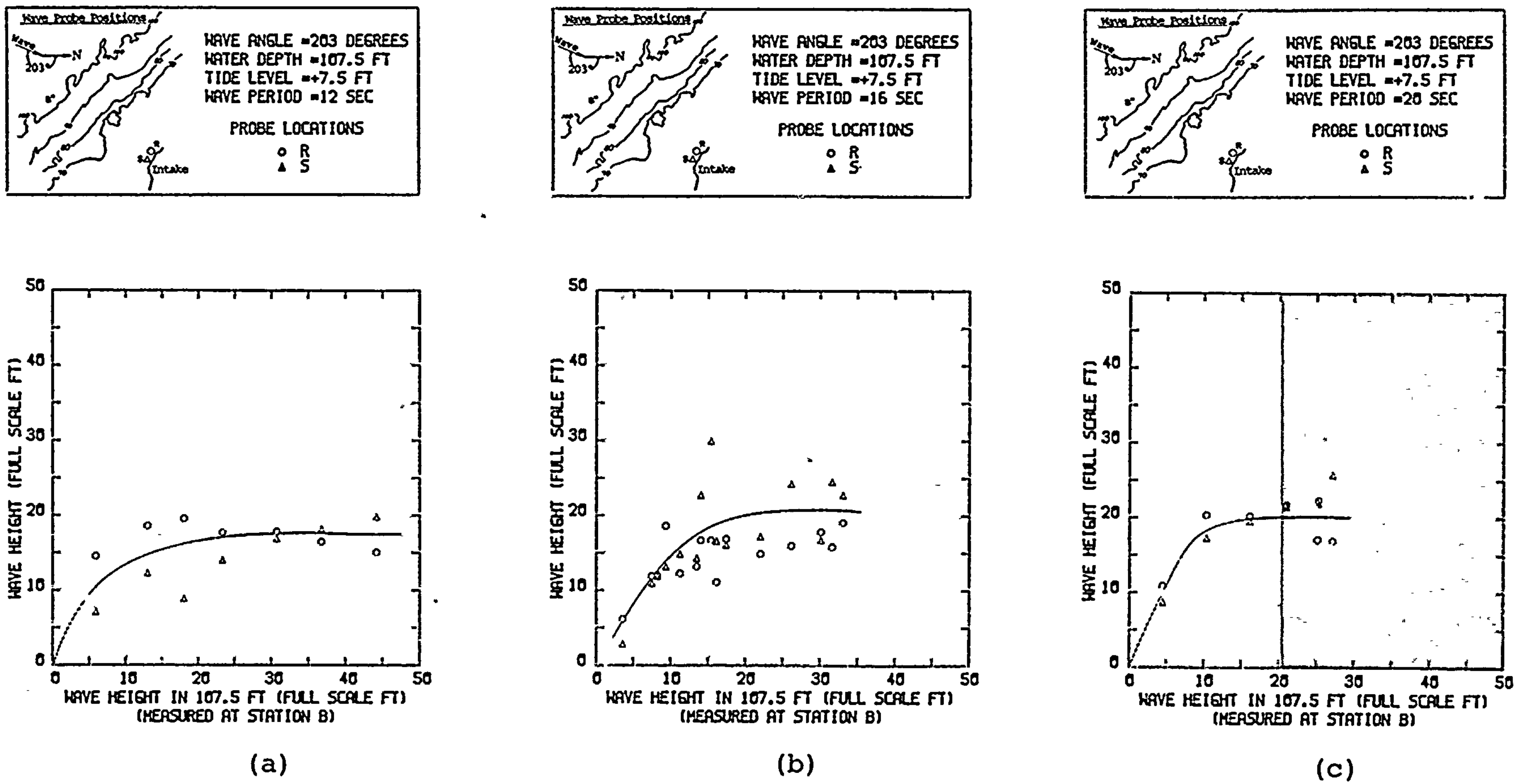


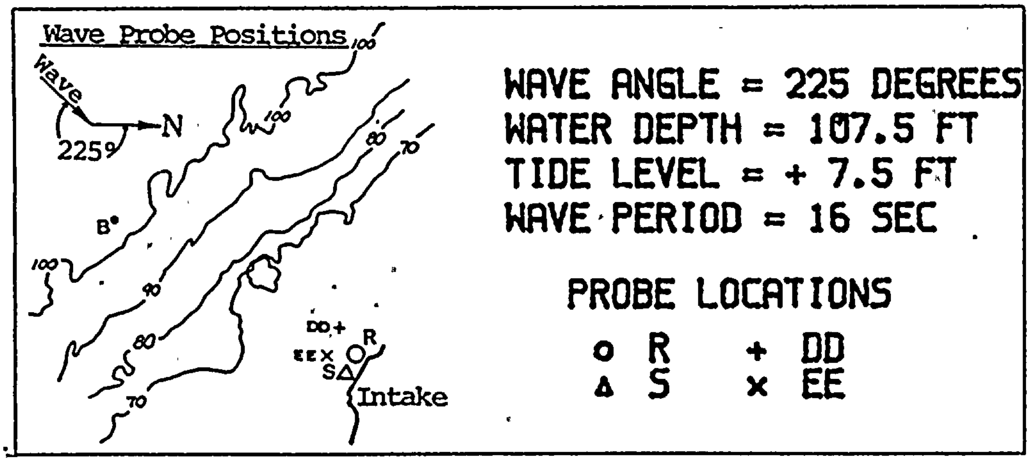
Figure 28

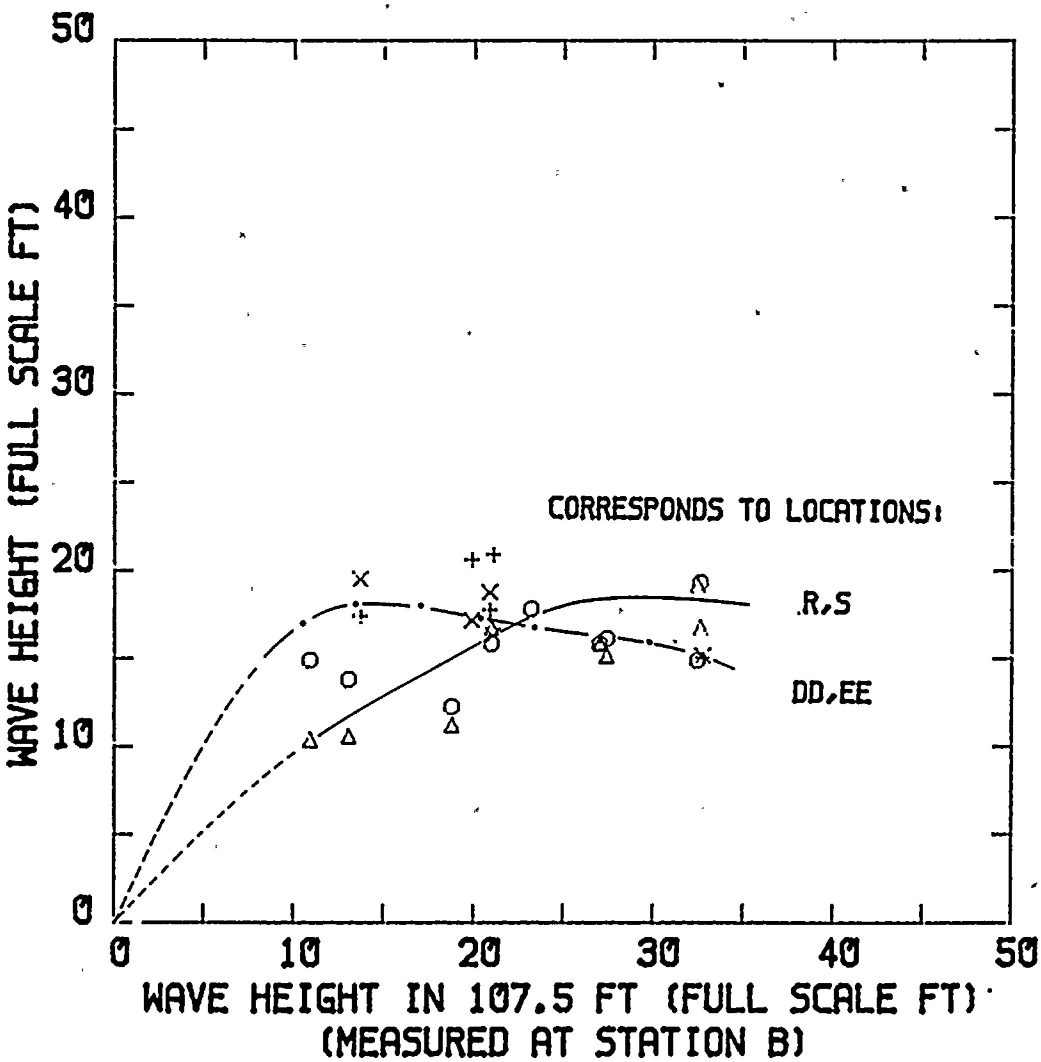
Mean Lower Low Water (Position B). The ordinate of each graph is the wave height measured at locations R and S. Those locations were about 100 feet in the prototype out from the Intake's seaward face. Shown also are experimental curves fitted to the data to indicate the trend of these data. A cursory examination of Figure 28 indicates that, in general, after wave heights near the wave machine reach about 10 feet, the waves are limited in height in front of the Intake Structure to approximately 20 feet, possibly a little more. Thus, it appears that the offshore terrain, with no breakwaters existing, caused the larger waves to break and then to move toward the intake structure with heights that would then be relatively independent of offshore conditions.

The question of whether the location of the wave gages might uniquely influence such conclusions was investigated. For waves with a direction of 225° in deep water, additional wave gages were located approximately 200 feet in the prototype from the face of the Intake, at points labeled DD and EE, and their recordings were compared with those made by gages R and S which were at about 100 feet from that face. The length of a wave with a 16 seconds period in a 30 feet water depth would be about 485 feet; thus wave gages R and S are not far from being one-quarter of a wave length away from the Intake Structure and wave gages EE and DD are close to being one-half of a wave length from the structure. In terms of a standing wave, this would produce the most severe test of the degree of reflectivity of this structure.

In Figure 29 results are shown for gages at locations R and S and at locations DD and EE for waves with a period of 16 seconds. It is seen that for all these locations the wave height in the basin is limited to a maximum of approximately 20 feet. The data show the wave height is

Figure 29. COMPARISON OF WAVE HEIGHTS AT 100 FEET DISTANCE WITH HEIGHTS AT 200 FEET FROM INTAKE STRUCTURE

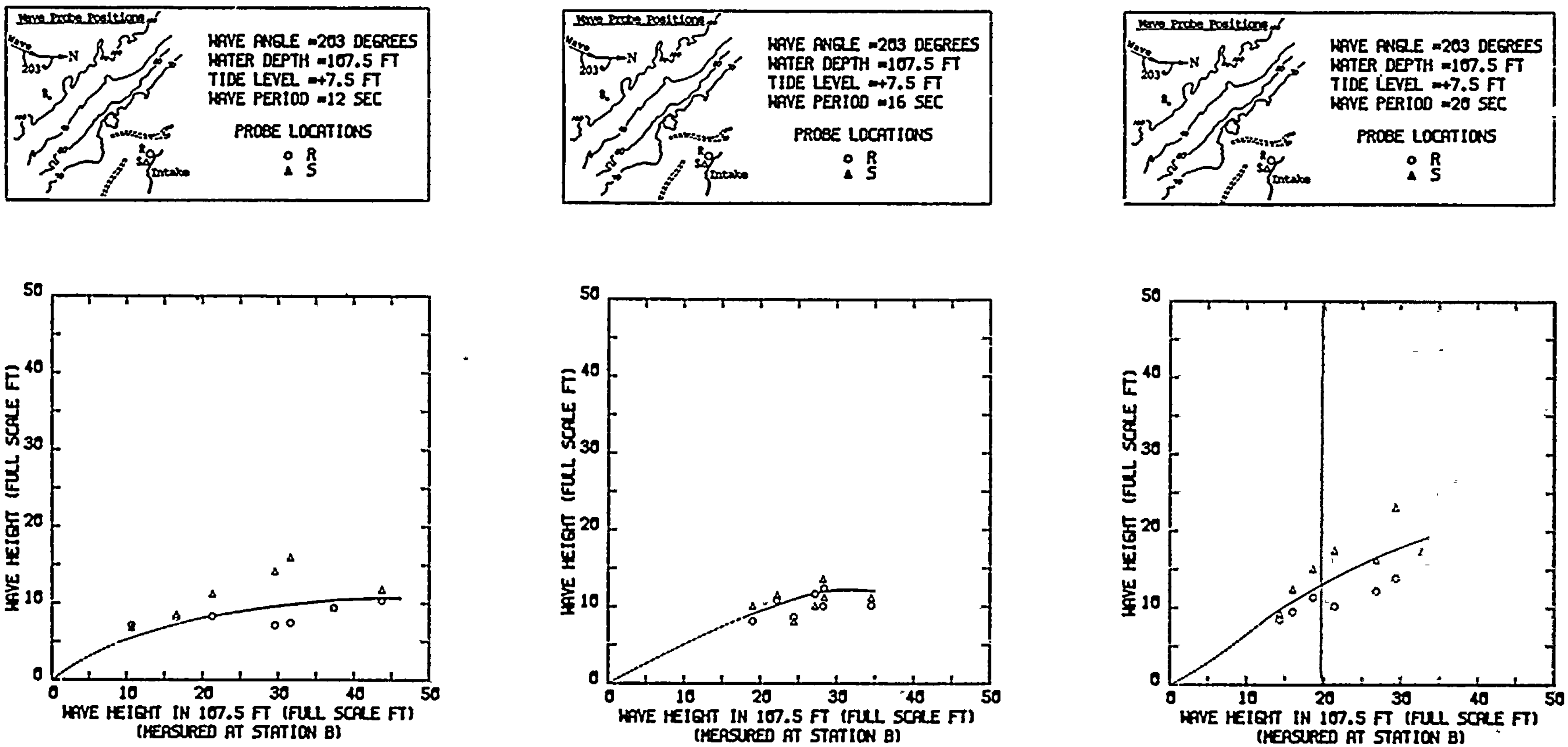




relatively independent of location; therefore, due to significant dissipation of wave energy within it and by runup and spray on the deck of the structure, there must be minimal reflection from the Intake Structure. This lends confidence, that wave height measurements in front of the Intake Structure at locations R and S do describe satisfactorily the heights of depth limited progressive waves and that therefore the measurements at those gages are representative of the waves striking the Intake Structure for the series of experiments where the breakwaters have been levelled.

Experimental results are presented on the following pages for wave heights in front of the Intake Structure for southerly and westerly waves for the model where the breakwaters are levelled to the elevation of Mean Lower Low Water. The variations of the wave heights at positions R and S in front of the Intake Structure with the wave heights at the wave machine are presented in Figure 30 for wave periods of 12, 16 and 20 seconds and with the water surface elevation for these records at 7.5 feet above Mean Lower Low Water. That is the elevation of maximum high tide. Results are also presented in Figure 31 for wave periods of 12, 16 and 20 seconds, but with a water surface elevation of +17.0 feet, referred to Mean Lower Low Water. That assumes coincidence of a high tide of 7.5 feet plus a tsunami of 8.5 feet plus a meteorological tide of 1 foot. For these two cases, depths at B (and at the wave machine) of 107.5 feet and 117 feet are shown on the figures. Experimental curves which describe the trend of the data are presented in each figure. It is seen that, for both depths, the wave height is limited in front of the intake to between 10 and 20 feet, practically independent of what the wave height offshore in the region of the wave machine may be. This

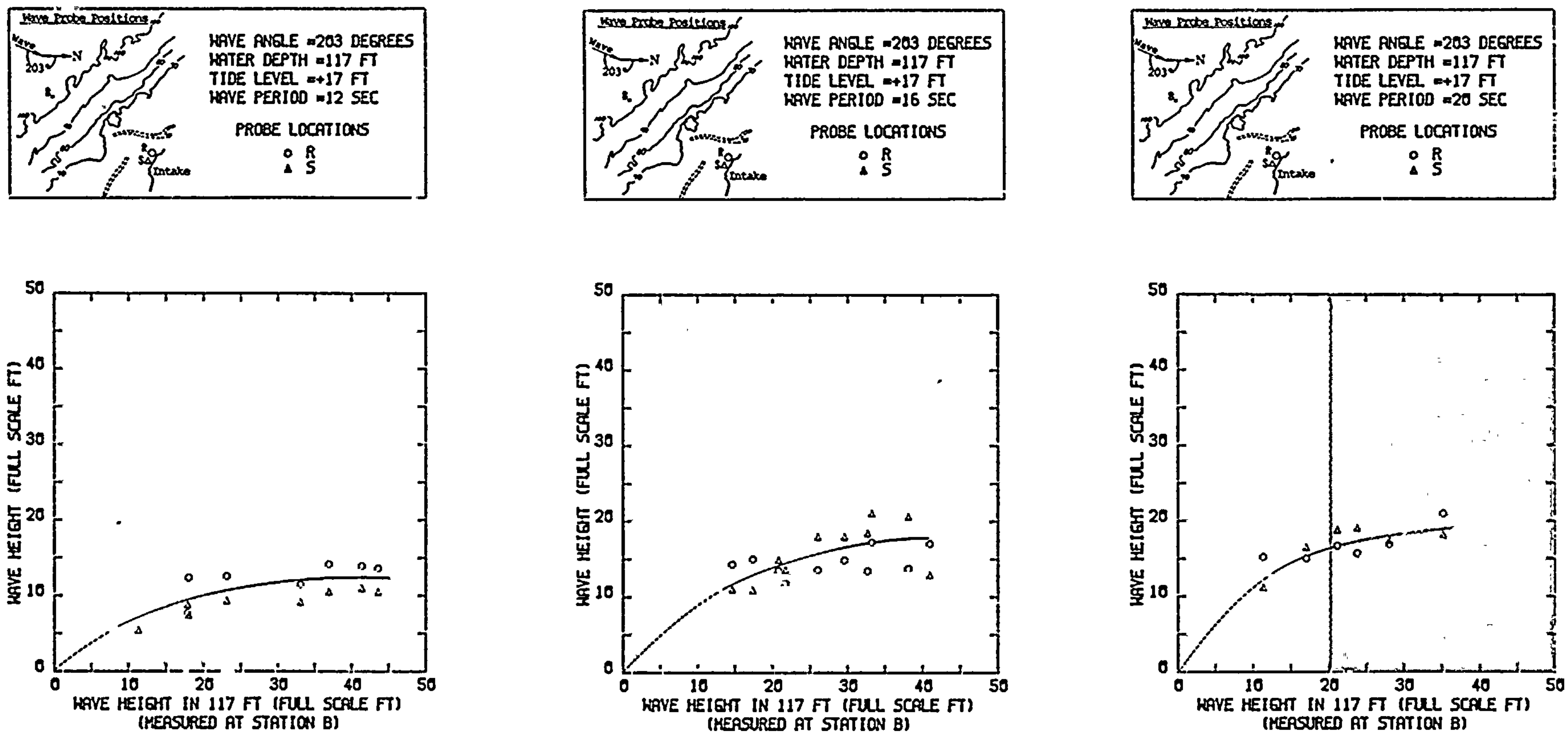
HEIGHTS OF WAVES FROM SOUTH AT INTAKE STRUCTURE VERSUS HEIGHTS OFFSHORE IN 107.5 FEET DEPTH WITH LEVELLED BREAKWATERS



(a) (b) (c)

Figure 30

HEIGHTS OF WAVES FROM SOUTH AT INTAKE STRUCTURE VERSUS HEIGHTS OFFSHORE IN 117 FEET DEPTH WITH LEVELLED BREAKWATERS



(a) (b) (c)

Figure 31

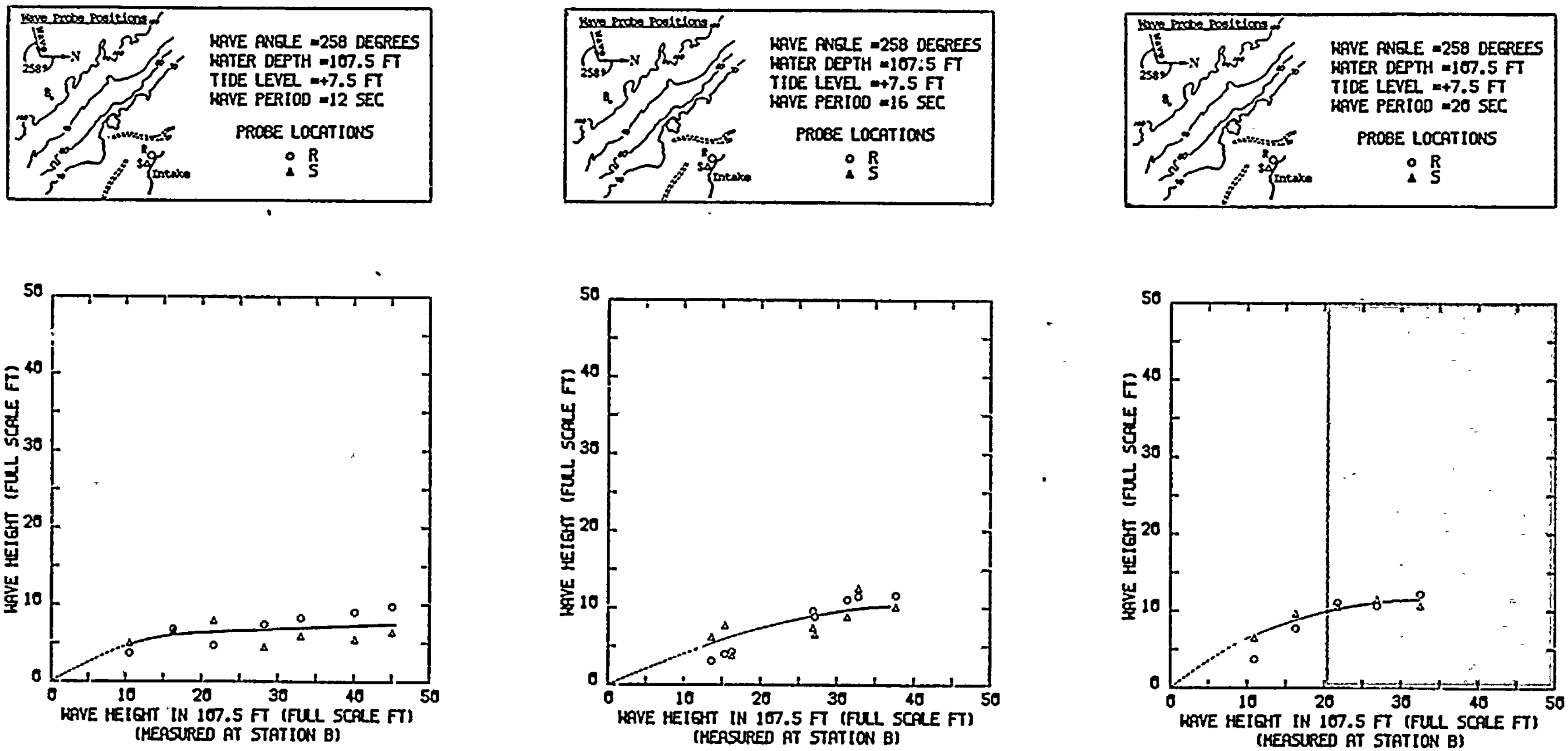
emphasizes that the combined effect of the sea floor terrain with the levelled breakwaters limits the height of the waves near the Intake Structure.

In the model with the levelled breakwaters it was observed that, as each wave overtops a breakwater, a mass of water is delivered into the Cooling Water Intake Basin. When the overtopping jet plunges into the basin water surface its impact starts a new wave system on the basin side of the breakwaters; it is these "regenerated" waves that move across the basin to the Cooling Water Intake Structure.

In the model it was possible to produce waves of 20 seconds periods that were higher at the 100 feet depth contour than 20 feet. At the site, such wave heights do not occur when periods are as long as or longer than 20 seconds. Nevertheless model data for these non-credible heights were acquired in order to better visualize the trends before entering those height plots. That they would not actually occur is emphasized on all graphs by shading the plots beyond the 20 feet abscissae.

For waves approaching from West (270°), the refracted direction at the depth of the wave machine is approximately 258°. The results for this case with the levelled breakwaters, for the lower and the higher still water levels, as before are presented in Figures 32 and 33 for the same three wave periods. Again, the abscissa is the wave height near the wave machine (Position B) and the ordinate is the wave height measured at Positions R and S in front of the Cooling Water Intake Structure. It is observed that for the case with the lower still water level the wave heights in the basin are again limited, to slightly more than 10 feet even for waves that in deeper water are of the order of 45 feet in height. Again the limit appears to be caused by the protection

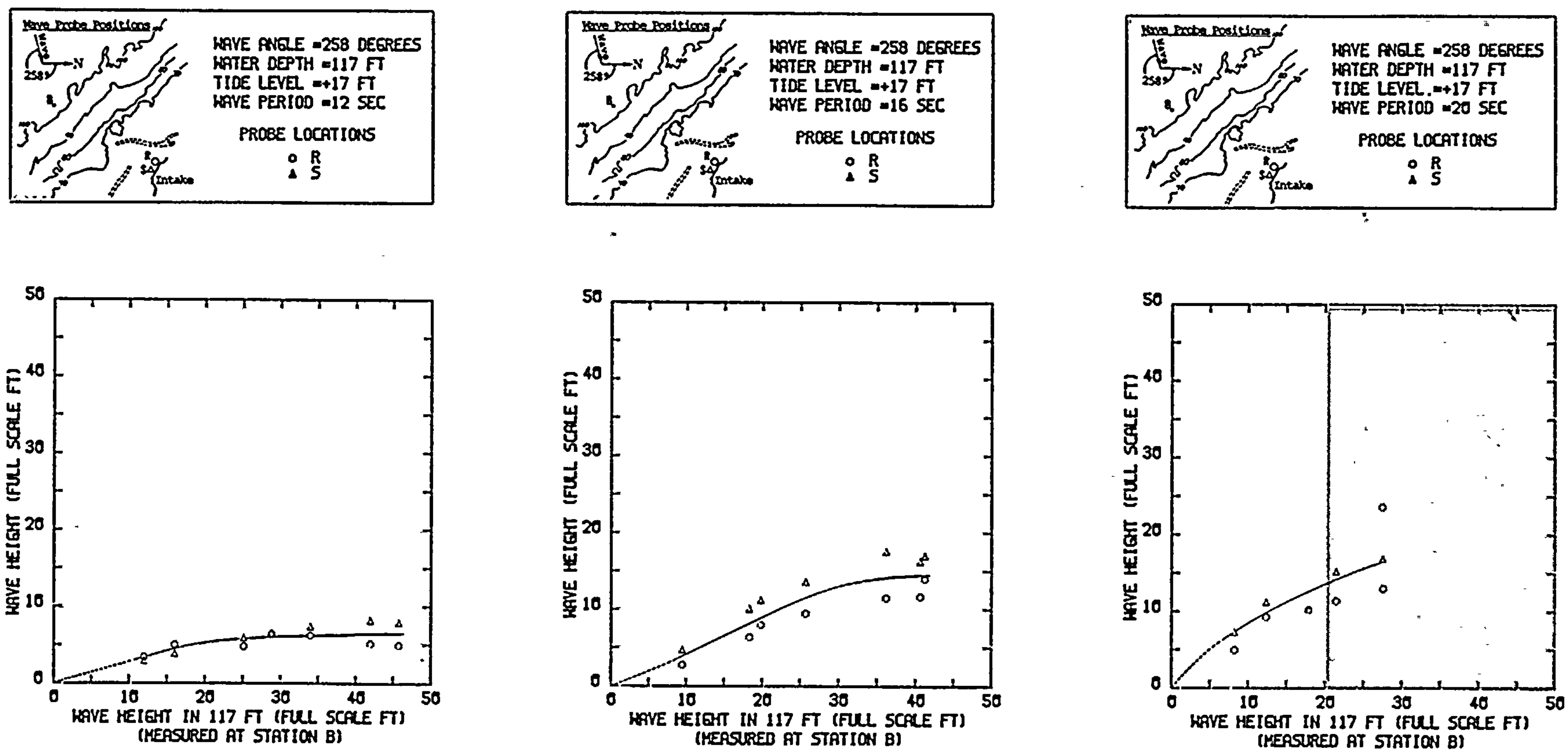
HEIGHTS OF WAVES FROM WEST AT INTAKE STRUCTURE VERSUS HEIGHTS OFFSHORE IN 107.5 FEET DEPTH WITH LEVELLED BREAKWATERS



(a) (b) (c)

Figure 32

HEIGHTS OF WAVES FROM WEST AT INTAKE STRUCTURE VERSUS HEIGHTS OFFSHORE IN 117 FEET DEPTH WITH LEVELLED BREAKWATERS



(a) (b) (c)

Figure 33

afforded by the combined influences of the sea floor terrain and the levelled breakwaters. For the higher still water level, a depth of 117 feet at Position B, the wave heights inside the Cooling Water Basin for the longer wave periods are somewhat greater than those shown at the same locations for the lower water level. Again, it should be recalled that for the waves with periods as long as or longer than 20 seconds, attention should be limited to only those waves which in deep water are less than 20 feet high.

Recapitulating, it appears that for the case of the levelled breakwaters, the wave heights in the Cooling Water Basin in front of the Intake Structure are limited by the combined effects of the offshore terrain, the levelled breakwaters and the Intake Structure itself.

A visual summary of certain important aspects of the limit wave concept is presented in Figure 34. Shown in the three parts of this figure are the wave heights at locations R and S for four different conditions:

(1) Figure 34a shows an incident wave of 16 seconds period approaching from azimuth 225° in a depth of 107.5 feet and with no breakwaters existing;

(2) In Figure 34b are two curves of an incident wave of 16 seconds period approaching from azimuth 203° in a depth of 107.5 feet and with both breakwaters existing but levelled to elevation zero, Mean Lower Low Water;

(3) And also in Figure 34b an incident wave of 16 seconds period approaching from azimuth 203° in a depth of 107.5 feet and with both breakwaters levelled;

COMPARISONS OF WAVE HEIGHT LIMITATIONS FOR THREE DIRECTIONS OF APPROACH

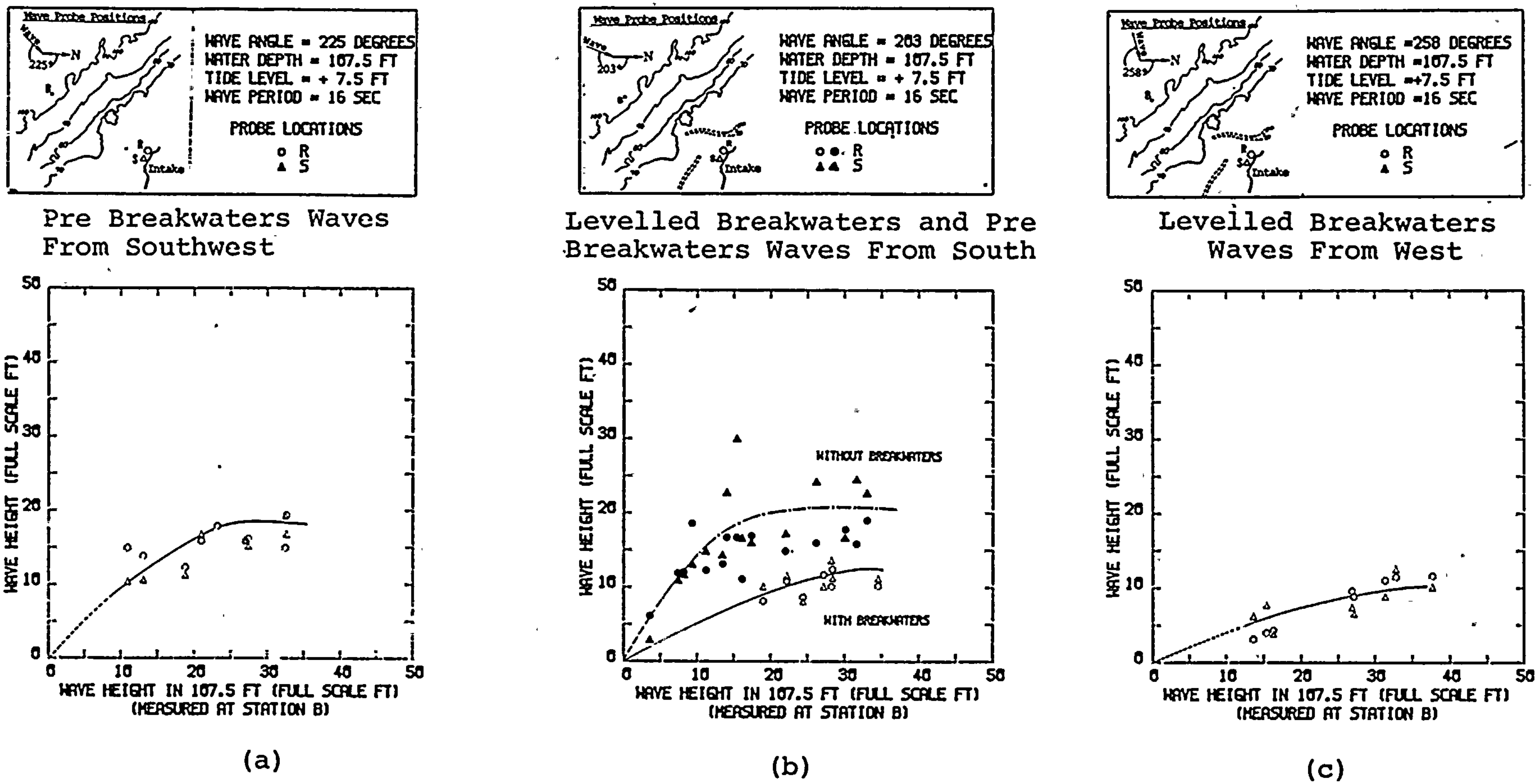


Figure 34

(4) Figure 34c shows an incident wave of 16 seconds period approaching from azimuth 258° in a depth of 107.5 feet with both breakwaters levelled.

In all of these it is evident that limiting effects on wave height takes place. As the wave height increases in a depth of 107.5 feet, a limiting wave height is reached near the Cooling Water Intake Structure.

The plotted data that compare wave heights at the Intake Structure's vicinity with the heights those waves had at the 100 feet contour locality of the wave machines illustrate the limiting effect of the terrain, of the levelled breakwaters and of the Intake Structure on the heights of waves that can reach the Intake.

It is also of interest to note that the extent to which wave heights are limited by the terrain and the structure alone, in the pre-breakwater conditions, is essentially the same for waves approaching from Southwest (225° azimuth) as for those approaching from South (203° azimuth at 100 feet contour). The gap between breakwaters at the basin entrance admits more energy to the basin when the waves approach from the South than is admitted when the waves approach from Southwest. For that reason the 203° azimuth wave direction was selected for testing the levelled breakwaters situation, instead of 225°.

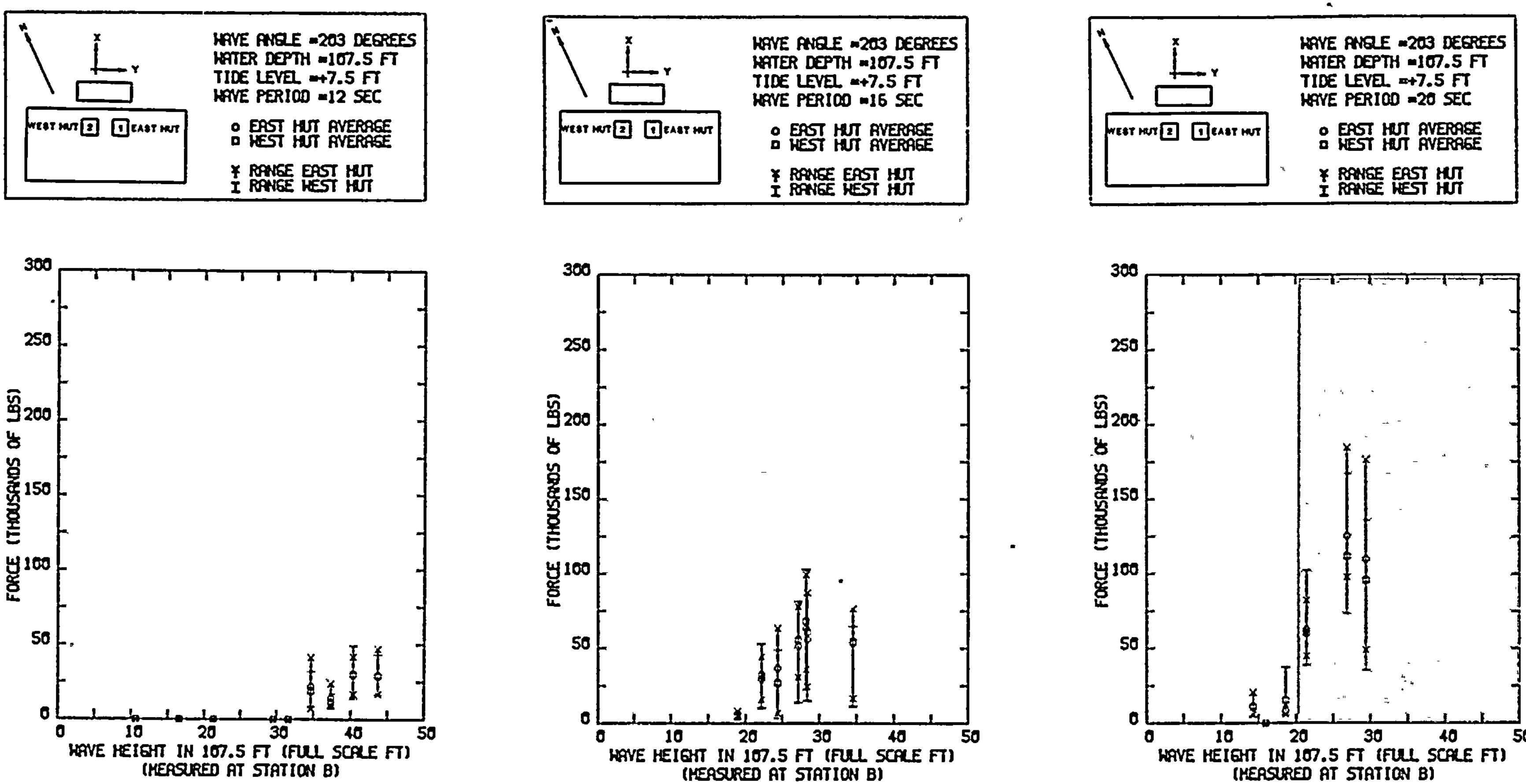
The effect of the offshore submarine terrain on waves is evident in a comparison of the wave heights at locations R and S due to waves from 203° and from 258° for the case with the levelled breakwaters. Waves from West arrive at the 100 feet depth curve with 258° azimuth. The waves in the Intake Basin for the southerly direction are somewhat higher than those from the westerly direction. Indeed waves of more

southerly approach generated larger overtopping of the levelled breakwaters, and correspondingly greater wave activity in the Intake Basin.

Forces On Ventilating Stacks Due To Waves

The forces acting perpendicularly on each of the two intersecting faces of each of the two air intake risers, or huts, and the corresponding bending moments exerted against each face were measured. Resolving the two perpendicular forces at each hut into their resultant and their moments, provides the basis for defining the magnitude, direction and the vertical distance above the deck to the effective point of application of the resultant. In addition, the maximum rise of the water level in the proximity of the air intake structure (referred to as the maximum runup) was observed by using the stop action capability of the laboratory video system. These observations were made to determine whether or not the air intakes would need modifications to remove the threat of ingestion of water. In Figures 35 and 36, the resultants of forces against each hut due to southerly waves, with an azimuth direction of 203° at the wave machines, are plotted. There are six graphs presented by the two figures, the abscissa on each is the wave height at a location which is four times the water depth away from and in front of the wave machine in the constant depth region of the model basin. The ordinates are the amount of the resultant of the measured forces. Data are presented for wave periods of 12, 16 and 20 seconds for each of the two depths considered, i.e., Mean Lower Low Water plus 7.5 feet high tide in Figure 35, and Mean Lower Low Water plus 7.5 feet, high tide, plus 8.5 feet tsunami, and plus 1 foot meteorological tide in Figure 36. Data points are indicated for what is termed the East hut and the West hut, sometimes called Huts 1 and 2 respectively. The symbols are

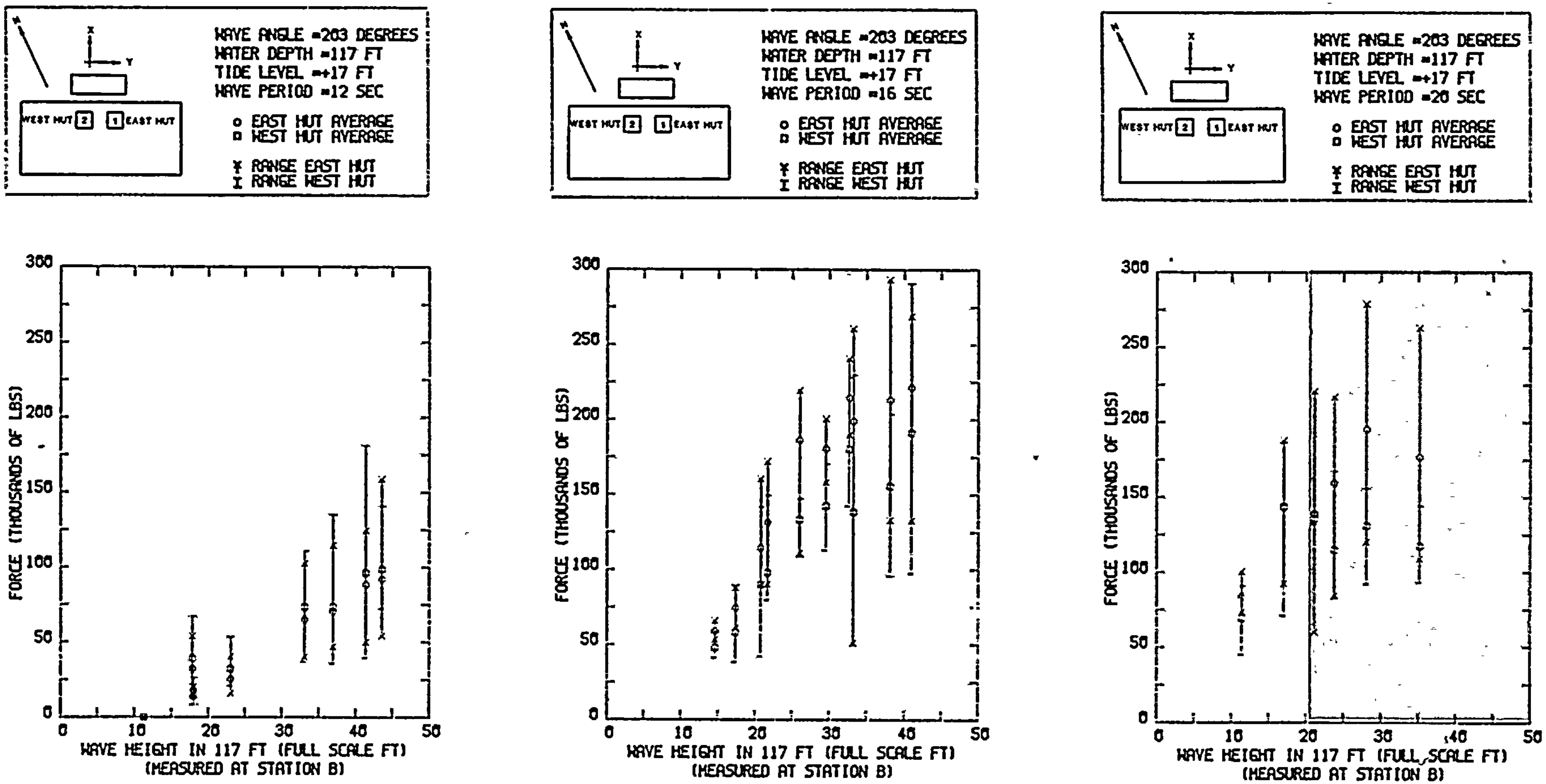
FORCES INDUCED ON HUTS BY WAVES FROM SOUTH FOR THREE WAVE PERIODS AT MAXIMUM ASTRONOMICAL TIDE LEVEL (+7.5 FEET)



(a) (b) (c)

Figure 35

FORCES INDUCED ON HUTS BY WAVES FROM SOUTH FOR THREE WAVE PERIODS WITH CONCURRENT MAXIMUM TIDE, TSUNAMI AND METEOROLOGICAL SURGE (+17 FEET)



(a) (b) (c)

Figure 36

described in the inset above each graph. The data points shown are the average of the force which occurs on the hut for five or six waves in the first part of the wave train, before the influence of reflected waves from the boundaries of the model can return from the wave machine to distort the measurements. The bar extending up and down from each data point indicates the range of the measurements, i.e., the maximum and the minimum measured forces among the five or six that have been averaged.

It should be kept in mind in viewing these graphs that with a force applied in the positive x-direction on the huts, which is a wave direction from azimuth 205.5°, the capacity of the huts as determined by an analysis conducted by others is 450,000 pounds. That is if the point of application is assumed to be at one-third of the overall height of the hut above the deck. The huts are 14.5 feet high, with parapets at elevation 34.6 feet above Mean Lower Low Water. Thus, the assumed point of application of the resultant force would be about 4.83 feet above the deck at an elevation of 24.93 feet above Mean Lower Low Water Datum. Note that in Figure 35, for the lower water level and for wave periods of 12 and 16 seconds, the average forces are less than 100,000 pounds. For the same water level with waves of 20 seconds period and for wave heights offshore of less than 20 feet, the measured forces also are less than 100,000 pounds.

When the still water level is increased to 17 feet above Mean Lower Low Water, overtopping of the levelled breakwaters and the water depth in the intake basin increase. This takes place in a transient manner, causing the resultant force to be larger compared to similar waves at the lower water level. For example, for the 16 seconds waves the maximum

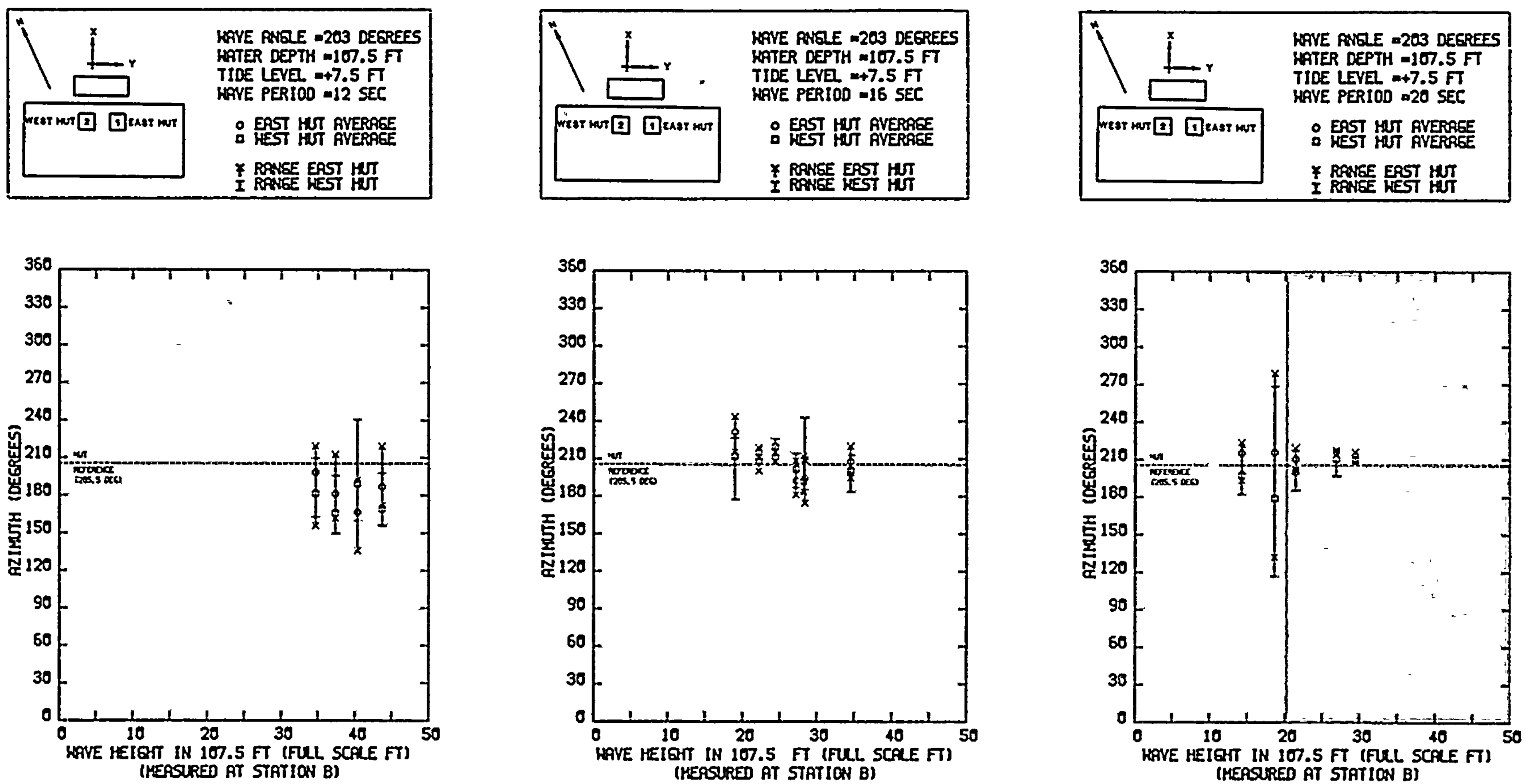
force recorded is 300,000 pounds, with the average force less than about 250,000 pounds. The forces measured with 20 seconds waves, with wave heights near the wave machines less than 20 feet, are of comparable magnitude with those measured with 16 seconds waves.

In Figures 37 and 38 the azimuths of the resultant forces are shown for the two water level conditions and for each of three wave periods. In each graph a dotted line indicates the direction 205.5°, which is perpendicular to the face of the Intake Structure and the azimuth of the plus x-direction. It is seen that in general, except for one isolated case for the 20 seconds wave (Figure 37), the direction of the resultant force is between approximately 205° and 220°. Thus the applied force is close to perpendicular to the front face of the air intake huts.

In Figures 39 and 40, the height above the Intake Structure deck of the point of application of the resultant force is shown for the two different water level conditions and the three different wave periods defined previously. It is seen that there is a tendency for the distance off the deck to the point of application to increase with increasing offshore wave height and with increasing wave period. For the runs with the lower water level the average point of resultant force application is always less than 7 feet above the deck. For the runs with higher water level the average points of application of the forces is somewhat higher on the huts but in general it is at distances from the deck close to or less than half their height.

It is apparent from these data that the resultant forces, the directions of the resultants and the points of application of the resultant forces are in keeping with the assumptions made in determining analytically the load capacity of the huts.

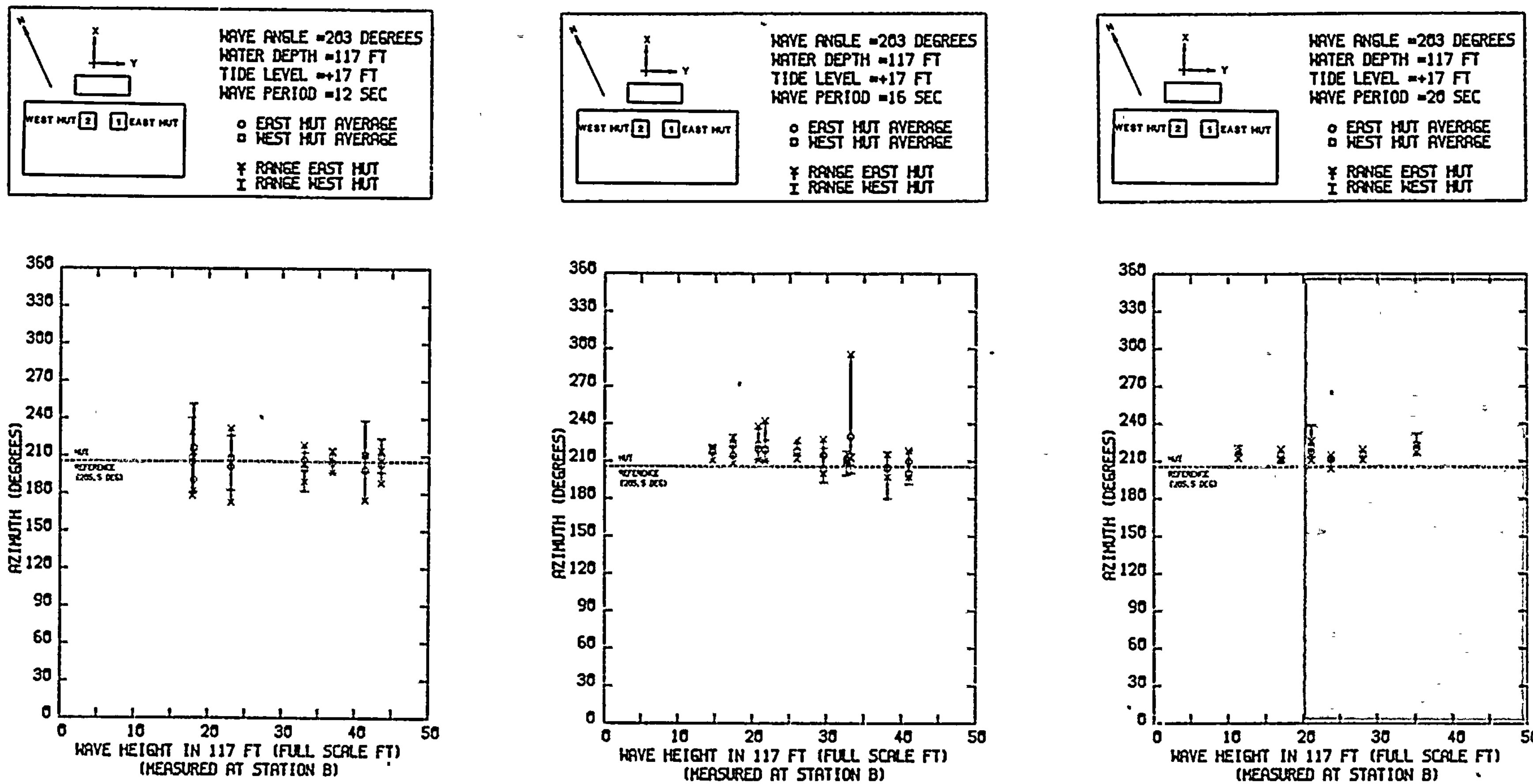
RESULTANT DIRECTION OF FORCES ON HUTS DUE TO WAVES FROM SOUTH FOR THREE WAVE PERIODS AT MAXIMUM TIDE LEVEL (+7.5 FEET)



(a) (b) (c)

Figure 37

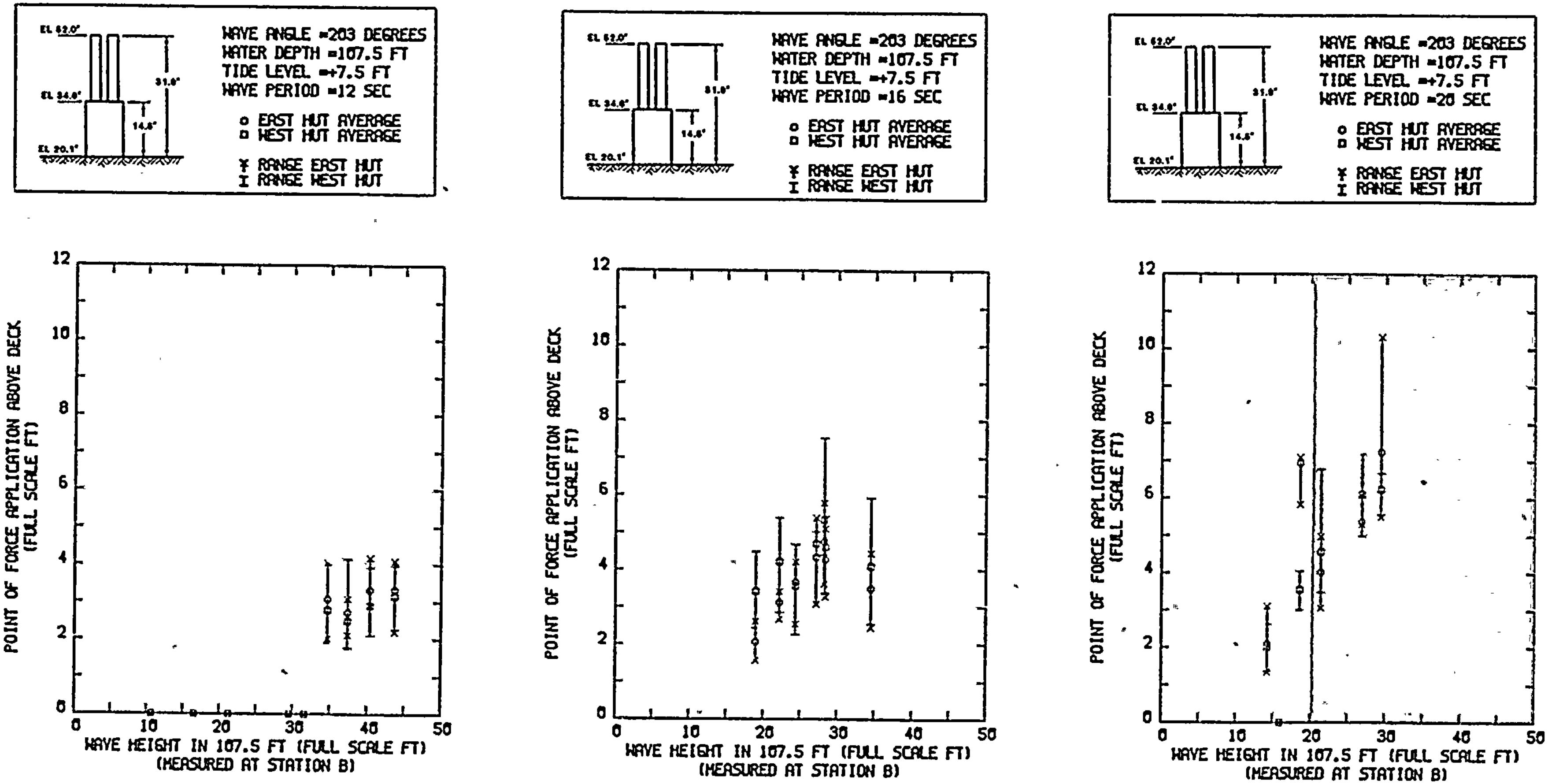
RESULTANT DIRECTION OF FORCES ON HUTS DUE TO WAVES FROM SOUTH FOR THREE WAVE PERIODS WITH CONCURRENT MAXIMUM TIDE, TSUNAMI AND METEOROLOGICAL SURGE (+17 FEET)



(a) (b) (c)

Figure 38

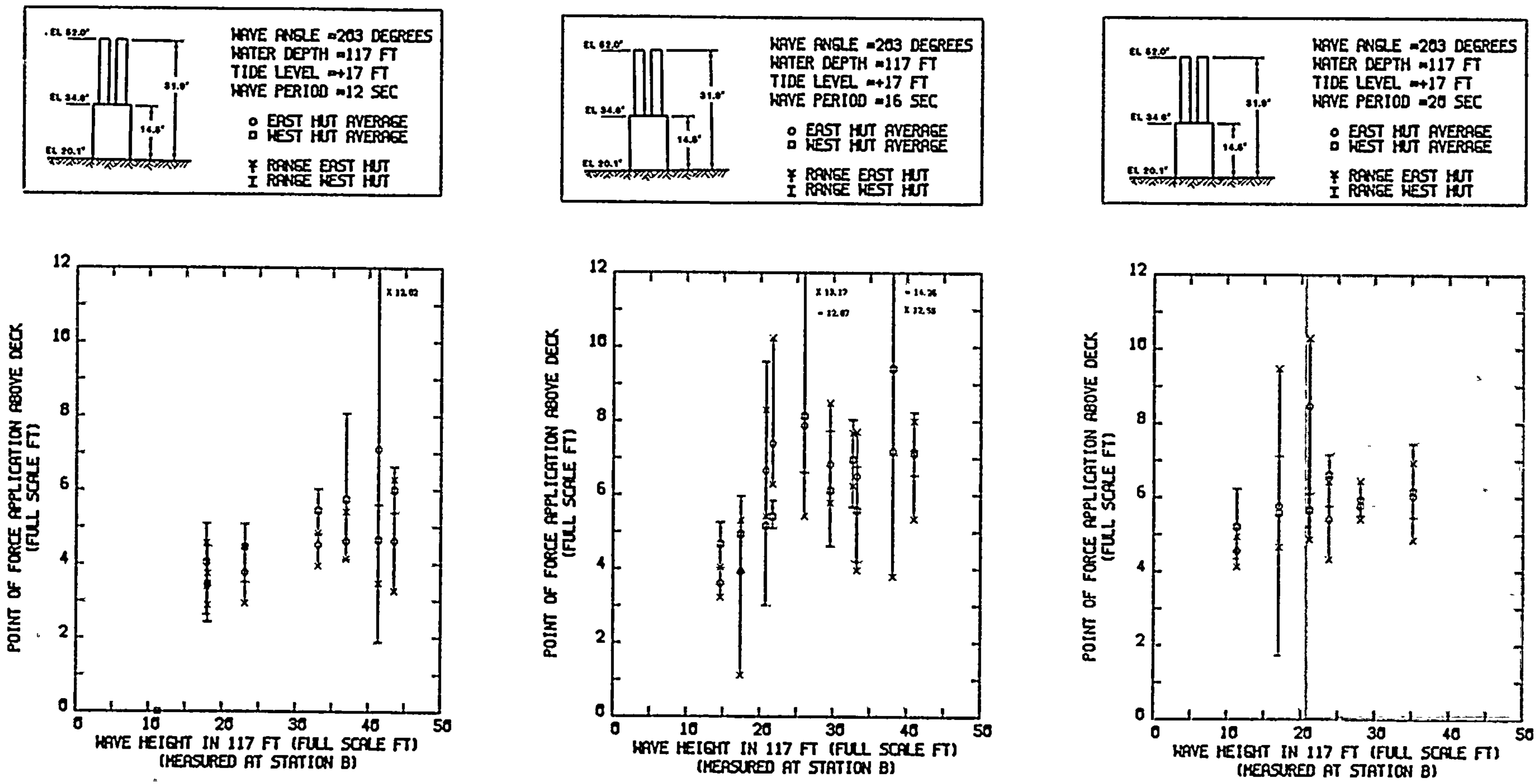
HEIGHT ABOVE DECK OF RESULTANT FORCES DUE TO WAVES FROM SOUTH FOR THREE WAVE PERIODS AT MAXIMUM ASTRONOMICAL TIDE LEVEL (+7.5 FEET)



(a) (b) (c)

Figure 39

HEIGHT ABOVE DECK OF RESULTANT FORCES DUE TO <u>WAVES FROM SOUTH</u> FOR THREE WAVE PERIODS WITH CONCURRENT MAXIMUM TIDE, TSUNAMI AND METEOROLOGICAL SURGE (+17 FEET)



(a) (b) (c)

Figure 40

It also is apparent that the huts as designed are stronger than necessary to resist the forces and moments recorded in the tests during the levelled breakwaters case with waves approaching from South.

Runup/Splash At Ventilating Stacks Due To Waves From South

Figures 41 and 42 show runup observations at the huts for the southerly waves, with the same two different water levels and the same three wave periods. The ordinate indicates the heights above the deck to which water rises or splashes at the air Intake Structures when it impacts against them. As shown earlier on Figure 15 (Page 25), apertures in the existing concrete huts have their sills at 9.92 feet above the deck, that is at 30 feet above Mean Lower Low Water Datum. Runup above that height presents the possibility of ingestion of water into the air intakes of the present structures, unless they are modified. The observations as presented by Figures 41 and 42 show that the elevation of the sills of the apertures in the existing huts is exceeded by runup due to waves at the high tide level (+7.5 feet) as well as at the combined high tide, tsunami and meteorological tide (+17 feet). Therefore the existing air intakes need to be modified to avoid water ingestion during the hypothetical events.

Snorkel Extensions Of Ventilating Facilities

Two cylindrical risers (usually referred to herein as snorkels) therefore were extended upward from each of the huts in the model to an elevation 52.0 feet above Mean Lower Low Water Datum, 31.9 feet above the Intake Structure deck, and the existing apertures were closed. A photograph of the concept has been seen earlier in Figure 2 (Page xiv) and in the outline sketch of the model, Figure 15.

HEIGHT OF SPLASH RUNUP ABOVE DECK DUE TO WAVES FROM SOUTH FOR THREE WAVE PERIODS AT MAXIMUM ASTRONOMICAL TIDE LEVEL (+7.5 FEET)

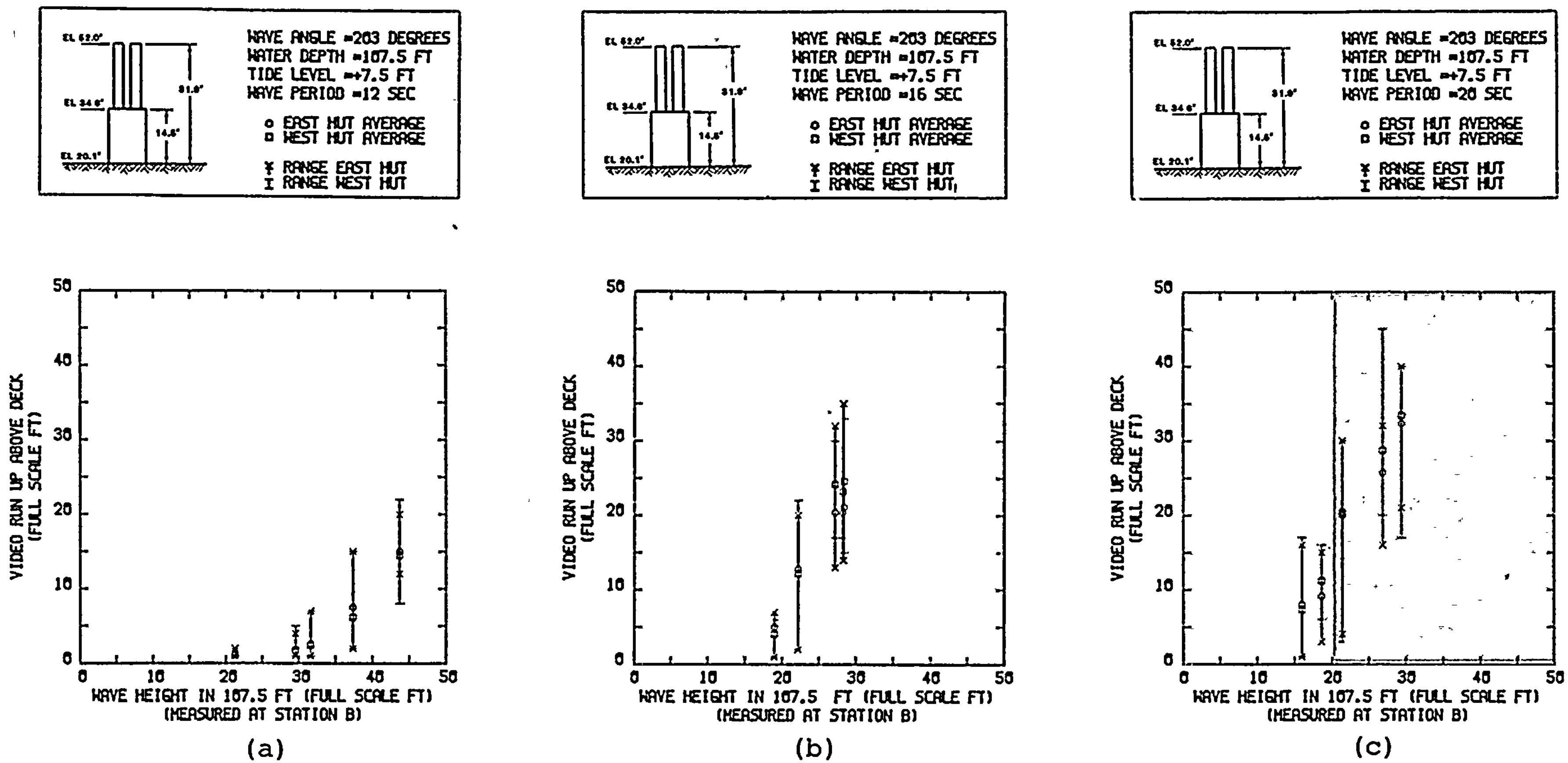
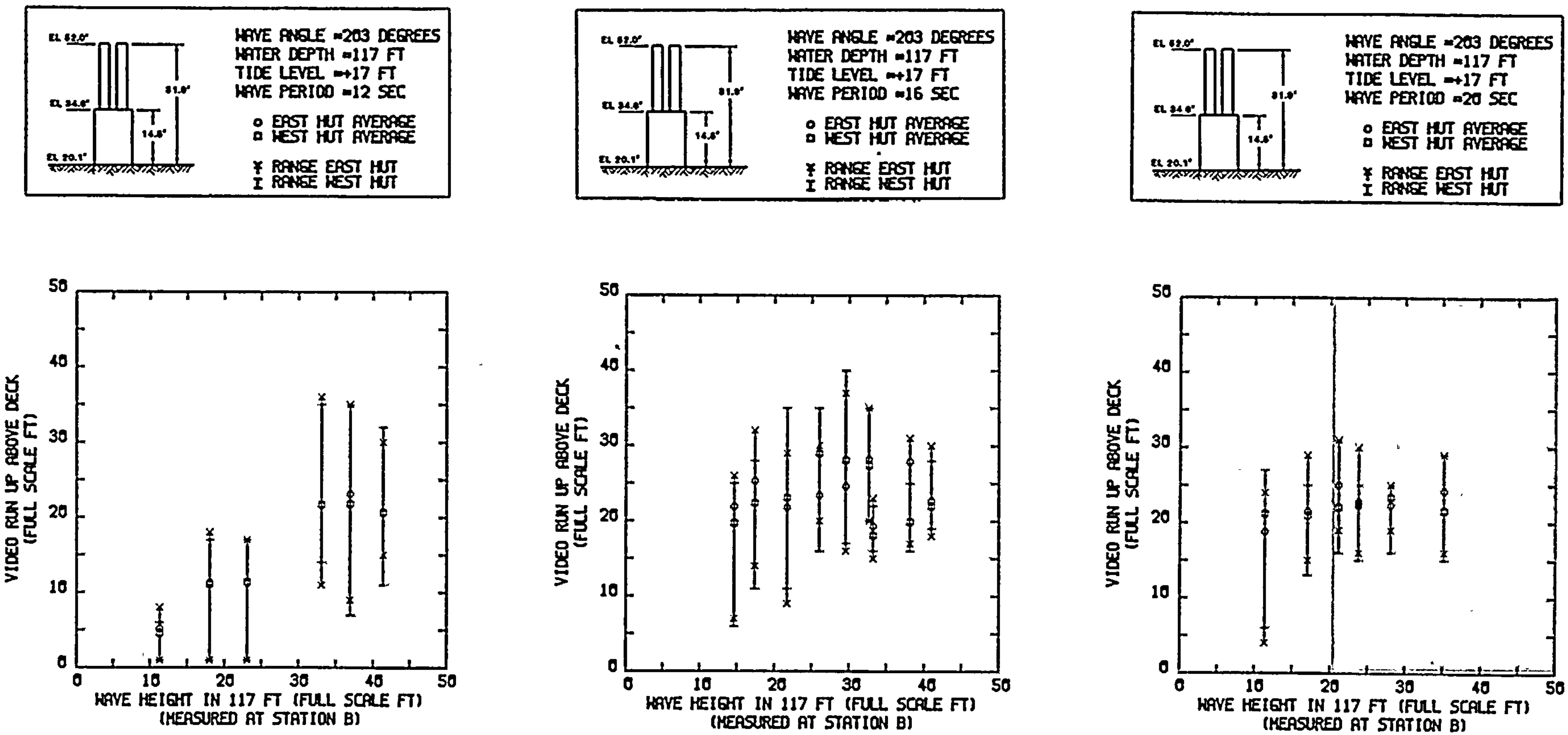


Figure 41

HEIGHT OF SPLASH RUNUP ABOVE DECK DUE TO WAVES FROM SOUTH FOR THREE WAVE PERIODS WITH CONCURRENT MAXIMUM TIDE, TSUNAMI AND METEOROLOGICAL SURGE (+17 FEET)



(a) (b) (c)

Figure 42

In addition to measuring the forces and bending moments on the existing air intake structures, the huts, similar measurements of forces and bending moments acting on the snorkels were measured concurrently. In the model the snorkels were not connected to the rectilinear concrete huts. Thereby the forces and moments on the snorkels and on the huts were separately determined. It was found that for all experiments the forces on the snorkels were negligible, or in many instances could not be detected at all. This is due to the setback of the snorkel pipes from the faces of the huts. As the water moving across the deck of the Intake Structure strikes the huts it rises nearly vertically, to a maximum height, and then falls back. Although at times the maximum elevation of the splash is significantly above the tops of the huts, solid water does not impinge against the snorkels. It is evident therefore, from these experiments, that solid water would not be ingested by the ventilation system if the snorkels were to be added to the present concrete huts and the existing apertures in the huts were closed. Further, considering that the forces on the snorkels were found to be negligible at most, and that forces, on the huts due to waves would be resisted readily by their present design, it is apparent that the snorkel solution is functionally and structurally feasible for conditions when waves approach from South and advance across the near coast terrain and the levelled breakwaters.

Waves From West

The same experiments as were carried out for waves from South were conducted with the wave machines moved to a position to generate westerly waves. At the 100 feet contour waves from West have been changed 12° more or less in direction by refraction, to about 258° as determined from the numerical refraction studies referred to earlier (see Figure 25,

Page 43). Therefore, for the westerly waves experiments the wave machines in the model tank were re-positioned to produce waves of that 258° direction. The limited height waves that were identified in this series of tests have been discussed earlier and are illustrated by Figures 32 and 33, Pages 58 and 59.

In Figures 43 and 44, the forces on the air intake huts are shown as before, as a function of the wave height near the wave machines for the same two still water levels and for the same three wave periods used throughout these studies. Again the average of the forces for the first five to six waves and the range of the maximum and minimum forces are presented. It is seen that even for the higher still water level these forces are considerably less than the forces for the southerly waves. The explanation for this lies in the difference in the submarine terrain features affecting the waves as they approach the levelled breakwaters from these two different directions, and also is related to the presence of the high rock mass at the shore just West of the Intake Structure. This large rock mass sometimes has been referred to as the "110 foot Rock", because it rises to an elevation of about 110 feet aboveMean Lower Low Water Datum. Although the waves from West are not greatly affected by refraction as they approach West Breakwater near or just West of the Intake Structure, the rock mass does provide significant shelter for the Intake Structure from waves from that direction.

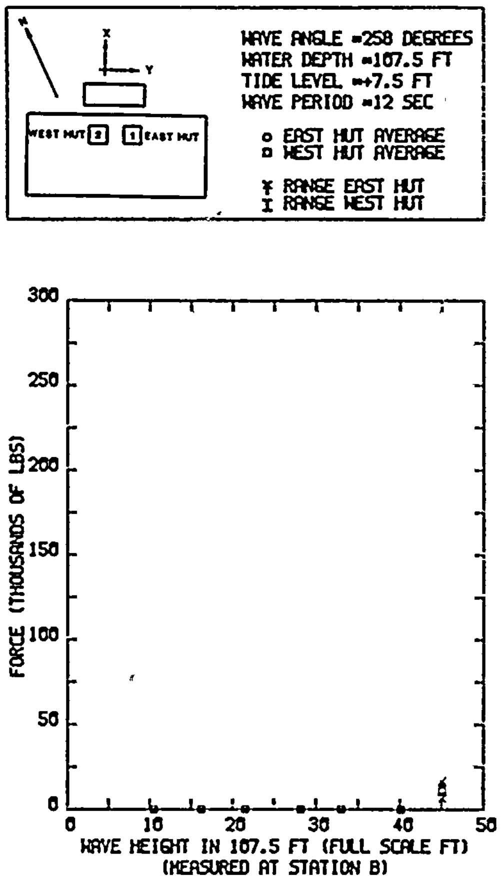
In Figures 45 and 46, the azimuths of the resultant forces on the huts for these West waves are presented and show that, on the average, the directions of the resultant forces are about 240°. As would be expected, this indicates a force which has more of a component in the y-direction (see the inset figure) than the forces which arose due to the

southerly waves. However, this difference may be unimportant, because of the relatively small forces the huts sustain from waves in these experiments.

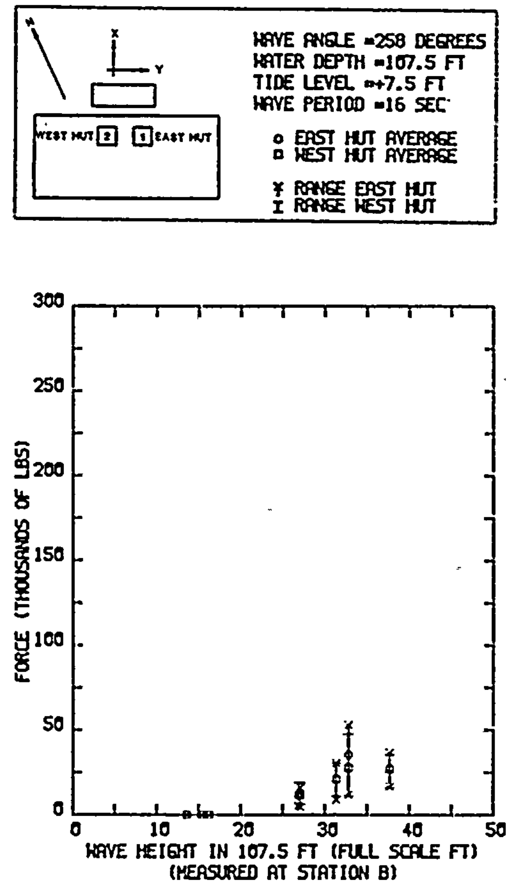
The locations of the point of application of the forces above the deck are shown in Figures 47 and 48.

The runup and splash on the huts due to westerly waves is presented in Figures 49 and 50. The elevations to which water rises are much less than are the elevations for waves from South. Nevertheless there could be some problems of water ingestion even for the westerly direction if the air intake level were not extended upward with snorkels. No force was measurable on the snorkels due to westerly waves, indicating that solid water does not dash against them.

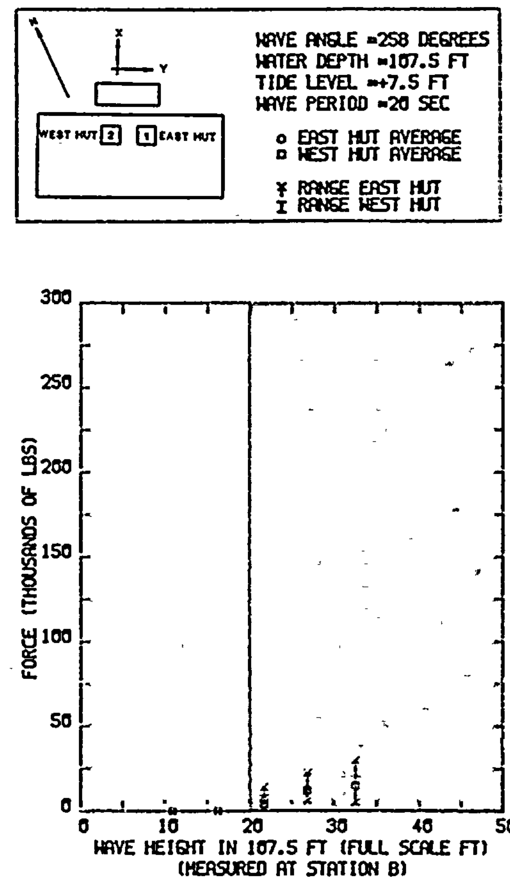
FORCES INDUCED ON HUTS BY WAVES FROM WEST FOR THREE WAVE PERIODS AT MAXIMUM TIDE LEVEL (+7.5 FEET)



(a)



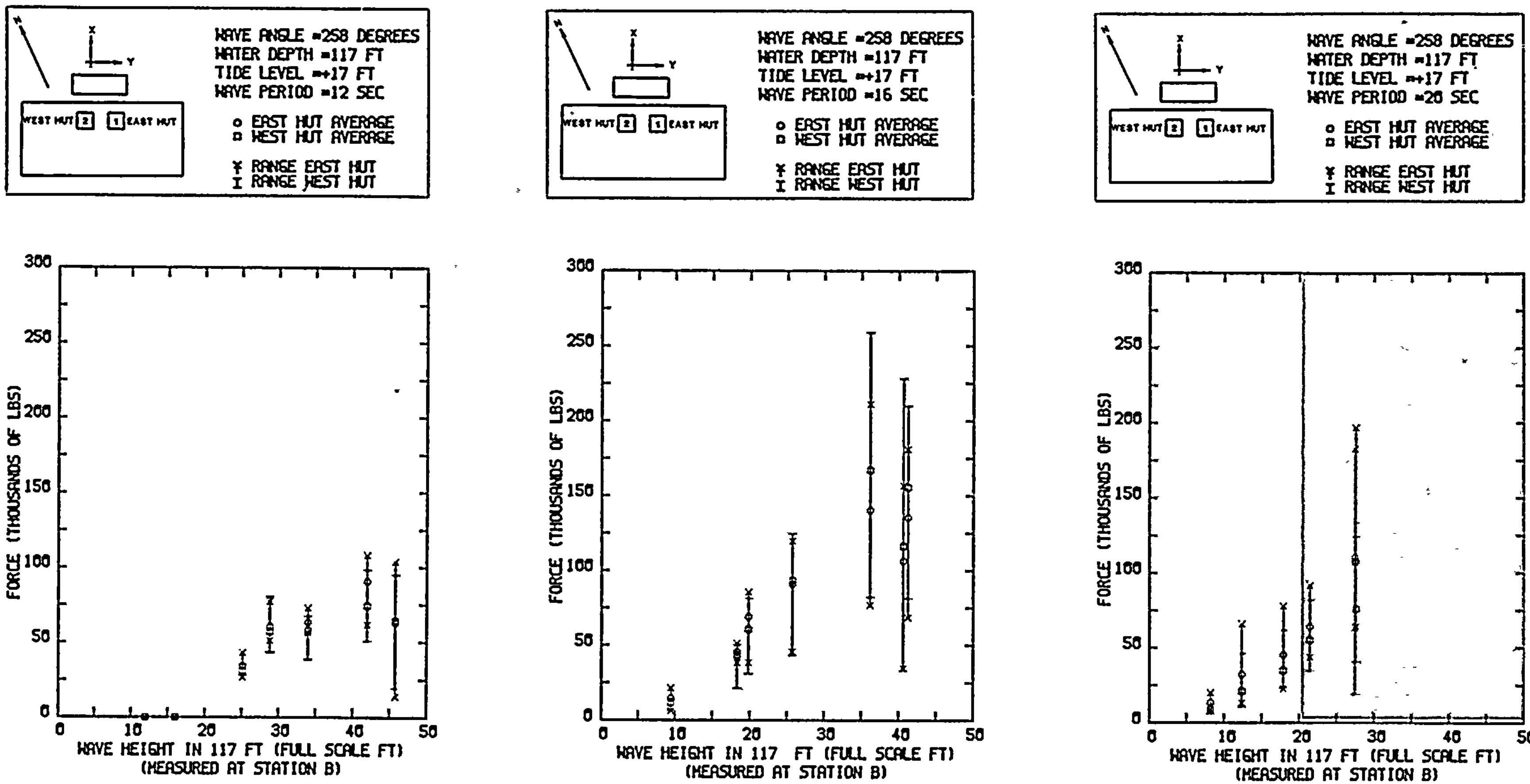
(b)



(c)

Figure 43

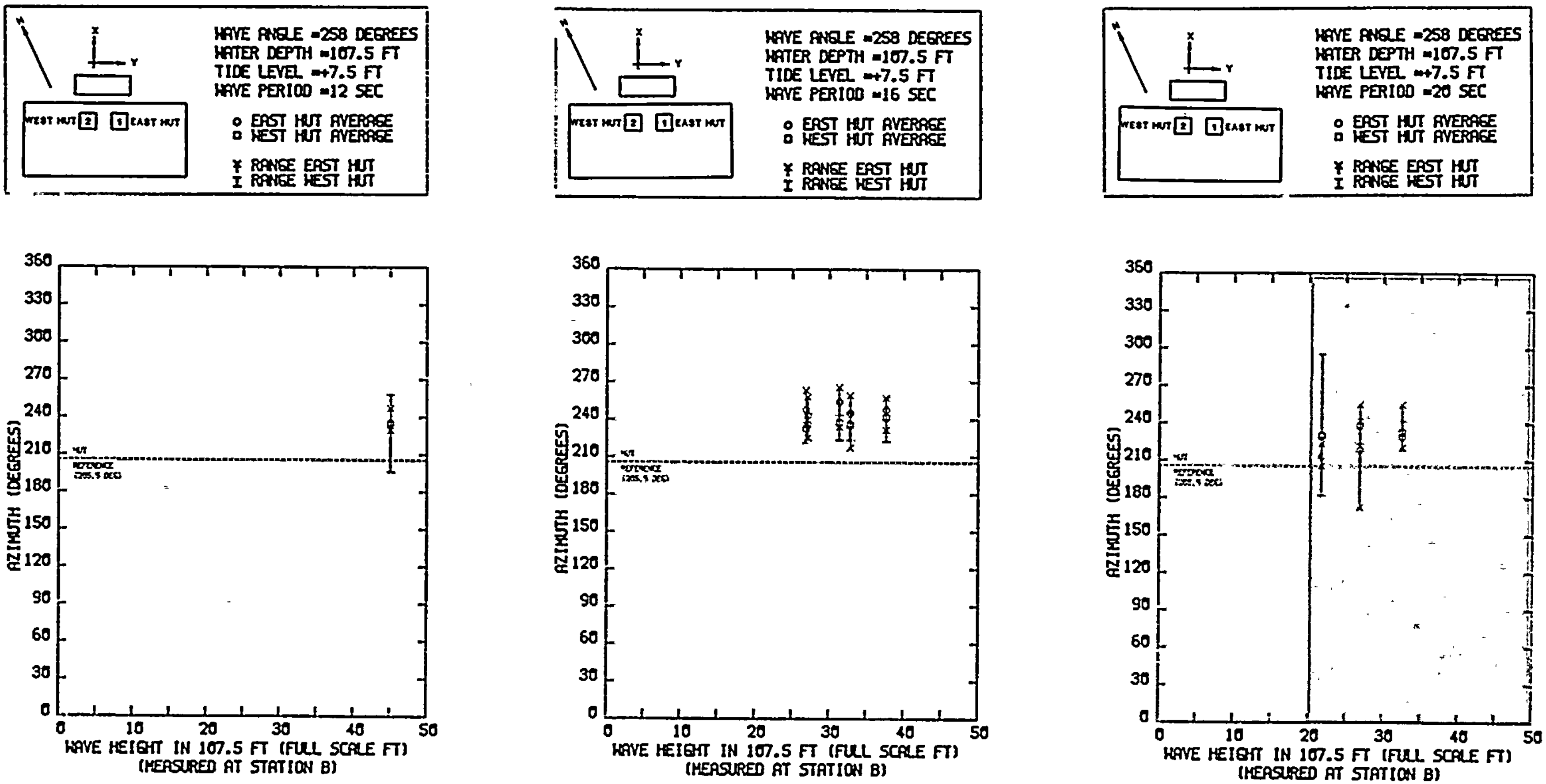
FORCES INDUCED ON HUTS BY WAVES FROM WEST FOR THREE WAVE PERIODS WITH CONCURRENT MAXIMUM TIDE, TSUNAMI AND METEOROLOGICAL SURGE (+17 FEET)



(a) (b) (c)

Figure 44

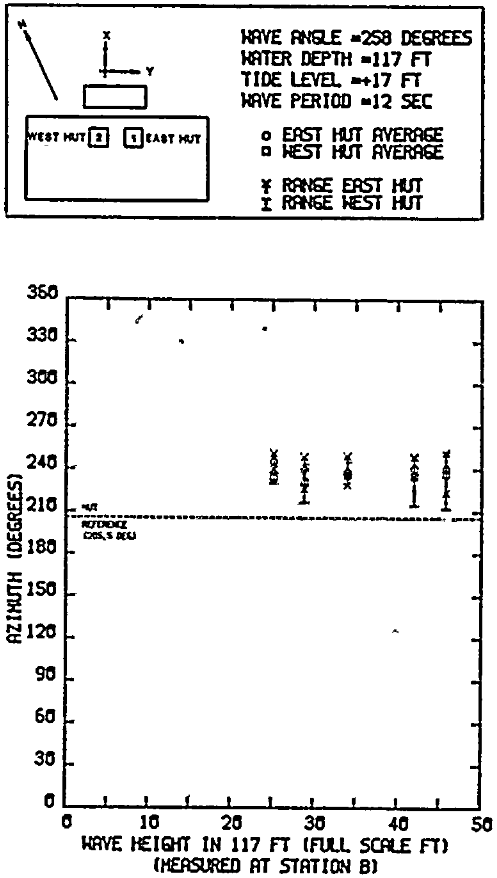
RESULTANT DIRECTION OF FORCES ON HUTS DUE TO WAVES FROM WEST FOR THREE WAVE PERIODS AT MAXIMUM ASTRONOMICAL TIDE LEVEL (+7.5 FEET)



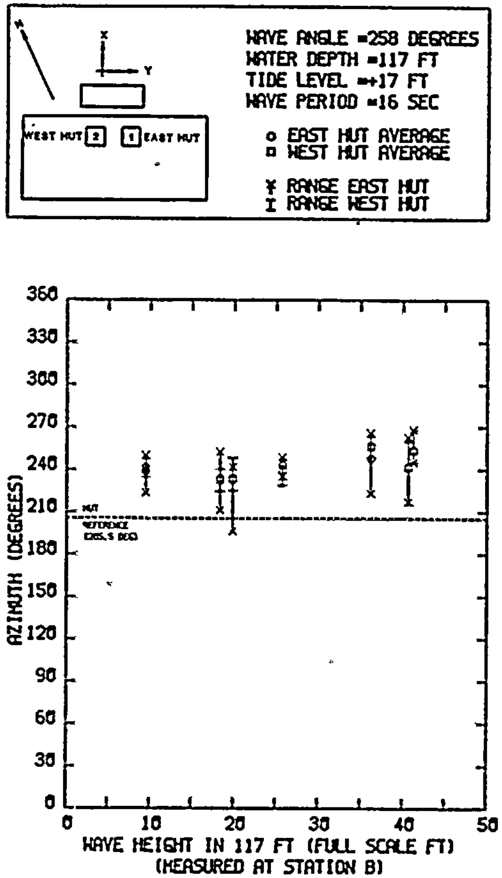
(a) (b) (c)

Figure 45

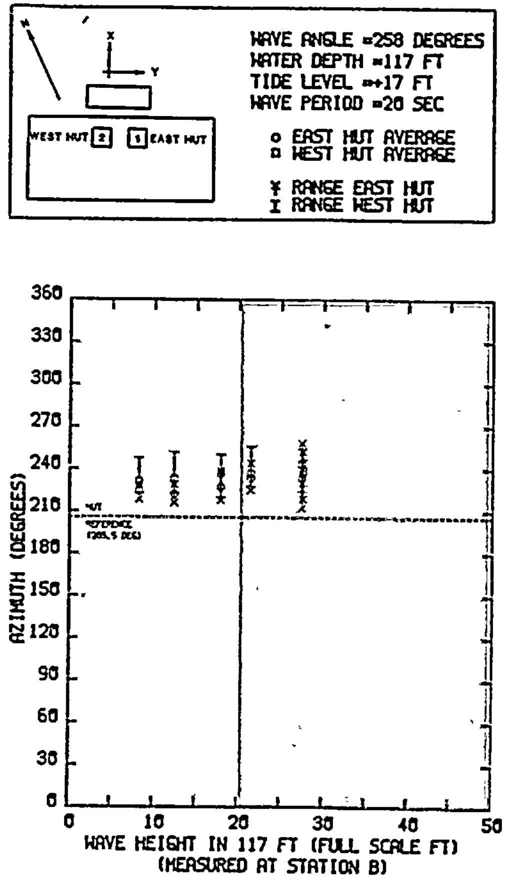
RESULTANT DIRECTION OF FORCES ON HUTS DUE TO WAVES FROM WEST FOR THREE WAVE PERIODS WITH CONCURRENT MAXIMUM TIDE, TSUNAMI AND METEOROLOGICAL SURGE (+17 FEET)



(a)



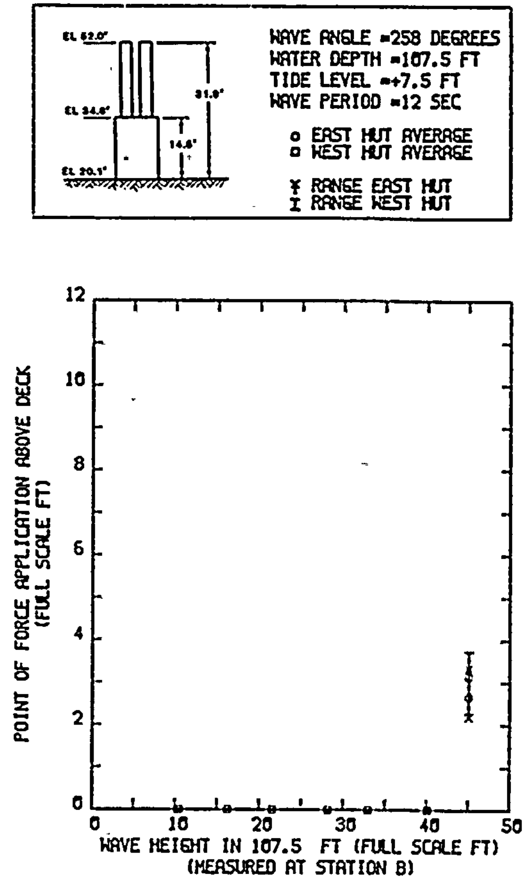
(b)



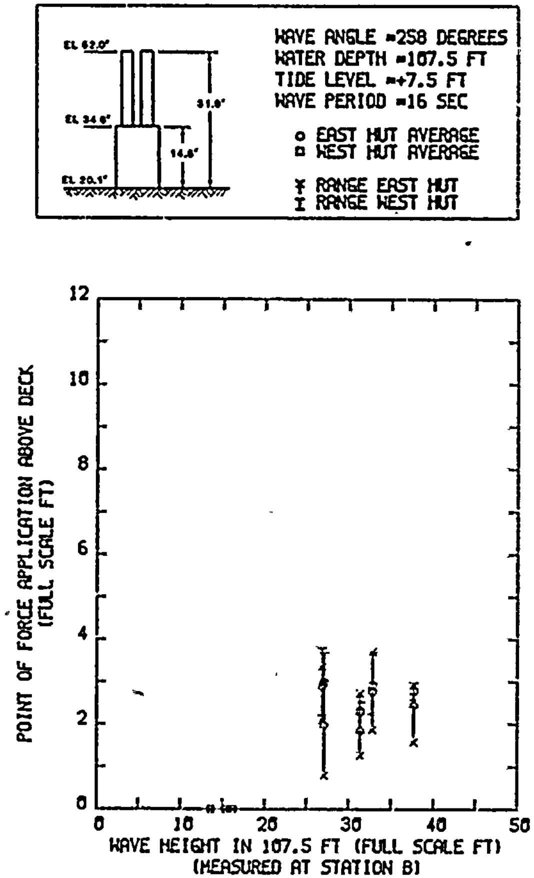
(c)

Figure 46

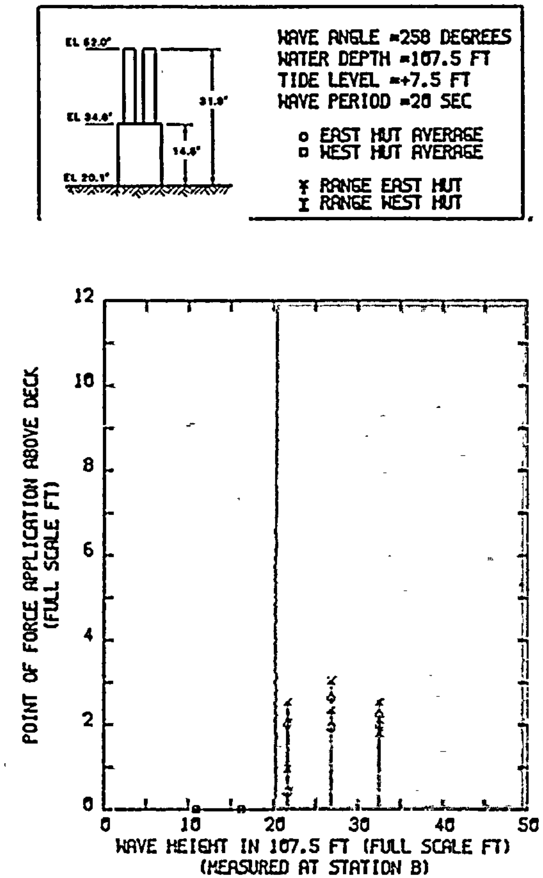
HEIGHT ABOVE DECK OF RESULTANT FORCES DUE TO WAVES FROM WEST FOR THREE WAVE PERIODS AT MAXIMUM TIDE LEVEL (+7.5 FEET)



(a)



(b)



(c)

Figure 47

HEIGHT ABOVE DECK OF RESULTANT FORCES DUE TO WAVES FROM WEST FOR THREE WAVE PERIODS WITH CONCURRENT MAXIMUM TIDE, TSUNAMI AND METEOROLOGICAL SURGE (+17 FEET)

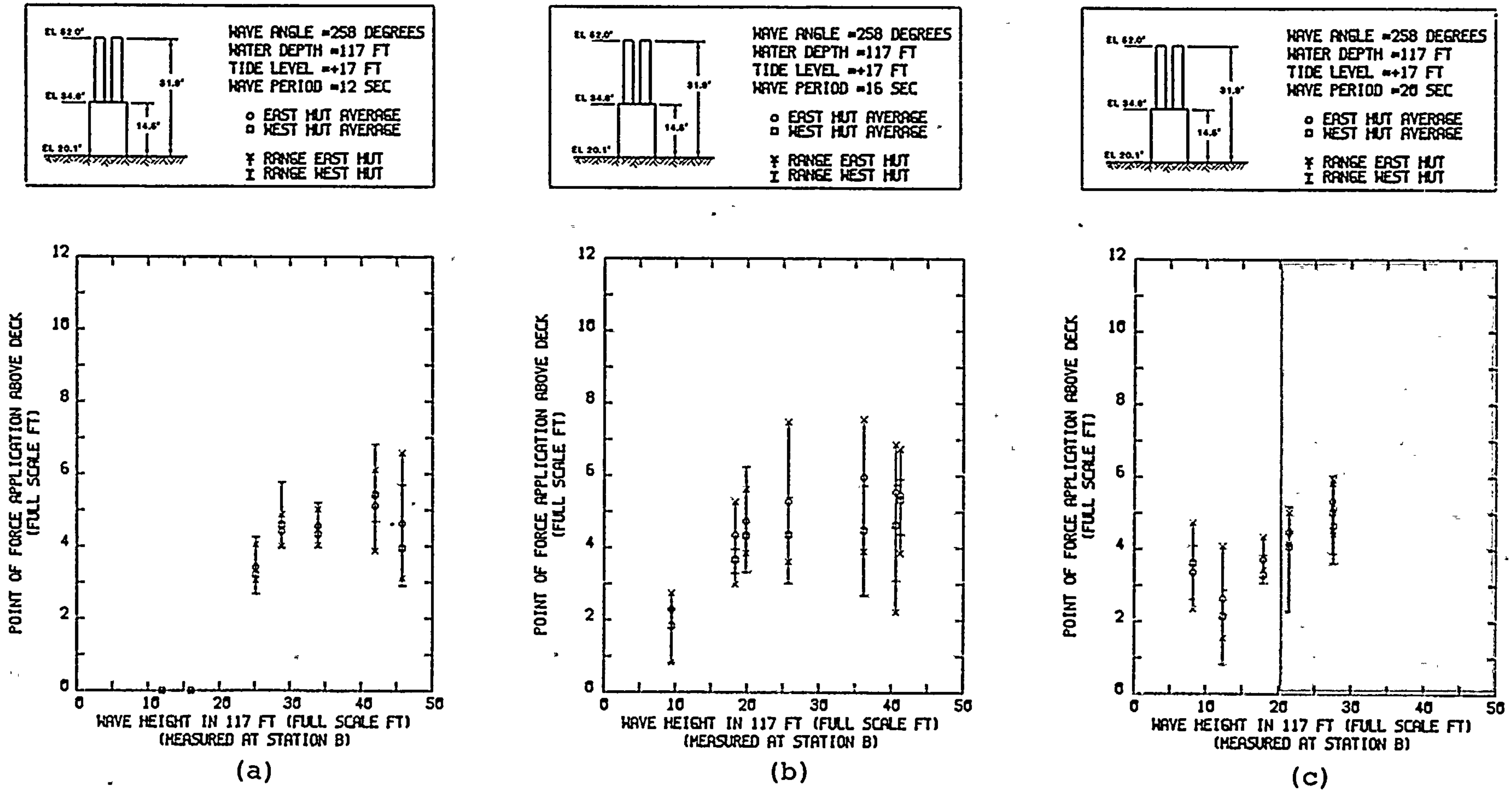
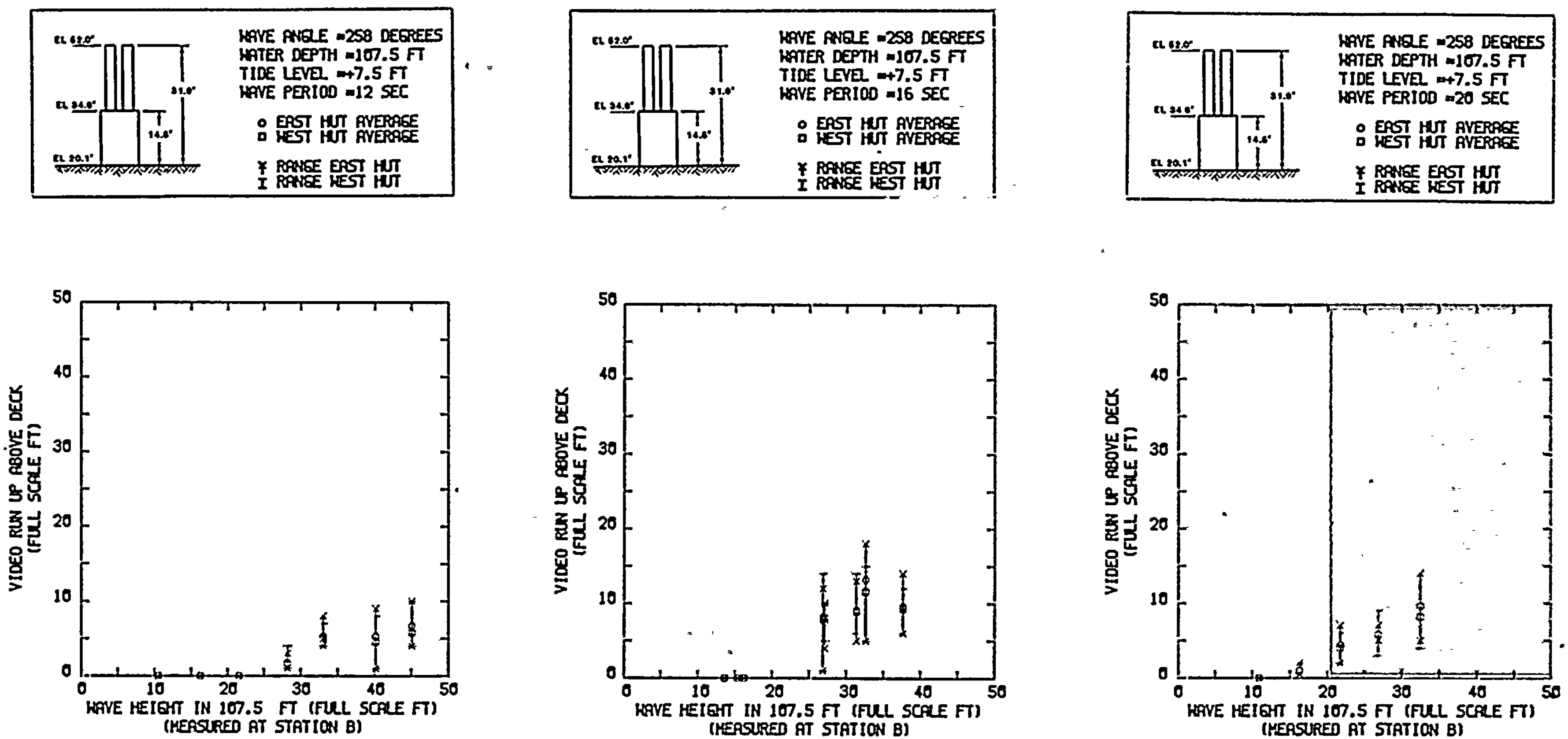


Figure 48

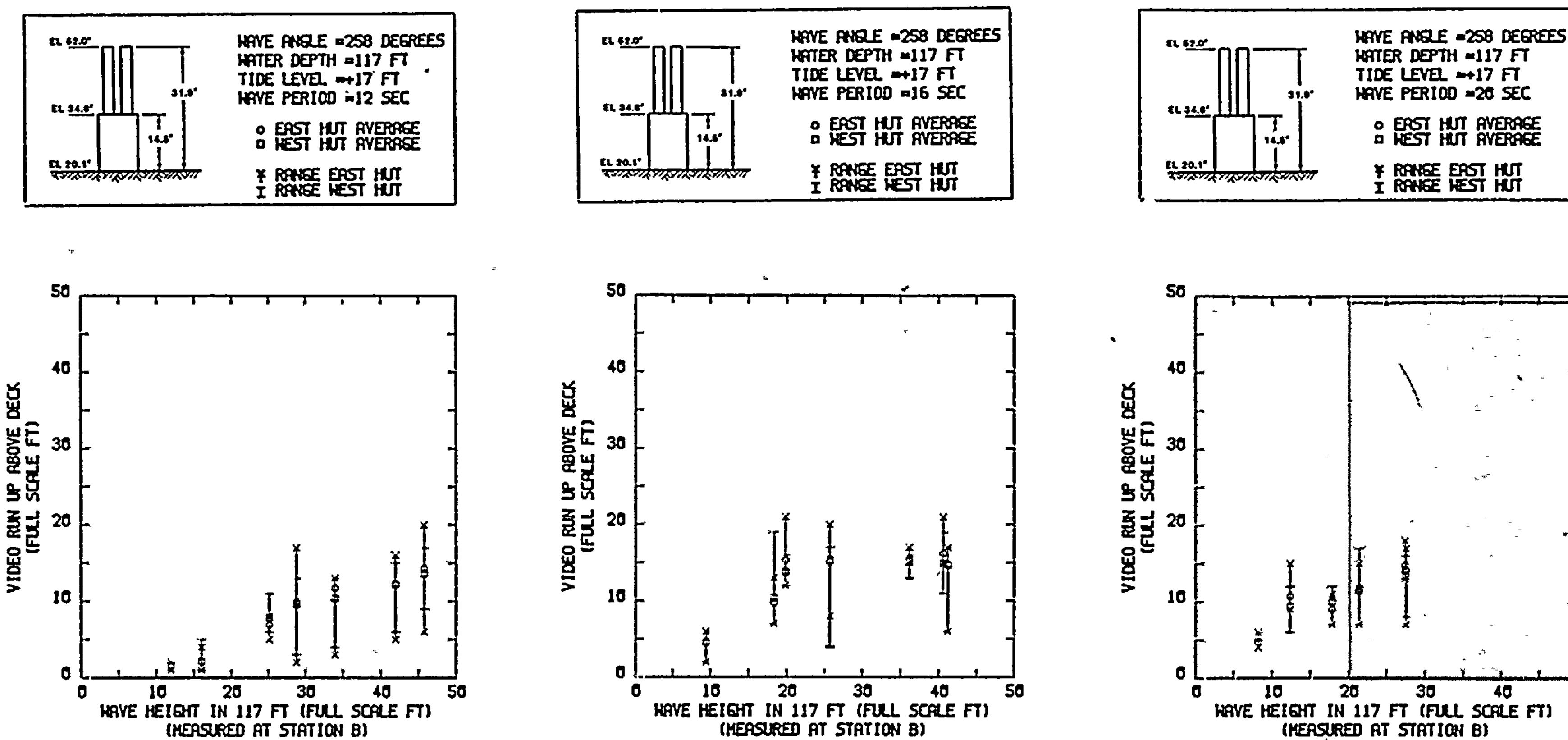
HEIGHT OF SPLASH RUNUP ABOVE DECK DUE TO WAVES FROM WEST FOR THREE WAVE PERIODS AT MAXIMUM ASTRONOMICAL TIDE LEVEL (+7.5 FEET)



(a) (b) (c)

Figure 49

HEIGHT OF SPLASH RUNUP ABOVE DECK DUE TO WAVES FROM WEST FOR THREE WAVE PERIODS WITH CONCURRENT MAXIMUM TIDE, TSUNAMI AND METEOROLOGICAL SURGE (+17 FEET)



(a) (b) (c)

Figure 50

CONCLUSIONS

1. The heights of waves at the locality of the Cooling Water Intake Structure reach "limited" values due to the effects of offshore terrain features and of the breakwaters. Further increases in the offshore wave heights above those values do not increase the height of waves at the Intake.

2. The limited heights for the waves at the Intake Structure locality differ according to the period or frequency of the waves that are occurring and according to the direction in offshore waters from which they approach the Intake Basin.

3. The limited heights of waves at the Intake Structure locality also differ according to the profile elevations of the breakwaters that bound the Intake Basin. The limited wave heights are greater when the breakwater profiles are lowered in elevation.

4. If the profiles of both breakwaters have been levelled to elevation 0.0 feet by cumulative unrepaired damage due to storm waves and seismicity the maximum rise of splashed water (runup) observed in the model near the Air Intake Structures due to maximum limited waves indicates that some modifications to the huts are necessary to prevent ingestion of splashed water.

5. Steel tube riser stacks (snorkels) added to the present Air Intake Structures remain clear of splashed water and appear to provide means for a satisfactory solution to the splash ingestion risk.

6. With maximum limited wave heights occurring with the profiles of both breakwaters levelled to Mean Lower Low Water elevation, the structural loading on the concrete huts due to moving water impinging against and rising around those huts is substantially less than the magnitude of loads for which the huts were designed.

7. Under the same conditions of limited wave heights set forth in Number 6 above, there are no measurable loads against twin cylindrical upward extensions (snorkels) of the ventilation air intake huts due to water splashed upward after impinging against the existing ventilation air huts. It appears therefore that structural adequacy of such snorkels can readily be attained.

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Whittier, California
March 15, 1982