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Laboratory Effects in Beach Studies

Volume VIII

Analysis of Results from 10 Movable-Bed Experiments

by
Charles B. Chesnutt

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Variation in wave reflection from a movable bed as it adjusted to the impinging waves was the primary source of wave height variability in 10 experiments in 6- and 10-foot-wide wave tanks. Re-reflection of waves from the wave generator, secondary waves, transverse waves, and cross waves also contributed to the wave height variability.

(continued)

The reflection coefficient, K_R, variation ranged from 0.02 to 0.12 in one experiment to as much as from 0.04 to 0.27 in another experiment. Changes in the foreshore slope and berm-crest elevation, the breaker type, the slope and top elevation of the offshore slope, and the distance between the foreshore and offshore were the sources of the K_R variability. For a constant initial profile slope, the average K_R increased with increasing wavelength; but for a constant wavelength, the average K_R decreased with increasing initial profile slope. In nine experiments the K_R tended to increase as the profile developed, indicating that the profile was reflecting, rather than absorbing, energy.

Profile equilibrium was not easily attained, particularly in five experiments with a wave steepness of 0.021, which is in the transition region between "winter" and "summer" waves. Experiments with winter or summer waves reached equilibrium more readily.

Laboratory effects, caused by differences in initial profile slope, initial test length (distance between the wave generator and the initial shoreline), tank width, and water temperature, affected the profile development and the wave height variability. Initial profile slope and initial test length should be kept constant to assure test repeatability in movable-bed experiments. The wavelength-to-tank width ratio should be greater than or equal to 3 to assure two dimensionality of profile development, but two-dimensional profiles may not be realistic replications of three-dimensional profiles.

PREFACE

Ten experiments were conducted at the Coastal Engineering Research Center (CERC) from 1970 to 1972 as part of an investigation of the Laboratory Effects in Beach Studies (LEBS), to relate wave height variability to wave reflection from a movable-bed profile in a wave tank. The investigation also identified the effects of other laboratory constraints. The LEBS project is directed toward the solution of problems facing the laboratory researcher or engineer in charge of a model study; ultimately, the results will be of use to field engineers in the analysis of model studies. The work was carried out under the CERC coastal processes research program.

This report (Vol. VIII) is the last in a series of eight volumes on the LEBS experiments. Volume I describes the procedures used in the 10 LEBS experiments, and serves as a guide for conducting coastal engineering laboratory studies; Volumes II to VII are data reports covering all experiments.

This volume is a comprehensive analysis of results from all 10 experiments, and includes a further analysis of each experiment and how it relates to the other 9 experiments on wave height variability, profile equilibrium, and laboratory effects.

This report was prepared by Charles B. Chesnutt, principal investigator, under the general supervision of Dr. C.J. Galvin, Jr., Chief, Coastal Processes Branch.

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Comments on this publication are invited.

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JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

LABORATORY EFFECTS IN BEACH STUDIES

Volume VIII. Analysis of Results from 10 Movable-Bed Experiments

by
Charles B. Chesnutt

I. INTRODUCTION

Laboratory effects, caused by differences in tank width, initial slope, distance between the generator and the profile, gaps at the end of the generator blade, and, perhaps, even water temperature, can hinder the solution of coastal engineering problems in movable-bed laboratory studies by distorting the development of the movable-bed profile and causing spatial and temporal variations in the wave height. Temporal wave height variability caused by the changing reflectivity of the developing profile complicates the study of the laboratory effects, as well as the investigation of coastal engineering problems. Temporal reflection variability would presumably be eliminated after the profile reached equilibrium, but equilibrium is difficult to define and attain in the laboratory.

1. Background.

The Laboratory Effects in Beach Studies (LEBS) project (called the Wave Height Variability project until 1971) was initiated in 1966 to investigate the sources of and possible solutions to the wave height variability observed in longshore transport experiments at the Coastal Engineering Research Center (CERC) in the late 1950's and early 1960's. Three-dimensional experiments were performed in 1967 to isolate the major sources of wave height variability. The superposition of incident and reflected waves was found to be a major source of spatial variability, and changes in the profile reflectivity was found to be a major source of temporal variability.

Two-dimensional tests were performed in 1968 and 1969 to study wave reflection and served mainly to develop improved techniques for collecting and reducing profile surveys and wave reflection data.

During 1970 to 1972, 10 lengthy experiments were conducted to define the amount of wave height variability due to wave reflection and variation in reflection. These experiments were to be continued until the profile reached equilibrium and the temporal wave height variability ceased. The effect of tank width was to be studied by conducting tests in both 6- and 10-foot-wide (1.8 and 3.0 meters) tanks. The results of these experiments have also pointed out other laboratory effects.

2. LEBS Reports.

This report (Vol. VIII), the last of a series of eight volumes on LEBS, analyzes the results of the 10 experiments.

The experimental conditions, facilities and equipment, quality control procedures, and data collection and reduction procedures common to all 10 experiments are documented in Volume I (Stafford and Chesnutt, 1977). Data reduction and collection procedures unique to individual experiments are described in appendixes to Volumes II to VII (Chesnutt and Stafford, 1977a, 1977b, 1977c, 1977d, 1978a, 1978b).

Volumes II to VII discuss the results from the 10 experiments and draw conclusions from the one or two experiments described in each volume. The experimental conditions of the 10 experiments are summarized in Table 1; the volume in which each experiment is reported, and reference to three other studies which discuss some of these experiments are also given in the table.

Table 1. Summary of experimental conditions.

Experiment[1] (No.)	Initial test length[2] (ft)	Initial slope	Wave period (s)	Nominal wave height[3] (ft)	MR 77-7 (Vol.)	Other references
72C-10	54.7	0.10	1.50	0.41	V	
70X-06	100.0	0.10	1.90	0.36	II	Chesnutt, et al. (1972) Chesnutt and Galvin (1974) Chesnutt (1975)
70X-10	61.7	0.10	1.90	0.36	II	Chesnutt, et al. (1972) Chesnutt and Galvin (1974)
71Y-06	93.0	0.10	1.90	0.36	III	Chesnutt, et al. (1972) Chesnutt and Galvin (1974) Chesnutt (1975)
71Y-10	54.7	0.10	1.90	0.36	III	Chesnutt, et al. (1972) Chesnutt and Galvin (1974)
72D-06	93.0	0.05	1.90	0.36	IV	Chesnutt (1975)
72B-06	93.0	0.10	2.35	0.34	VII	
72B-10	54.7	0.10	2.35	0.34	VII	
72A-06	93.0	0.10	3.75	0.31	VI	
72A-10	54.7	0.10	3.75	0.31	VI	

[1]The first two digits of the experiment number indicate the year of experiment; the letters X, Y, A, B, C, and D indicate the separate volumes in the LEBS series of reports. The last two digits indicate either the 6- or 10-foot-wide wave tank used for the experiment.

[2]Distance from generator to the initial stillwater level intercept.

[3]Determined for given wave period and constant water depth of 2.33 feet, so that the generated wave energy flux had a constant value of 5.8 foot-pounds per second per foot.

3. Scope.

The primary purposes of the LEBS reports are to:

(a) Relate temporal and spatial wave height variability to the changing reflectivity of the developing profile;

(b) measure the approach of the profile to an equilibrium condition; and

(c) identify, and if possible quantify, the effects of other laboratory constraints (e.g., water temperature, tank width and length, and initial slope) on the resulting laboratory profile.

The discussion of results in Section IV of Volumes II to VII covered (a) wave height variability, (b) profile equilibrium, and (c) laboratory effects. This volume discusses those topics in Sections II, III, and IV, respectively. The data from individual experiments are not repeated in this volume, but the results from Volumes II to VII are compared to develop more generalized conclusions (Sec. V) and recommendations (Sec. VI).

Definitions of coastal engineering terms used in LEBS reports conform to Allen (1972) and the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). A definition sketch of typical profile zones is shown in Figure 1. The backshore-foreshore boundary is at the upper limit of wave uprush, the foreshore-inshore boundary at the lower limit of wave backrush (low water line), and the inshore-offshore boundary at a point just seaward of the breaker.

Plots of contour movement (CONPLT plots) are used in all experiments to show, in one figure, the changes in profile shape along a given profile line throughout an entire experiment. An interpretation of these CONPLT plots is given in Section II,2 of Volumes II to VII.

The LEBS data have other uses to both the laboratory and field engineer. For example, the profile surveys, sediment-size distribution data, and breaker conditions reported in Volumes II to VII, and color slides of the ripple formations (available at CERC) can be used in a more detailed analysis of coastal processes. The shoreline recession rates from several of the experiments can be used by the field engineer, after consideration of scale and laboratory effects, in determining generalized shoreline recession rates. A further analysis of the profile surveys is currently being conducted by CERC to determine temporal variations in net onshore-offshore material transport. The profile data would be useful in calibrating a numerical model of profile evolution.

The LEBS reports are not an all-inclusive study of laboratory effects, because several other known laboratory effects have yet to be examined intensively. These reports serve as an introduction to the subject of laboratory effects and as a guide to some of the problems involved in performing movable-bed coastal engineering model studies and research experiments.

II. WAVE HEIGHT VARIABILITY

The nominal (generated) wave height, H_G, in Table 1 is the height of the wave traveling from the generator toward the profile unaffected

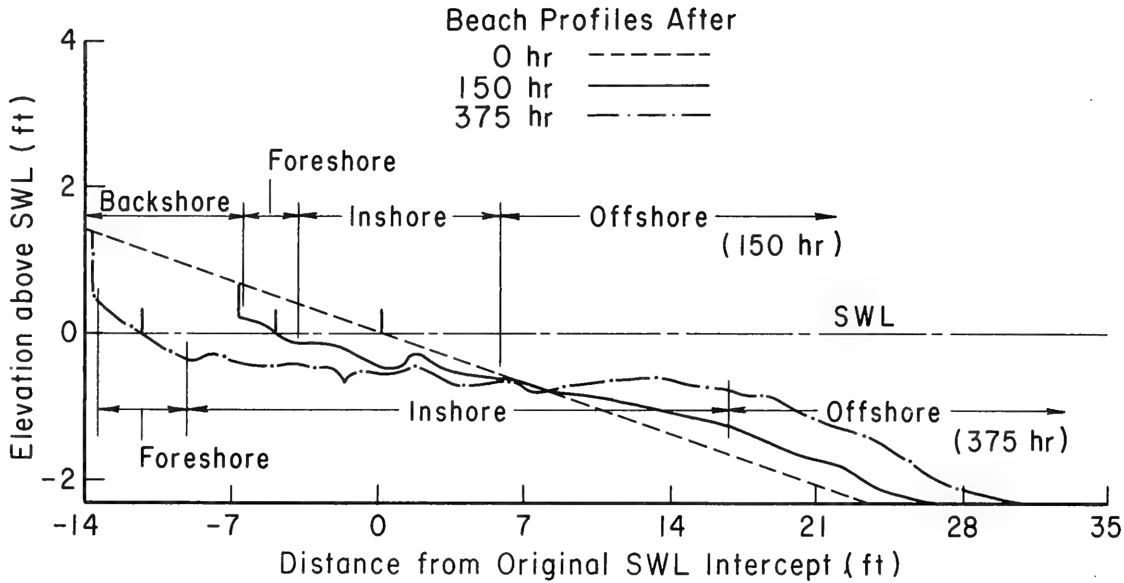


Figure 1. Definition sketch of profile zones (experiment 71Y-06).

by reflection, wave instabilities, or tank oscillations. This wave height (referred to as the generated wave height in Vols. I to VII) is assumed to remain constant as long as the generator operates smoothly.

Wave height variability is any deviation in wave height from H_G. This variability can be spatial (the wave height varies with position along the tank (longitudinally) or across the tank (laterally)), or temporal (wave height varies with time at any point).

The terms used in describing and calculating wave height variability are defined below. Variation in wave reflection from the profile, which is the major source of wave height variability, and other sources of wave height variability are discussed in this section.

1. Definitions of Terms.

a. Operational Terms. The following terms were used in the measurement and calculation of wave height variability parameters.

(1) *Wave record*--a strip-chart recording containing all the water surface elevation measurements during a given run. Wave records include recordings made with a stationary gage or a slowly moving gage.

(2) *Crest and trough elevations and positions*--determined from wave records using a digitizer, which produced a deck of punchcards containing the (a) position (on the recording) and elevation of all wave troughs, (b) position and elevation of all wave crests, and (c) position of all tick marks relating chart paper position to stations along the wave tank.

(3) *Computer programs WVHTCN and WVHTC2*--written to automate the analysis of wave height variability data.

(4) *Local wave height* (H_ℓ)--the difference in elevation between a trough and the succeeding crest, with its position defined midway between the two points (determined by the program WVHTCN).

(5) *Average wave height* (H_M)--the average of all the local wave heights in a record (determined by the program WVHTCN).

(6) *Running average wave height* (H_m)--the average of all local wave heights within a standing wavelength (one-half the generated wavelength) of a point (calculated for each H_ℓ by the program WVHTCN).

(7) *Running average wave height deviation* (D_m)--calculated by subtracting H_M from each H_m along the tank (plotted as a function of tank position by the program WVHTCN).

(8) *Amplitude of the running average deviation* (A_m)--determined by measuring the maximum deviations on the plot of D_m versus tank position and averaging the absolute values of the maximum deviations.

(9) *Local wave height deviation from the average* (D_ℓ)--calculated by subtracting H_M from each H_ℓ and then removing any long waves or tank oscillations from this curve by subtracting the local D_m value from each H_ℓ (calculation is performed by the program WVHTCN, which then plots D_ℓ as a function of tank position).

(10) *Amplitude of local wave height deviation from the average* (*A*)--the amplitude of the best fit size curve to the plot of D_ℓ versus tank position (computed by program WVHTC2).

(11) *Reflection coefficient* (K_R)--calculated by dividing A by H_M. This procedure for estimating K_R is referred to as the automated method in Volumes I to VII. A manual method for determining K_R is described in Volume I, which also contains a description of the automated method. Most K_R values in this volume were obtained with the automated method. The K_R values not determined directly by the automated method were determined by the manual method and adjusted by an amount equal to the average difference between the two methods to make the values comparable to the automated K_R's. Volumes II to VII contain further information on this difference.

b. Conceptual Terms. The following terms describe the different physical components of the deviation of the water surface from the still-water level.

(1) *Reflected wave height* (H_R)--the height of the seaward-traveling waves which have been reflected from the profile. Waves are reflected from any segment of the profile where the depth change is significant; i.e., the depth change is an appreciable fraction of the average depth over a horizontal distance less than one wavelength. Thus, waves can be reflected from more than one segment of the profile so that more than one reflected wave component with the same period may be present. However, over the constant depth section of the wave tanks the various components superpose, and in effect, they become a coherent reflected wave. The amplitude, A, of the deviation of the local wave height from the average (defined above) is a measure of the reflected wave height, H_R, in the constant-depth section of the tank. H_R is also equal to the product of K_R and H_I. H_I is defined in (3) below.

(2) *Re-reflected wave height* (H_{RR})--the height of the shoreward-traveling wave which has been reflected from the profile and then reflected from the wave generator. This wave height is the product of H_I, K_r of the profile, and the reflection coefficient of the generator, K_{RR}. Since wave filters were not used in front of the generator in the LEBS experiments, K_{RR} is assumed to be 1 and thus H_{RR} is equal to H_R.

(3) *Incident wave height* (H_I)--the height of the shoreward-traveling wave that results from the superposition of the nominal generated wave height, H_G, and the re-reflected wave height, H_{RR}. H_I varies with time as the phase difference between H_R and the generator motion varies. At any given time, H_I is equal to H_M (defined above).

(4) *Lateral tank oscillations*--long waves (with a period other than the period of the generator) resulting from critical combinations of wavelength and tank width, which occurred in some experiments and could not be controlled. These waves can be identified by examining the deviation of the running average wave height, D_m, along ranges other than the center range.

(5) *Wave instabilities*--variations in wave shape, which result from nonlinear shallow-water waves propagating in the tank.

2. Variations in Wave Reflection.

Reflection coefficients varied noticeably throughout the LEBS experiments (Table 2), and an important part of the experiments is the attempt to identify the causes of this variation.

Each of the two tanks had an adjacent control tank situated so that the same generator simultaneously produced the waves in both the test tank and the control tank. The control tank had a 0.10 smooth concrete slab instead of a movable bed. K_R variability in the fixed-bed tank is a measure of the K_R measurement accuracy in the movable-bed tank.

Table 2. Average reflection coefficient and limits of values in each LEBS experiment.

Experiment	Movable-bed tank		Fixed-bed tank	
	Avg K_R	Limits of K_R	Avg K_R	Limits of K_R
72C-10	0.05	0.02 to 0.12	0.01	0.01 to 0.02
70X-06	0.08	0.04 to 0.14	0.05	0.05 to 0.06
70X-10	0.09	0.00 to 0.15	0.05	0.03 to 0.07
71Y-06	0.08	0.01 to 0.23	0.05	0.03 to 0.06
71Y-10	0.07	0.01 to 0.13	0.05	0.04 to 0.07
72D-06	0.12	0.04 to 0.27	0.05	0.04 to 0.07
72B-06	0.08	0.03 to 0.14	0.04	0.03 to 0.06
72B-10	0.17	0.10 to 0.21	0.05	0.02 to 0.09
72A-06	0.26	0.17 to 0.31	0.08	0.06 to 0.08
72A-10	0.30	0.24 to 0.36	0.05	0.02 to 0.07

a. Processes. Three processes are involved in wave reflection from a movable-bed profile. These are the conversion of potential energy stored in runup on the foreshore into a seaward-traveling wave, the seaward radiation of energy from a plunging breaker, and reflection of the incident wave from the submerged profile, particularly where the depth over the movable-bed changes significantly (Chesnutt and Galvin, 1974).

(1) Reflection from the Foreshore. The foreshore developed a relatively stable shape within the first 10 minutes to 5 hours of each experiment. Since the foreshore shape remained fairly constant throughout each experiment, the reflection coefficient of the foreshore probably remained constant. The height of the wave reflected from the foreshore is assumed to vary directly with the height of the wave incident to the foreshore for each experiment.

Measuring the reflection from the foreshore alone was difficult, because the distance between the foreshore and the breaker was frequently too short to make an accurate measurement. Fluctuations in the measured K_R during the first 5 to 10 hours are likely due to fluctuations in the foreshore reflection.

(2) Reflection as a Result of Wave Breaking. Since surging and collapsing breakers break on the foreshore they do not contribute to the reflection process separately, but rather as part of the foreshore reflection. Spilling breakers, essentially a crumbling of the wave crest, do not involve any change in direction of the water particles, and thus are not a source of reflection. The plunging breaker propagates energy in both directions as the crest of the wave plunges into the water. However, in most experiments the breaker type changed from plunging to spilling as the profile developed, and thus the breaker reflection is assumed to decrease throughout an experiment.

Measuring the breaker K_R was even more difficult than the foreshore K_R, since the breaker reflection component is always superposed with the foreshore component and in a short distance becomes superposed with the offshore component. Estimates can be made from comparisons of the reflection from the concrete slope, which had a breaker and no foreshore, and reflections from the early profiles of the movable bed, which had reflection from both the foreshore and the breaker but very little from other parts of the profile.

(3) Reflection from the Inshore and Offshore Zones. Wave energy is reflected all along the submerged profile, but the reflection does not become significant until the profile slopes become significant. In most experiments, the profile developed into an almost flat shelf between two steep slopes (see Fig. 1). The development of these zones contributed greatly to the reflection variability and hence the temporal wave height variability. Three particular profile changes apparently caused significant wave height variability: changes in the steepness of the offshore slope, changes in the elevation of the shelf at the top of the offshore slope, and changes in the length of the shelf.

Increases in the offshore slope steepness increased the reflection; likewise, decreases in the slope steepness decreased the reflection. As the elevation of the shelf and top of the offshore slope increased, the reflection increased; as that elevation decreased, the reflection decreased. Increases in the length of the flat shelf, which was the distance between the two reflecting slopes, caused the phase difference between the two reflected wave components to vary. When the components were in phase, the measured H_R (in the constant-depth section) was high; when the components were out of phase, the measured H_R was lower than the absolute sum of the two reflected waves.

Because the phase difference between the two reflected components varied, the amount of energy reflected from the submerged profile could not be measured. However, the effect of the three profile changes can be seen in the reflection variability of some of the experiments.

b. Reflection of the 1.50-Second Wave. Figure 2 shows the K_R versus time for experiment 72C-10, the only experiment with a 1.50-second wave period. The K_R varied between 0.02 and 0.12 during the experiment, with no apparent increasing or decreasing trend in the maximum or minimum values or in the amount of variation. Minimum values occurred at 35, 60, 90, 95, and 120 hours; maximum values occurred at 1.5, 25, 55, and 105 hours.

Steep foreshore and offshore slopes developed almost immediately and then began to separate as the foreshore eroded landward and the offshore prograded seaward (Table 3). As the two reflecting zones separated, the change in phase difference between the two reflected waves would have caused a variation in the measured (total) K_R. Assuming linear theory and an average depth of 0.6 foot (18.3 centimeters), an increase of 3.12 feet (0.95 meter) in the distance between the two reflecting zones (i.e., the width of the inshore) would have caused a 360° change in phase difference. The distance between the 0- and -1.0-foot (0 to 30.5 centimeters) contour increased from 10 to 28.5 feet (3.0 to 8.7 meters) during the experiment. Therefore, five cycles of 360° phase-difference change were possible and if the cycle started with the two waves 180° out of phase, four in-phase (maximum) values were possible, as observed. The average K_R was 0.05 (Table 2).

The seaward movement of the seawardmost -0.8-foot (24.4 centimeters) contour (Fig. 2) is an indicator of the general steepening of the offshore zone and the shoreward movement of this contour that the elevation at the top of the submerged offshore slope dropped to -0.9 foot (27.4 centimeters). The shoreward movement of the -0.8-foot contour near the end of the experiment did not cause any noticeable reduction in K_R, as was observed for -0.7-foot (21.3 centimeters) contour during tests with the 1.90-second wave (see Fig. 45 in Vol. III), but here the average K_R was already smaller than the 1.90-second wave.

c. Reflection of the 1.90-Second Wave.

(1) Experiment 70X-06. The reflection coefficient, K_R, versus time for experiment 70X-06 is shown in Figure 3. During the first 10 hours, K_R varied between 0.03 and 0.14. At 10 to 25 hours, K_R remained fairly constant (0.08 to 0.11) and then dropped to 0.02 at 31 hours. From 33 to 45 hours, the K_R was lower, between 0.04 and 0.08,

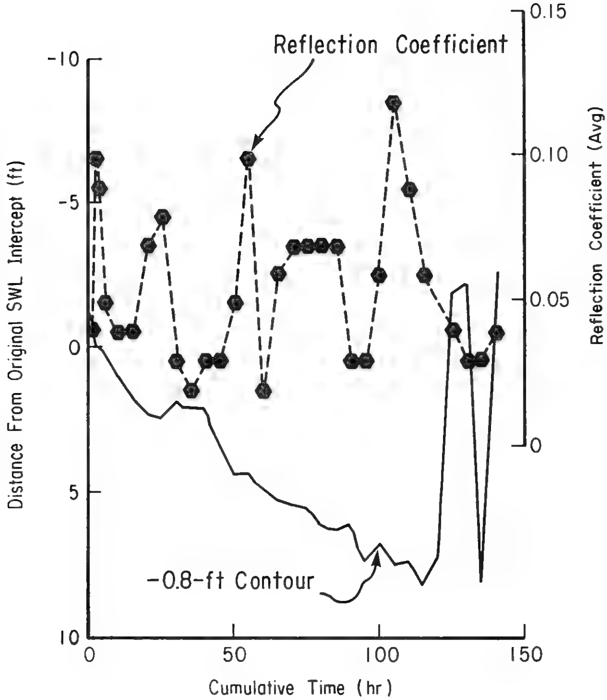


Figure 2. Reflection variability and movement of the -0.8-foot contour in experiment 72C-10.

Table 3. Summary of profile development in experiment 72C-10.

Time (hr)	Foreshore	Inner inshore	Outer inshore	Offshore	Breaker conditions: Position	Breaker conditions: Type	Water temperature (°C)
0 to 0.67	Developed basic shape	Longshore bar developed	Flat shelf developed, and grew in seaward direction; shoreward edge stable	Deposition at -0.9 to -1.4 ft	Moving seaward with outer edge of inshore	P[1]	19
0.67 to 1.5	Eroded at rate of 0.15 ft/hr						20
1.5 to 5		Bar stable					15
5 to 15		Bar eroded; shelf developed		Deposition throughout			15 to 16
15 to 30		Shelf grew in shoreward direction			Varied across outer inshore		9 to 14
30 to 50	Eroded at rate of 0.041 ft/hr; d_{50} = 0.20 mm	mean d_{50} = 0.21 mm		d_{50} = 0.20 mm		P,S[2]	10 to 16
50 to 85		Seaward edge stable	Bar and trough developed				6 to 9
85 to 115	100 hr: d_{50} = 0.25 mm	mean d_{50} = 0.22 mm		d_{50} = 0.20 mm	Two breaker positions; outer edge of outer inshore	S[3]	5 to 8
115 to 130	Approaching equilibrium		Depth over trough increasing beginning along outside walls and progressing toward center				
130 to 140	mean d_{50} = 0.25 mm	mean d_{50} = 0.22 mm		Deposition at -0.9 to -1.3 ft decreasing. Continuing at other elevations; mean d_{50} = 0.21 mm	Outer edge of inner inshore	P	6 to 8

[1]P = plunging.
[2]P,S = plunging and spilling.
[3]S = spilling.

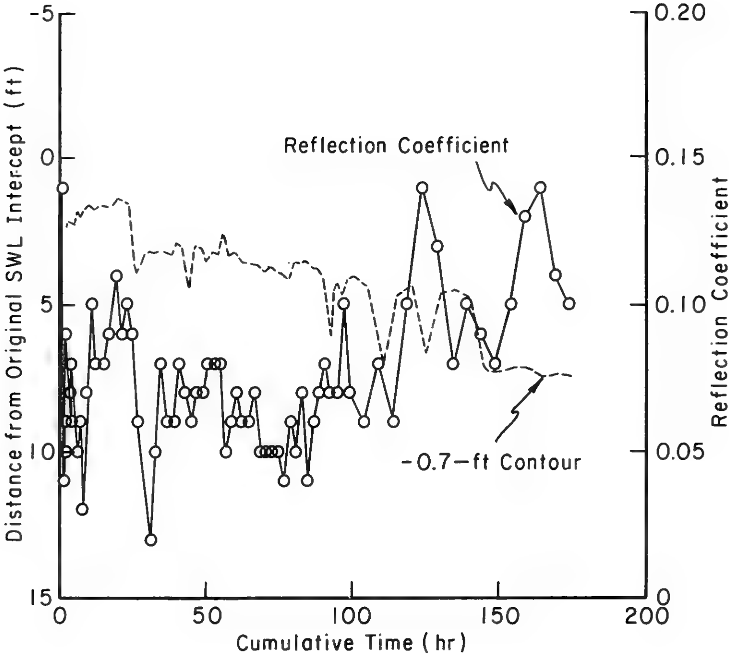


Figure 3. Reflection variability and movement of the -0.7-foot contour in experiment 70X-06.

and was very gradually decreasing; after 95 hours, K_R fluctuated between 0.06 and 0.14 and, in general, increased.

While K_R was fluctuating so greatly during the first 31 hours, the foreshore developed and eroded landward, a longshore bar developed, the bar and the plunging breaker moved landward and then seaward, and (after 26 hours) the offshore zone began to steepen (Table 4). All of these profile and breaker changes could have contributed to the K_R variations during that time. Between 33 and 95 hours, when K_R was less variable and very gradually decreasing, the foreshore position stabilized, the breaker type changed to spilling (and thus no longer reflected any energy), the longshore bar eroded (and thus was no longer a reflector), and the offshore slope gradually steepened at the base and prograded slowly seaward (and thus the phase difference between waves reflected from the two zones may have gradually changed). A change of 4.5 feet (1.4 meters) between the foreshore and offshore would have caused a 360° change in phase difference. After the shelf developed, the distance between the 0- and -1.5-foot (45.7 centimeters) contour increased only 1.9 feet (57.9 centimeters).

Table 4. Summary of profile development in experiment 70X-06.

Time (hr)	Foreshore	Inner inshore	Outer inshore	Offshore	Breaker conditions		Water temperature (°C)
					Depth (ft)	Type[1]	
0 to 1	developed characteristic shape	bar formed			0.5	P	28 to 30
1 to 5	avg. erosion rate of 0.06 ft/hr	elevation of bar increased to -0.3 ft		deposition > 1.1 ft	0.5	P	25 to 26
5 to 8		bar moved shoreward, depth 0.3 ft		deposition > 0.8 ft	0.5	P	24 to 27
8 to 22		bar stable (depth and position)		deposition > 0.8 ft	0.5	P	26 to 30
22 to 26	avg. erosion rate of 0.14 ft/hr	bar moved seaward, depth 0.4 ft	large deposition at depths of 0.7 and 0.8 ft	deposition at 0.9 ft	0.5	P	28; drop to 18
26 to 30		position of bar stable, depth varied 0.3 to 0.4 ft	deposition at 0.8 ft	large deposition at 1.1 and 1.0 ft	0.5	P	17 to 18
30 to 40	0.10			deposition at all depths	position moving seaward to 0.6-ft depth	P	17 to 20
40 to 44					0.6	changed from P to SP	21
44 to 54	SWL stable erosion of last of scarp		erosion at 0.5 and 0.6 ft		0.6	SP	21; drop to 16
54 to 66	fill started erosion of fill << avg.	bar eroded	erosion at 0.5 ft		position moving seaward to 0.7-ft depth	SP	14 to 18
66 to 90	erosion < avg.	stable slope	shoreward edge stabilized for remainder		0.7	SP	14 to 15; drop to 11
90 to 100	erosion >> avg.				0.7	SP	11
100 to 135	erosion = avg.		seaward edge stabilized for remainder	deposition > 0.9 ft	0.7	SP	11; rise to 15; drop to 8
135 to 140		erosion formed steeper slope	deposition at 0.6 and 0.7 ft		0.7	SP	8
140 to 175		stable slope	0.7-ft depth at seaward edge		0.7	SP	7 to 10; avg. 8
175 (median grain size in mm)	range 0.34 to 0.56 avg. 0.39	0.27 to 0.33 0.31	0.26 to 0.31 0.28	0.22 to 0.29 0.25			

[1]P = plunging; SP = spilling-plunging.

After 85 hours the seaward movement of the -0.7-foot contour in Figure 3 corresponds to the steepening of the upper part of the offshore slope and that roughly corresponds to the increase in K_R after 95 hours. The large fluctuation in K_R did not result from any apparent profile change, but the general relationship between the -0.7-foot contour and K_R did exist.

(2) Experiment 70X-10. K_R versus time for experiment 70X-10 is shown in Figure 4. During the first 20 hours, K_R varied from 0.07 to 0.12, and between 21 and 89 hours, K_R ranged between 0 and 0.08. From 89 to 174 hours, K_R increased from 0.04 to 0.14 with a maximum of 0.15 at 139 hours. After 174 hours, K_R decreased, to as low as 0.06 at 204 hours.

The higher K_R values during the first 20 hours occurred while the foreshore developed and eroded landward, a longshore bar developed, and the bar and the plunging breaker moved landward (Table 5). Between 21 and 89 hours, while K_R was lower but gradually increasing, the foreshore and the bar moved landward, then the foreshore stabilized and the bar eroded. During the same time the breaker moved seaward and changed to plunging (at 70 hours), and the offshore slope slightly steepened and prograded seaward. The distance between the 0- and -1.5-foot contours increased 2.2 feet (67.1 centimeters), enough for a 180° change in phase difference between the two reflected wave components.

The gradually increasing K_R after 21 hours followed the general seaward movement of the -0.7-foot contour (Fig. 4), but individual K_R fluctuations were not directly relatable to the movement of this or other contours. The increase in both K_R and K_R variability between 89 and 174 hours occurred while the foreshore was stable, the breaker was spilling (no reflection), and the offshore was gradually steepening.

(3) Experiment 71Y-06. K_R versus time for experiment 71Y-06 is shown in Figure 5. During the first 10 hours, K_R varied from 0.01 to 0.10. Then, for 115 hours the K_R remained relatively low, ranging from 0.01 to 0.07 with most of the values near 0.05. For the remainder of the experiment, K_R increased in mean value and in variability, varying from 0.05 to 0.22.

The higher K_R values during the first 10 hours occurred while the foreshore zone and longshore bar were developing and retreating landward (Table 6). Between 10 and 125 hours, when K_R was low and fairly constant, the foreshore zone and longshore bar were retreating landward and the offshore zone was prograding seaward but did not steepen. After 125 hours, when K_R was increasing and becoming more variable, the foreshore zone continued to erode, the onshore zone developed into a flat shelf with the depth over the shelf varying between 0.7 and 0.8 feet, and the offshore zone became steeper and continued to prograde seaward.

Some variations in K_R were related to the movement of the -0.7-foot contour (Fig. 5). The general seaward movement of the -0.7-foot contour

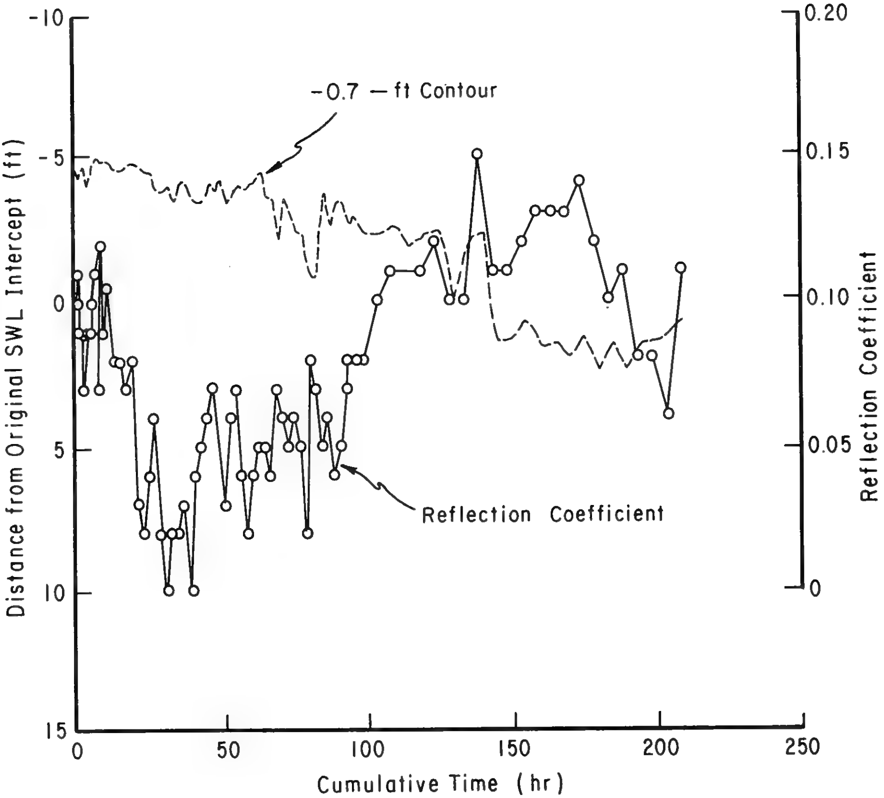


Figure 4. Reflection variability and movement of the -0.7-foot contour in experiment 70X-10.

Table 5. Summary of profile development in experiment 70X-10.

Time (hr)	Foreshore	Inner inshore	Outer inshore	Offshore	Breaker conditions: Depth (ft)	Type[1]	Angle[2]	Water temperature (°C)
0 to 1	developed characteristic shape	bar formed	no change	deposition between depth of -1.0 and -1.5 ft	0.4 to 0.5	P	C	----------------
1 to 5	no erosion; no change	bar moving shoreward			0.4 to 0.5	P	C	----------------
5 to 12				deposition at -1.0 ft	0.4 to 0.5	P	C	----------------
12 to 14	eroded at rate of 0.08 ft/hr	position of bar stable; elev. varied 0.3 to 0.4 ft		deposition at -0.9 and -1.0 ft	0.4 to 0.5	P	R	----------------
14 to 36			extending seaward	deposition at all depths except -2.0 and -2.1 ft along range -1	0.4 to 0.5	P	R	--- ------------
36 to 40			erosion at depth of 0.5 ft		0.4 to 0.5	P	R	----------------
40 to 56		erosion of bar started; range -1 at 40 hr, range -1 at 56 hr, and range -9 at 84 hr completed			0.6	P	R	25 to 30
56 to 62			erosion at depth of 0.6 ft		0.6	P	R	27 to 29
62 to 70	SWL retreated still; beach fill began				0.6	P-SP	R	26 to 27
70 to 84	rate of fill = avg.				0.6	SP	R	28 to 30
84 to 94		further erosion			0.7	SP	R	24 to 28
94 to 130		stable	still extending seaward; lateral variation in depth R-1, 0.6 to 0.7 ft; R-9, 0.7 to 0.9 ft		0.7	SP	R	26 to 15
130 to 140	rate of fill >> avg.				0.7	SP	R	14 to 15
140 to 150				deposition at all depths	0.7	SP	R	14 to 15
150 to 160	rate of fill = avg.				0.7	SP	R	12 to 15
160 to 170	rate of fill << avg.	further erosion along ranges -1 and -3			0.7	SP	R	12
170 to 190	rate of fill = avg.				0.7	SP	R	10 to 15
190 to 200	rate of fill = avg.			contours stable for -1.0 to -1.5 ft; ft; deposition below -1.5 ft	0.7	SP	R	7 to 10
200 to 210	rate of fill << avg.				0.7	SP	R	7
200 sand samples mean (mm)	0.29 to 0.68	0.27 to 0.50	0.26 to 0.33	0.25				

[1] P = plunging; SP = spilling.
[2] R = breaks first along range 1; C = breaks uniformly across tank.

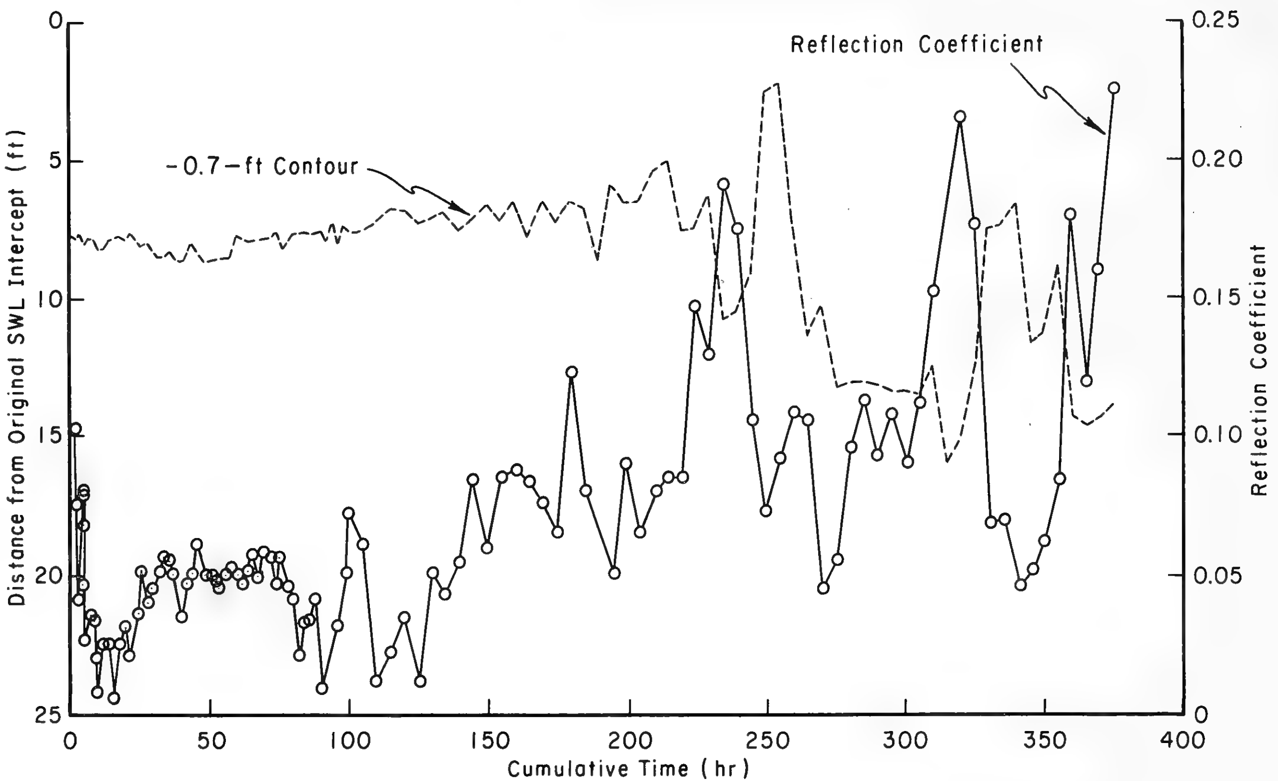


Figure 5. Reflection variability and movement of the -0.7-foot contour in experiment 71Y-06.

Table 6. Summary of profile development in experiment 71Y-06.

Time (hr)	Foreshore	Inner inshore	Outer inshore	Offshore	Breaker conditions			Water temperature
					Depth (ft)	Position	Type[1]	(°C)
0 to 1	Characteristic shape developed	Longshore bar formed	Deposition at elevations -0.6, -0.7, and -0.8 ft	Deposition mostly at elevations -0.9 to -1.2 ft	0.6		P	19
1 to 2	Average rate of erosion 0.113 ft/hr	Crest elevation of bar varied between -0.3 and -0.4 ft; bar moved shoreward at rate of 0.018 ft/hr						21
2 to 10								19 to 24
10 to 15				Deposition uniformly at all depths				22 to 24
15 to 105	Average rate of erosion 0.025 ft/hr							24 to 29
105 to 175					0.6		PS	24 to 29
175 to 180			Erosion at -0.6 ft, deposition at -0.7 and -0.8 ft					23
180 to 200					0.7	Moving seaward	S	22 to 28
200 to 220		Bar eroded	Shelf developed	Deposition mostly at elevations -0.9 to -1.3 ft				25 to 26
220 to 250		Maintained fairly steep slope	Shelf grew in length in both directions		0.7	Inner inshore	SP	19 to 24
250 to 315				Deposition uniformly at all depths	0.3		P	17 to 22
315 to 340				Deposition mostly at elevations -0.9 to -1.2 ft	0.7		S	17 to 21
340 to 375				Deposition at all depths				7 to 21

[1]P = plunging; S = spilling.

indicates the steepening and increasing of the reflectivity of the offshore zone. The highest K_R values, at 235, 320, 360, and 375 hours, occurred at times when the -0.7-foot contour was at its seawardmost position; low K_R values at 195, 240, and 340 to 355 hours occurred when the -0.7-foot contour was at more shoreward positions. An exception to this occurred at 270 to 275 hours, when the -0.7-foot contour was in a seaward position and the K_R was low. At other times the relationship existed, but the variation was not as great.

The continued separation of the foreshore and offshore zone would have caused the phase difference between the two reflected waves to vary and the measured reflected wave to have a long-period variation. After the shelf developed, the distance between the 0- and the -1.5-foot contour increased 8.6 feet (2.6 meters), enough for two cycles of phase-difference change, which may have contributed to some of the long-term K_R variation.

(4) Experiment 71Y-10. K_R versus time for experiment 71Y-10 is shown in Figure 6. During the first 10 hours, K_R varied from 0.05 to 0.11. Then, for 195 hours the K_R remained relatively low, varying from 0.01 to 0.08. For the remainder of the experiment, K_R was generally higher, varying from 0.05 to 0.13.

The higher K_R values during the first 10 hours occurred while the foreshore and longshore bar were developing, the breaker was plunging, and the foreshore was eroding (Table 7). Between 10 and 205 hours, while K_R was low, the foreshore retreated at a rate of 0.016 foot (0.5 centimeter) per hour, the bar was first stationary and then eroded, the breaker type changed from plunging to plunging and spilling, the inshore developed into a long, flat shelf, and the offshore zone gradually steepened. The K_R was higher, after 205 hours, when the inshore zone had fully developed, the foreshore was eroding and the offshore prograding. The distance between the 0- and -1.5-foot contours increased 7 feet (2.1 meters), enough for a 560° change in phase difference, after the shelf developed.

Variations in K_R relate only generally to the movement of the -0.7-foot contour (Fig. 6); i.e., the K_R increased about the time the -0.7-foot contour began moving seaward with the prograding offshore zone. The development of the profile in this experiment varied laterally, the development of the shelf began first along one side and progressed across the tank. This lateral variation in development obviously created a lateral variation in the profile reflectivity. Although this variation could not be measured by the one gage in the center of the tank, the variable profile reflectivity certainly contributed to the variations measured along the center of the tank.

(5) Experiment 72D-06. This experiment varied from the four other experiments with a 1.90-second wave in having an initial slope of 0.05 rather than 0.10. The K_R versus time for experiment 72D-06 is shown in Figure 7. During the first 15 hours, K_R varied from 0.04 to

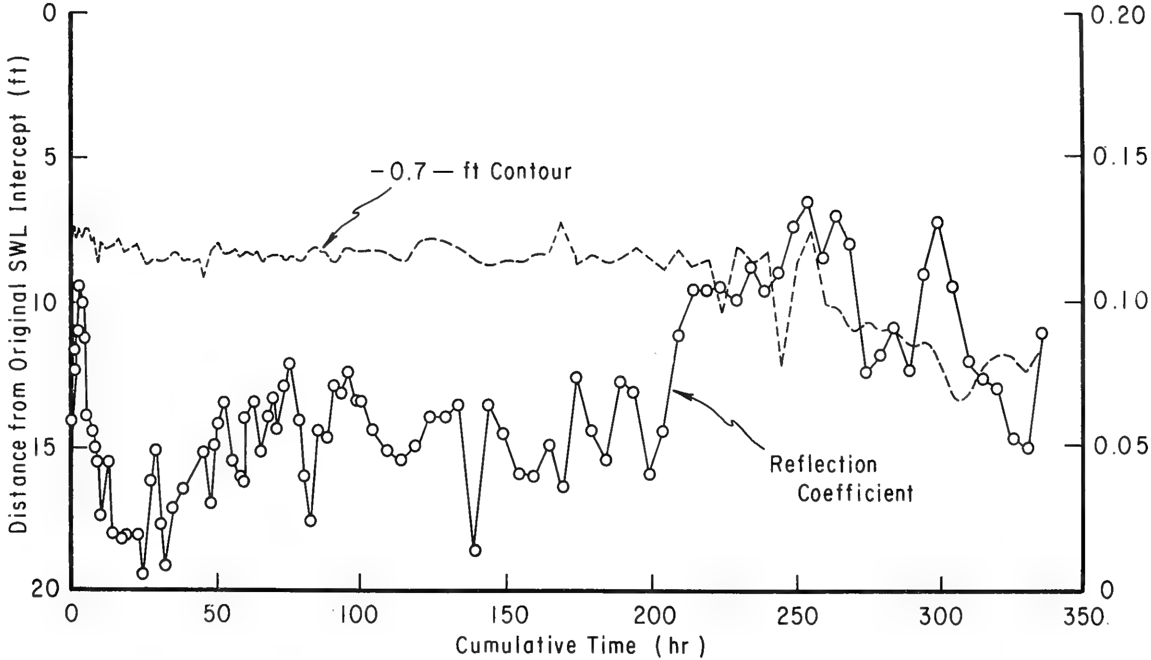


Figure 6. Reflection variability and movement of the -0.7-foot contour in experiment 71Y-10.

Table 7. Summary of profile development in experiment 71Y-10.

Time (hr)	Foreshore	Inner inshore	Outer inshore	Offshore	Breaker conditions			Water temperature (°C)
					Depth (ft)	Position	Type[1]	
0 to 1	Characteristic shape developed	Longshore bar formed	Deposition at elevations -0.6, -0.7, and -0.8 ft	Deposition between elevations -0.9 and -14 ft	0.6		P	23 to 27
1 to 5	Shoreline recession uniform across tank at 0.133 ft/hr	Bar stationary; crest elevation varied from -0.4 to -0.3 ft						26 to 29
5 to 10			No change					26 to 29
10 to 15				Deposition along ranges 5 and 9 at 0.02 ft/hr; along ranges 1 and 5, offshore stationary				25 to 26
15 to 110	Shoreline recession uniform across tank at 0.016 ft/hr			Deposition along ranges 5 and 9 at 0.02 ft/hr; along range 1, offshore stationary				23 to 28
110 to 115								28
115 to 125		Erosion of bar began along range 9 at 115 hours and along range 1 at 190 hours	Shelf development progressed across tank beginning along range 9 at 115 hours and ending along range 1 at 215 hours					28
125 to 170					0.6 0.7	R 1 R 9	PS	20 to 26
170 to 205				Deposition along all ranges at 0.02 ft/hr				18 to 22
205 to 215	Shoreline recession varied across tank; range 5 at 0.016 ft/hr; range 1 at 0.025 ft/hr							17
215 to 265		Maintained fairly steep slope	Shelf grew in length in both directions					17 to 19
265 to 280						R 9 stationary; R 1 moving inshore	S	18 to 21
280 to 335						R 0 to R 2 inner inshore; R 8, S 10 to R 2, S 3	P S	6 to 16

[1] P = plunging; S = spilling.

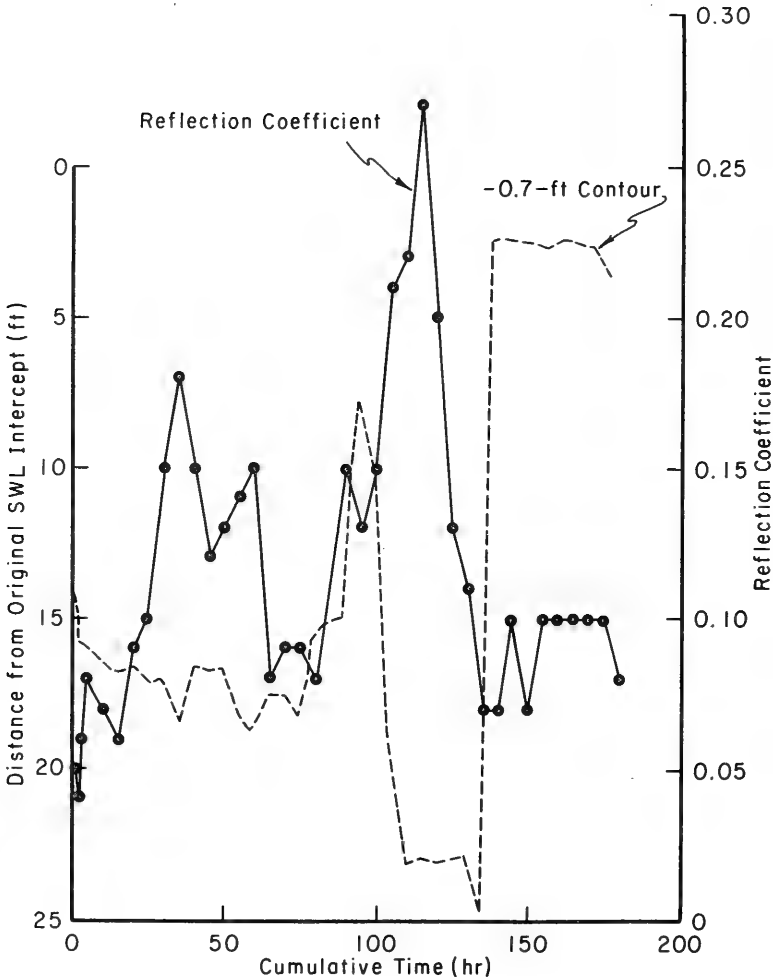


Figure 7. Reflection variability and movement of the -0.7-foot contour in experiment 72D-06.

0.08. Between 20 and 130 hours the K_R was higher and highly variable, varying between 0.08 and 0.27. For the remainder of the experiment, K_R was lower and less variable, varying between 0.07 and 0.10.

The lower values during the first 15 hours occurred while the foreshore developed (slower than in the other four experiments) and began retreating, the longshore bar developed and then eroded, and the breaker type was strictly plunging (Table 8). Between 20 and 130 hours, when the K_R was high and varied greatly, the foreshore was retreating (except for advancing between 125 and 130 hours), the breaker was mixed between plunging and spilling (indicating minimal reflection), the inshore was becoming longer and flatter, and the offshore was steepening, particularly after 95 hours. Between 135 and 180 hours, when K_R was smaller and less variable, the foreshore was stationary, the offshore zone continued to prograde seaward, and the inshore zone changed from an almost flat shelf with an average elevation of -0.7 foot to a flat region at the seaward end of the inshore (elevation -0.8 foot) and a trough at the shoreward end of the inshore (elevation -1.3 feet).

Some K_R variations after 100 hours, when the offshore slope was a significant reflector, correlate well with the movement of the -0.7-foot contour (Fig. 7). When the -0.7-foot contour was at a more seaward position, K_R was high; when the contour moved shoreward, K_R was low. The K_R reached higher values quicker than in the first four experiments, even though the initial slope was flatter. This earlier high in K_R may have been caused by the earlier seaward movement of the -0.7-foot contour in this experiment.

The K_R was measured over the inshore shelf several times between 100 and 155 hours and varied between 0.06 and 0.12 (see Vol. IV). This measurement included reflection both from the foreshore zone and from the plunging breaker near the toe of the foreshore. The distance between the 0- and -1.5-foot contours, after the shelf developed, increased 12.4 feet (3.8 meters), enough for more than two 360° phase-difference changes.

(6) <u>Summary of the Five Experiments</u>. The average K_R in each of the 1.90-second experiments with the 0.10 slope (70X-06, 70X-10, 71Y-06, and 71Y-10) varied from 0.07 to 0.09 (Table 2). However, in experiment 72D-06 with the flatter initial slope, the average K_R was 0.12, much higher than the tests with the steeper initial slope, contrary to the hypothesis that as the ratio of the wave steepness to the slope steepness increases, the K_R decreases. The close correlation between the -0.7-foot contour and K_R variations in experiments 71Y-06 and 72D-06 suggests that the elevation of the top of a steep, submerged slope can be as important as the steepness of the slope in determining the K_R.

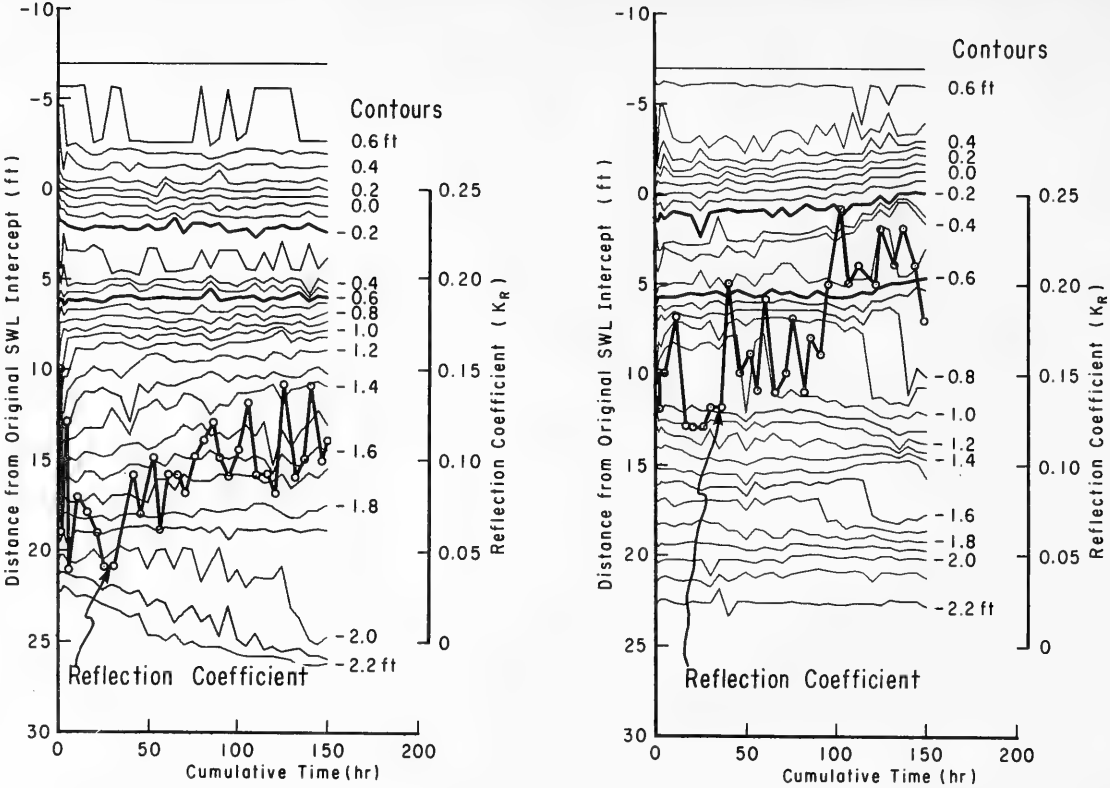
d. <u>Reflection of the 2.35-Second Wave</u>.

(1) <u>Experiment 72B-06</u>. The K_R versus time for experiment 72B-06 is shown in Figure 8(a). During the first 10 hours, K_R varied

Table 8. Summary of profile development in experiment 72D-06.

Time (hr)	Foreshore	Inner inshore	Outer inshore	Offshore	Breaker conditions Depth (ft)	Breaker conditions Type[1]	Water temperature (°C)
0 to 0.16	Development of equilibrium slope and length	Development of bar	Deposition at -0.6, -0.7, and -0.8 ft	Deposition at -0.9 ft	0.6 to 0.7	P	19 to 20
0.16 to 3		Bar stable					
3 to 5		Bar eroded					
5 to 20	Erosion; shoreline recession rate of 0.05 ft/hr	Erosion; fairly steep slope, retreating with foreshore	Deposition at -0.7 and -0.8 ft	Some deposition, mainly at -1.3, -1.4, and -1.5 ft at various times			14 to 16
20 to 35					0.6 to 0.7	P,S	
35 to 60			Not much change; elevation over shelf varying between -0.6 and -0.7 ft				9 to 13
60 to 65			Erosion at -0.6 ft				
65 to 75			No change				11 to 12
75 to 85			Large erosion at -0.7 ft				
85 to 95				Large depositions from -0.9 to -1.5 ft			
95 to 100			Large deposition at -0.7 ft				
	d_{50} = 0.26 to 0.27 mm		d_{50} = 0.20 to 0.27 mm	d_{50} = 0.20 to 0.21 mm			
100 to 110			Large deposition at -0.7 and -0.8 ft		0.7 to 0.8	S	7 to 10
110 to 120			Continued deposition mainly at -0:8 ft; erosion near station 8				6 to 7
120 to 125				Significant deposition at all elevations above -1.9 ft	0.2 to 0.4	P	4 to 5
125 to 135	Deposition; shoreline advance	Deposition					
135 to 140	Foreshore stable	No change	Significant erosion at -0.7 ft; deposition at -0.8 ft				6
140 to 180			Erosion near station 10 reached -1.3 ft; deposition at -0.8 ft				4 to 9
	d_{50} = 0.20 to 0.22 mm		d_{50} = 0.17 to 0.26 mm	d_{50} = 0.19 to 0.23 mm			

[1]P = plunging; S = spilling.



a. Experiment 72B-06

b. Experiment 72B-10

Figure 8. Reflection variability and contour movement in experiments with a 2.35-second wave.

over the widest range, between 0.04 and 0.15. Between 10 and 150 hours, K_R fluctuated (maximum 5-hour fluctuation of 0.06) about an increasing mean, reaching peak values at 125 and 140 hours.

The major profile adjustments in Figure 8(a) and Table 9 were the development of an equilibrium foreshore and longshore bar and steepening of the offshore zone just below the inshore zone. These adjustments occurred during the first 10 hours when K_R was fluctuating greatly. Between 10 and 150 hours, when K_R was gradually increasing, the only profile changes were the gradual steepening of the upper part of the offshore zone and the seaward movement of the offshore bar (crest elevation of -2.1 to -2.0 feet or 64.0 to 61.0 centimeters). The steepening of the upper offshore most likely caused the increases in K_R.

(2) Experiment 72B-10. The K_R versus time for experiment 72B-10 is shown in Figure 8(b). During the first 10 hours, K_R increased from 0.13 to 0.18, and then between 15 and 35 hours, K_R varied only between 0.12 and 0.13. At 40 to 90 hours, K_R was higher, fluctuating about a mean of 0.16. Between 90 and 100 hours, K_R increased from 0.16 to 0.24 and then fluctuated about a mean of 0.21 for the remainder of the experiment.

The increasing K_R during the first 10 hours coincides with the development of most of the profile features: the steep foreshore zone, the flat inshore zone, and the flat region near station 10 in the offshore zone (Fig. 8,b and Table 10). There was little profile change between 15 and 35 hours when the K_R was low and almost constant. At 40 to 90 hours the elevation of the flat region near station 10 gradually increased while the K_R was higher and more variable. Between 90 and 100 hours, when K_R increased by 0.08, a longshore bar was forming between ranges 1 and 5. The high values of K_R at the end of the experiment (after 100 hours) occurred while slopes near stations 20 and 14 were steepening.

(3) Summary of the Two Experiments. These experiments with the 2.35-second wave are compared in Volume VII. The average K_R in experiment 72B-06 was 0.08 and in experiment 72B-10 was 0.17 (Table 2). The gradual steepening of segments of the offshore zone appeared to be the primary source of long-term K_R variability in these two experiments. The development of a more convex offshore region with several steep sections in experiment 72B-10 and a more concave offshore region with only one steep section in experiment 72B-06 possibly explains the lower K_R values in experiment 72B-06. The distance between the foreshore and offshore zones changed very little, so that the K_R variability was not a result of phase-difference changes between reflected wave components.

e. Reflection of the 3.75-Second Wave.

(1) Experiment 72A-06. The K_R versus time for experiment 72A-06 is shown in Figure 9(a). The K_R dropped from an initial value

Table 9. Summary of profile development in experiment 72B-06.

Time (hr)	Foreshore	Inshore	Offshore	Breakers and currents	Temperature (°C)
0 to 0.16	Developed equilibrium shape; shoreline prograded	Longshore bar formed	Erosion at -0.7 to -1.3 ft, formed steep slope just below inshore; deposition at -2.1 and -2.2 ft	Breakers plunging at depths of 0.3 to 0.4 ft; no discernible circulation patterns; bobs inside breaker zone never moved outside breakers	30
0.16 to 5		No change; bar crest elevation varied between -0.3 and -0.4 ft at different times along different ranges			30 to 31
5 to 10	Reached equilibrium position after total advance of 1 ft				31
10 to 90	No change		Erosion at -1.3 to -1.7 ft; deposition at -2.1 and -2.2 ft		23 to 29
	50 hr Mean d_{50} = 0.21 mm	Mean d_{50} = 0.22 mm	Mean d_{50} = 0.19 mm		
90 to 150	100 hr Mean d_{50} = 0.23 mm	Mean d_{50} = 0.24 mm	Mean d_{50} = 0.20 mm		21 to 29
			Erosion at -1.3 to -1.7 ft; deposition at -2.0 to -2.2 ft		
	150 hr Mean d_{50} = 0.23 mm	Mean d_{50} = 0.22 mm	Mean d_{50} = 0.20 mm		

Table 10. Summary of profile development in experiment 72B-10.

Time (hr)	Foreshore	Inshore	Offshore	Breakers	Currents	Temperature (°C)
0 to 0.16	Developed stable shape; shoreline not normal to tank walls	Longshore bar formed near station 2, and at range 9, station 5; flat region formed near station 5, ranges 1, 3, and 5	Steep slope developed at upper edge, and flat area at station 10; deposition along range 1 below -1.8 ft	Plunging at -0.2 to -0.4 ft (range 5) Plunging at -0.3 to -0.5 ft (ranges 1 and 9)	No circulation pattern observed; surface bobs moved shoreward from station +15 and stayed if moved into breaker zone; bottom bobs moved shoreward from station +7 and seaward from station +9	29
0.16 to 5		Bar at station 2 began eroding in order of ranges 3, 1, and 5				30 to 31
5 to 10	No change					31
10 to 65	50 hr Mean d_{50} = 0.22 mm	Mean d_{50} = 0.21 mm	Mean d_{50} = 0.18 mm			24 to 29
65 to 70		Flat area near station 5 developed along range 7	Elevation of flat area near station 10 increased with time at each range and varied with range at each time; deposition below -1.8 ft along ranges 1 and 3			25
70 to 75	Shoreline becoming normal to tank walls					24
75 to 90		Flat area near station 2 began eroding, first along ranges 1 and 3; erosion of bar near station 2 completed along ranges 7 and 9				26 to 27
90 to 100	**Net recession at 100 hrs: 0.4 ft**	Bar formed at station 5 in order of ranges 5, 3, and 1				28 to 29
100 to 115	105 hr Mean d_{50} = 0.24 mm	Mean d_{50} = 0.22 mm	Mean d_{50} = 0.19 mm			20 to 25
115 to 130	Shoreline recession rate: 0.018 ft/hr	Erosion of flat area near station 2 continuing	Elevation near station 10 still rising; no deposition below -1.8 ft	Spilling at -0.2 to -0.4 ft (range 5) Plunging at -0.3 to -0.5 ft (ranges 1 and 9)		22 to 24
130 to 150	Recession continuing; large lateral variations in position 150 hr Mean d_{50} = 0.23 mm	Mean d_{50} = 0.22 mm	Mean d_{50} = 0.19 mm			19 to 25

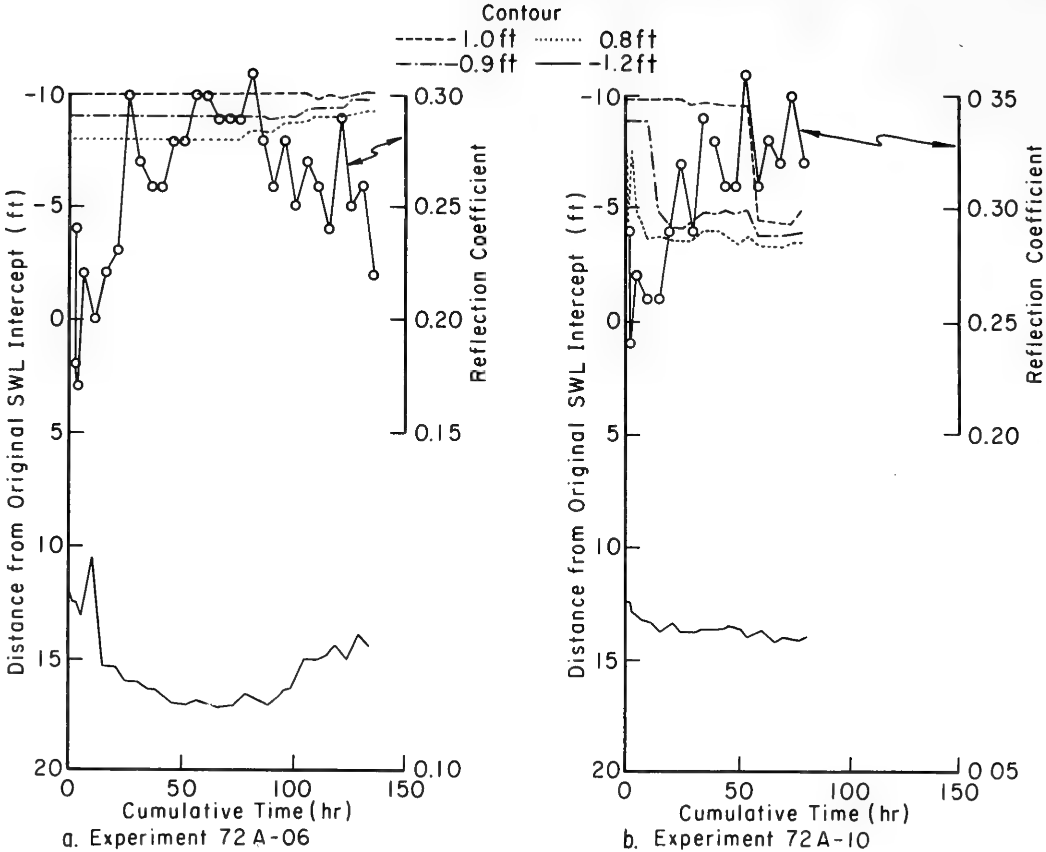


Figure 9. Reflection variability and movement of critical contours in experiments with a 3.75-second wave.

of 0.24 to 0.18, then to 0.17 at 3 hours, and then began to increase, reaching 0.30 at 25 hours. Between 25 and 80 hours, K_R remained high, fluctuating between 0.25 and 0.31. After 80 hours, K_R started to decrease while continuing to fluctuate, and was 0.22 at the end of the experiment (135 hours).

Within the first 5 hours the foreshore developed an equilibrium shape, which was steep along range 5 and quite flat along range 1 as a result of the counterclockwise flow pattern of the wave uprush and backwash (Table 11; Vol. VI). Since the waves broke on the foreshore, most of the wave energy reached the foreshore; as the foreshore became steeper, K_R increased, except at 1.5 and 3 hours. At those times, the erosion and deposition patterns at the base of the foreshore (-0.2 to -0.9 foot or 6.1 to 27.4 centimeters) were reversed and K_R reached its lowest values.

An almost flat shelf developed during the first 10 hours in the inner offshore region, caused by the erosion at the toe of the foreshore and deposition in the outer offshore at depths from -1.3 to -1.6 feet (39.6 to 48.8 centimeters). As the foreshore eroded landward at a rate of 0.015 foot (0.46 centimeter) per hour and the outer offshore slope steepened and prograded seaward with deposition at the higher elevations, the shelf on the inner offshore grew in length in both directions and a bar and trough developed. During this period of greatest profile development, K_R rose sharply, reaching a maximum at 25 hours. As a result of the high reflection, a significantly large standing wave developed, with antinodes at the foreshore and station 18, over the steepest part of the profile just seaward of the flat shelf. Between the first two antinodes of the standing wave, over the flat shelf of the inner offshore, a clockwise circulation pattern developed, apparently driven by the counterclockwise circulation in the foreshore zone. Apparently, the circulation over the inner offshore moved the sand to the edge of the shelf, but the lack of current movement through the antinode prevented further transport and thus increased the steepness.

Between 25 and 70 hours, while the profile changed 3 feet (0.9 meter) in the length of the shelf between the two reflecting zones (foreshore zone and submerged offshore slope), K_R did not increase or decrease significantly, but fluctuated over a range of 0.05. Part of this variation, which was greater than the 0.02 maximum variation in the fixed-bed tank, may have been caused by the 90° change in phase difference between the waves reflected from the two slopes as they separated.

After 70 hours the seaward edge of the shelf began eroding, moving landward, even though the foreshore was still retreating and the offshore was still prograding. Simultaneously, the clockwise circulation pattern over the inner offshore began disintegrating and K_R began decreasing. By 100 hours the bar had eroded and the trough had almost filled completely. From 15 to 100 hours the outer offshore steepened, with deposition at the upper elevations and erosion at -2.0- and -2.1-foot elevations. The eroded material was moved seaward to form a bar over part of the concrete bottom.

Table 11. Summary of profile development in experiment 72A-06.

Time (hr)	Foreshore	Inner offshore	Outer offshore	Breakers	Currents	Water temperature (°C)
0 to 5	Developed equilibrium shape	An almost flat shelf developed	Deposition at -1.3 to -1.6 ft	Surging or collapsing, breaking on lower part of foreshore	Counterclockwise circulation on foreshore; clockwise circulation between first 2 antinodes of standing wave envelope	13 to 19
5 to 10	Retreated landward					20
10 to 15		Shelf grew in length in both directions; bar and trough developed				19
15 to 70			Deposition at -1.3 to -1.9 ft; erosion at -2.0 to -2.1 ft			18 to 22
	Mean d_{50} = 0.20 mm	Mean d_{50} = 0.20 mm				
70 to 100	At rate of 0.015 ft/hr	Seaward edge of shelf began moving shoreward; bar eroded, trough filled in	Causing slope to steepen		Clockwise circulation on foreshore; circulation between first 2 antinodes breaks down, and becomes confused	22 to 26
	Mean d_{50} = 0.20 mm	Mean d_{50} = 0.20 mm				
100 to 135		Gently sloping region; seaward edge moving shoreward Shoreward edge stationary except along range 3	Erosion at -1.2 to -1.5 ft; deposition at -1.7 to -2.2 ft, causing slope to decrease in steepness			23 to 26
	Mean d_{50} = 0.21 mm	Mean d_{50} = 0.20 mm				

Between 100 and 135 hours the foreshore continued to retreat, the inner offshore became a gently sloping region, the outer offshore slope steepness decreased, and K_R continued to drop.

The movement of the -1.2-foot (36.6 centimeters) contour in Figure 9(a) is an indication of some of these profile adjustments and correlates well with K_R variations. The -1.2-foot contour moved seaward at 15 hours and K_R began rising. After 70 hours the -1.2-foot contour began moving shoreward, as the inner offshore eroded and the outer offshore slope became less steep, and K_R began to decrease.

(2) Experiment 72A-10. The average K_R for three ranges versus time for experiment 72A-10 is shown in Figure 9(b). The K_R dropped initially to 0.24 and then began a gradual long-term increase, reaching a maximum of 0.37 at 55 hours. Between 60 and 80 hours, K_R varied between 0.31 and 0.35.

During the first 1.5 hours the foreshore developed a steep slope and within the first 10 hours an almost flat shelf developed in the inner offshore region (Table 12). From 1.5 to 25 hours the foreshore prograded 0.5 foot (15.2 centimeters), beginning first along the outside ranges. For the first 20 hours sand was deposited in the outer offshore at depths from 1.2 to 1.5 feet; from 20 to 25 hours sand was eroded at depths of 1.6 and 1.7 feet (48.8 and 51.8 centimeters), thus forming a slightly steeper slope on the upper part of the outer offshore. During this initial profile development, K_R rose sharply.

After 25 hours the only profile changes were a slight general increase in the foreshore slope and a gradual increase in the foreshore berm-crest elevation. The K_R continued to increase, but at a slower rate. The short-term variations in K_R after 35 hours was ±0.03, on the order of the ±0.025 variation in the fixed-bed tank.

Throughout the experiment the foreshore slope was slightly flatter along the outside ranges and K_R was significantly lower along the outside ranges.

The movements of the +1.0-, +0.9-, and +0.8-foot contours in Figure 9(b) indicate the gradual increase in the foreshore berm-crest elevation which apparently caused the increase in K_R. The distance between the foreshore and offshore did not vary.

(3) Summary of the Two Experiments. The average K_R in experiment 72A-06 was 0.26 and in experiment 72A-10 was 0.30 (Table 2). The elevation of the top of the submerged offshore slope appeared to be the primary source of long-term K_R variability in experiment 72A-06. The gradually increasing berm-crest elevation appeared to be the source of increasing K_R in experiment 72A-10. The development of a steeper slope and higher crest in the foreshore in experiment 72A-10 explains the higher K_R in that experiment. More details on the 3.75-second experiments are in Volume VI.

Table 12. Summary of profile development in experiment 72A-10.

Time (hr)	Foreshore	Inner offshore	Outer offshore	Currents and breakers	Temperature (°C)
0 to 1.5	Developed equilibrium shape	An almost flat shelf developed	Deposition at -1.2 to -1.5 ft	No discernible pattern of wave-generated currents developed	18 to 21
1.5 to 10	Advanced seaward 0.5 ft, beginning along outside ranges first				20 to 24
10 to 20		No significant changes occurred; some minor lateral variations in elevation of bar crest		Breaker was surging or collapsing on lower part of foreshore	23 to 24
20 to 25			Erosion at -1.6 and -1.7 ft		22
25 to 80	In equilibrium in shape and position		No major change		22 to 25
	50 hr: Mean d_{50} = 0.22 mm	Mean d_{50} = 0.20 mm			
	80 hr: Mean d_{50} = 0.22 mm	Mean d_{50} = 0.19 mm			

f. Summary. The K_R results from the 10 experiments are summarized in Table 3. For the two experiments with a wave period of 3.75 seconds on an initial slope of 0.10 the average K_R was 0.28; the difference between the two experiments was caused by a current pattern which developed only in experiment 72A-06. For the two experiments with a wave period of 2.35 seconds on an initial slope of 0.10 the average K_R was 0.125; the difference between the two experiments was caused by a transverse wave which occurred only in experiment 72B-10. In the four experiments with a wave period of 1.90 seconds on an initial slope of 0.10 the average K_R was 0.08 for each experiment. In the one experiment with a wave period of 1.50 seconds on an initial slope of 0.10, the average K_R was 0.05. These results support the following hypothesis: as the wavelength decreases (or the wave steepness increases) on a given initial profile slope, K_R decreases.

The K_R would then be expected to decrease if the initial profile steepness were decreased for a given wavelength. However, the average K_R in the experiment with a wave period 1.90 seconds on an initial slope of 0.05 was 0.12, higher than the four experiments with a wave period of 1.90 seconds on an initial slope of 0.10.

The effect of the different reflecting processes does not appear to correlate with any change in wave period (or wavelength). The effect of the steepness of submerged slopes may have been important in all of the experiments, but the correlation between K_R and the offshore slope was much better in the 6-foot tank (Fig. 10). A predominant cause of the variability in experiments 71Y-06 (1.90-second wave), 72D-06 (1.90-second wave; 0.05 initial slope), and 72A-06 (3.75-second wave) was the effect of the elevation at the top of the submerged slope. In all experiments except 72A-10, the foreshore remained fairly stable in shape and the K_R from the foreshore appeared to have been fairly constant, but in 72A-10 the changing foreshore was the predominant cause of K_R variability. The effect of reflection from a plunging breaker appeared to be small and difficult to measure. The increasing width of the inshore shelf (increasing distance between foreshore and offshore) appears to have been a cause of long-term K_R variability in the experiments with the 1.90-second wave and the predominant cause of K_R variability in the experiments with the 1.50-second wave (Fig. 11). In the other experiments the distance between the foreshore and offshore changed relatively little and K_R variability was shown to be related to other sources.

3. Variations in Incident Wave Height.

In the 10 experiments, the measured incident wave (Table 13) was composed of the nominal (generated) wave, the re-reflected wave, and, in experiment 72B-10, the transverse wave. Secondary and cross waves were also observed, but they did not affect the measurement of the incident wave height.

Barnard and Pritchard (1972) state that "Cross waves are standing waves whose crests are at right angles to a wavemaker; they oscillate

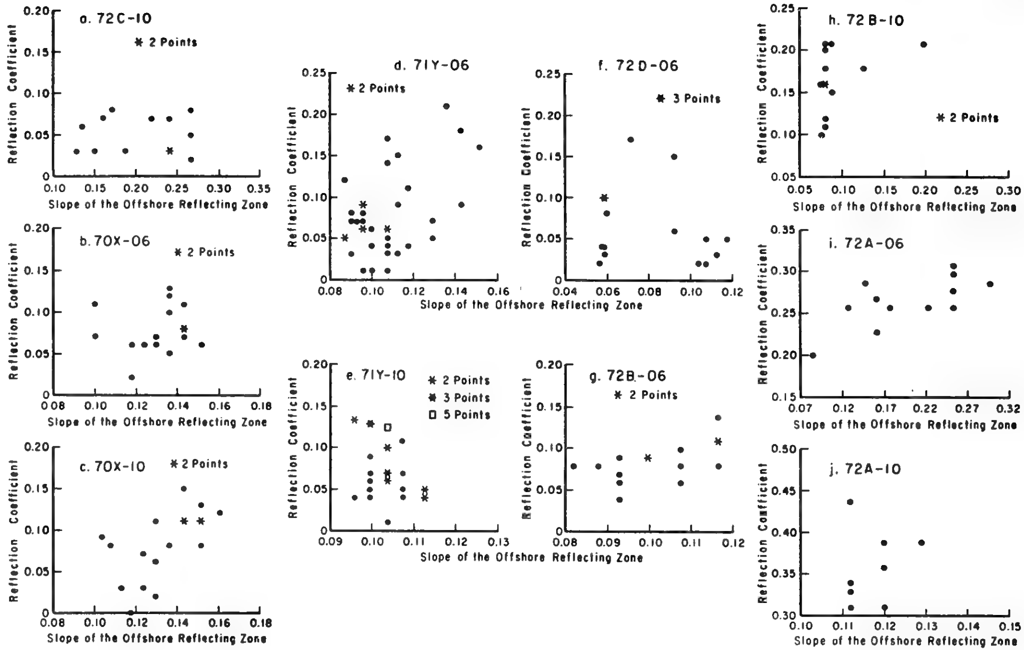


Figure 10. Correlation between K_R and offshore slope steepness in each experiment.

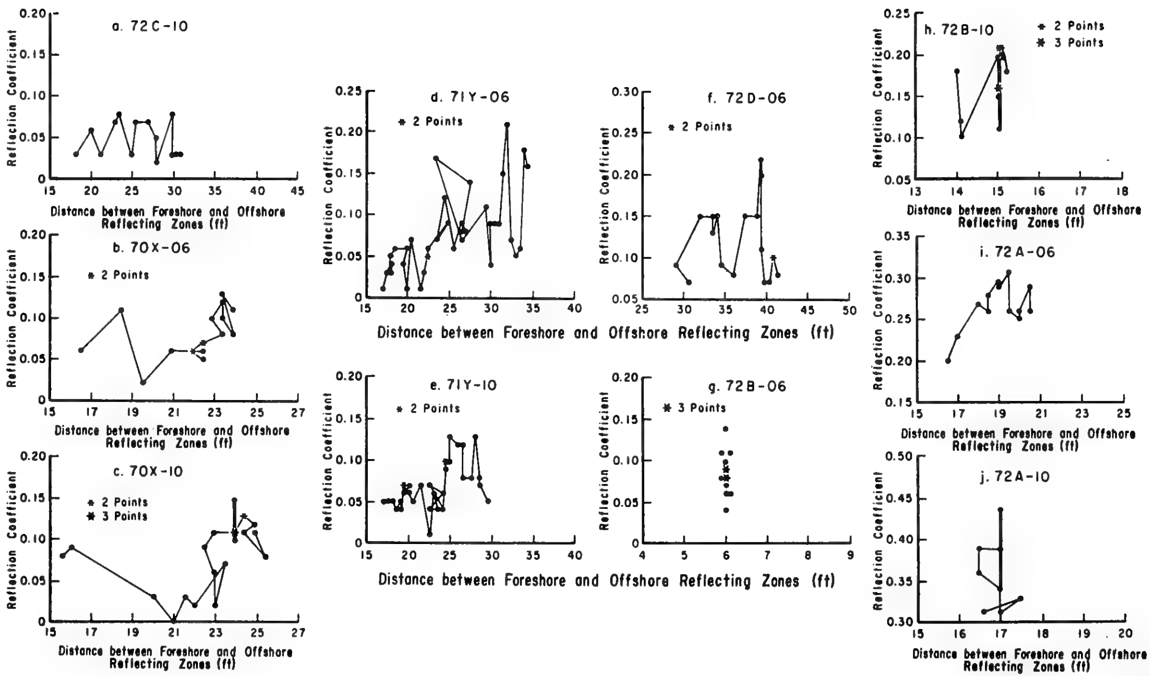


Figure 11. Correlation between K_R and shelf length in each experiment.

Table 13. Incident wave heights.

Experiment	Movable bed				Fixed bed			
	Avg H_I (ft)	Limits of H_I (ft)	Range of variation (ft)	Obsns (No.)	Avg H_I (ft)	Limits of H_I (ft)	Range of variation (ft)	Obsns (No.)
72C-10 (0.41)[1]	0.43	0.37 to 0.46	0.09	19	0.44	0.43 to 0.46	0.03	18
70X-06 (0.36)	0.34	0.32 to 0.38	0.06	24	0.37	0.36 to 0.39	0.03	27
70X-10 (0.36)	0.37	0.34 to 0.39	0.05	34	0.36	0.35 to 0.38	0.03	32
71Y-06 (0.36)	0.37	0.34 to 0.41	0.07	75	0.38	0.36 to 0.40	0.04	31
71Y-10 (0.36)	0.36	0.32 to 0.41	0.09	67	0.36	0.34 to 0.37	0.03	21
72D-06 (0.36)	0.39	0.36 to 0.42	0.06	23	0.38	0.37 to 0.40	0.03	23
72B-06 (0.34)	0.38	0.35 to 0.41	0.06	21	0.36	0.36 to 0.39	0.05	19
72B-10 (0.34)	0.31	0.30 to 0.33	0.03	22	0.34	0.32 to 0.36	0.04	19
72A-06 (0.31)	0.38	0.33 to 0.43	0.10	16	0.36	0.34 to 0.41	0.07	16
72A-10 (0.31)	0.35	0.30 to 0.42	0.12	14	0.35	0.33 to 0.37	0.04	14

[1]Nominal wave height in feet.

at half the frequency of the wavemaker." Normally, cross waves occur at the generator and result from critical combinations of generated wavelength and tank width. In movable-bed tests with gradual bottom slopes, cross waves have been observed by the author at isolated sections over the profile where the wavelength, as it decreased in shoaling, passed through a critical value with respect to the tank width and remained at that value for sufficient distance to generate a cross wave. Cross waves are a spatial variation in the lateral direction. Cross waves were observed over a short segment of the movable-bed profile in experiment 72B-06; however, the waves lasted only a brief period of time and were not measured.

Secondary waves (or solitons) result from the breakdown of a finite-amplitude wave of nonpermanent form into a primary and one or more secondary waves traveling at different speeds dependent on depth. Secondary waves can be generated by a sinusoidally moving generator blade or by a wave as it passes a slope onto a shelf of smaller but constant depth (see Madsen and Mei, 1969 and Galvin, 1972) and are a spatial variation in the longitudinal direction. Secondary waves caused by waves passing onto a shelf probably occurred, but were not recorded. Secondary waves caused by sinusoidal generator blade motion occurred, but (as pointed out in Volume VI for the experiments where secondary waves were most pronounced) the wave height variation due to secondary waves was at least an order-of-magnitude less than the variation due to wave reflection from the profile. Because the incident wave height measurement was an average of wave heights all along the tanks, the measured incident wave height was not affected by any spatial variation in height due to secondary waves.

Transverse waves, generated by a gap at the side of the blade and a critical combination of wavelength and tank width, have an amplitude that varies across the tank, but since the transverse wave has the same period as the plane progressive wave, the combined wave motion causes the wave height at one point to increase from right to left and at another point, farther down the tank, to increase from left to right. (See Madsen, 1974.) Transverse waves are spatial variations in both the lateral and longitudinal directions. Transverse waves were observed and recorded in only experiment 72B-10; a complete discussion of the wave height variability resulting from transverse waves is given in Volume VII.

Re-reflection was the primary source of incident wave height variability in these experiments. The effect of re-reflection on incident wave height variability in an experiment can be determined by comparing the difference in the range of wave heights between the fixed- and movable-bed tanks. The wave height variation in the fixed-bed tank is a measure of the wave height measurement accuracy in the movable-bed tank, and subtracting the measurement accuracy from the total variation in the movable-bed tank gives a measure of the incident wave height variation due to re-reflection in the movable-bed tank.

a. <u>1.50-Second Wave</u>. The nominal (generated) wave height for the 1.50-second wave period was 0.41 foot (12.5 centimeters). In the fixed-bed tank the average incident wave height was 0.44 foot (13.4 centimeters), 0.03 foot (0.9 centimeter) above the nominal (generated) height, and the range of heights was only 0.03 foot.

In the movable-bed tank the range of values was 0.09 foot (2.7 centimeters), so that 0.06 foot (1.8 centimeters) is assumed due to varying profile reflectivity. The average incident wave height was 0.43 foot (13.1 centimeters), just over the nominal (generated) height by 0.02 foot (0.6 centimeter).

b. <u>1.90-Second Wave</u>. The nominal (generated) wave height for the 1.90-second wave period was 0.36 foot (11.0 centimeters). In the fixed-bed tanks the average incident wave heights for the five 1.90-second tests were all within 0.02 foot of the nominal (generated) height. In the 10-foot tank, initial test length of 61.7 feet (18.8 meters), the average was 0.36 foot, the same as the nominal (generated) height; in the 6-foot tank, initial test length of 100 feet (30.5 meters), the average was 0.37 or 0.38 foot (11.3 or 11.6 centimeters). In four of the five experiments the range of variation in incident wave height was 0.03 foot and in experiment 71Y-06 the range was 0.04 foot (1.2 centimeters).

In the movable-bed tank in experiment 70X-06 the range of values was 0.06 foot, 0.03 foot due to varying reflectivity; in experiment 70X-10 the range was 0.05 foot (1.5 centimeters), 0.02 foot due to varying reflectivity; in experiment 71Y-06 the range was 0.07 foot (2.1 centimeters), 0.03 foot due to varying reflectivity, and in experiment 72D-06 the range was 0.06 foot, 0.03 foot due to varying reflectivity.

The average incident wave height in the movable-bed tanks was less than the nominal (generated) height in experiment 70X-06, equal to the nominal (generated) height in experiment 71Y-10, and greater than the nominal (generated) height in experiments 70X-10, 71Y-06, and 72D-06.

c. <u>2.35-Second Wave</u>. The nominal (generated) wave height for the 2.35-second wave period was 0.34 foot (10.4 centimeters). In the fixed-bed tanks the average incident wave height was 0.02 foot above the nominal (generated) height in experiment 72B-06 and equal to the nominal (generated) wave height in experiment 72B-10. The difference was likely due to the difference in initial test length. The range of incident heights was 0.05 foot in experiment 72B-06 and 0.04 foot in experiment 72B-10.

In the movable-bed tank in experiment 72B-06 the range of heights was 0.06 foot, only 0.01 foot (0.3 centimeter) due to varying reflectivity, and in experiment 72B-10 the range was 0.03 foot, which was within the accuracy of the wave height measurement; thus, the effect of re-reflection in each experiment was not measurable.

d. <u>3.75-Second Wave</u>. The nominal (generated) wave height for the 3.75-second wave period was 0.31 foot (9.4 centimeters). In the fixed-bed tanks the average incident wave heights were within 0.01 foot of one another and both were greater than the nominal (generated) height. The range of incident height variation was 0.07 foot in experiment 72A-06 and 0.04 foot in experiment 72A-10.

In the movable-bed tank in experiment 72A-06 the range of values was 0.10 foot (3.0 centimeters), 0.03 foot due to varying reflectivity, and in experiment 72-10 the range was 0.12 foot (3.7 centimeters), 0.08 foot (2.4 centimeters) due to varying reflectivity. The average incident heights in the movable-bed tanks were 0.07 foot and 0.04 foot, both greater than the nominal (generated) height.

e. Comparison of the Ten Experiments. Varying profile reflectivity caused no measurable change in the incident height in experiment 72B-10 (2.35 seconds), a moderate change (0.01 to 0.03 foot) in experiments 70X-06, 70X-10 (1.90 seconds), 71Y-06, 72D-06, 72A-06, and 72B-06, and a significant change (0.06 to 0.08 foot) in experiments 71Y-10 (1.90 seconds), 72C-10 (1.50 seconds), and 72A-10 (3.75 seconds). The effect in the 6-foot-wide tank was in the moderate range for all five experiments and in the 10-foot-wide tank ranged from no change to 0.08 foot, and the effect was not a function of wave period. It appears then that the wider tank may have amplified this effect.

III. EQUILIBRIUM PROFILES

1. Definitions and Importance of Equilibrium Profiles.

The term "equilibrium profile" implies a profile whose mean position is fixed in space for the given wave and sediment conditions, with the expectation that the actual profile at any given time will deviate somewhat from the mean profile. It has been assumed that equilibrium is a state which can be reached on a model profile with a constant wave action impinging on it for a sufficiently long time.

Laboratory studies of longshore transport often depend on having an equilibrium profile to determine the longshore transport rate without having an onshore-offshore transport component (Savage, 1959, 1962; Fairchild, 1970a). Coastal engineering models are frequently based on simulating the equilibrium profile. However, Savage (1962) and Fairchild (1970a) found that equilibrium profiles are not always easily attained. Collins and Chesnutt (1975, 1976) showed that the final unchanging profile for the same wave and sediment conditions was not always repeatable and that the initial slope could affect the final profile shape.

Swart (1974) found that for a single periodic wave impinging on a profile, 1,500 hours of wave action was required to reach equilibrium for some wave and sediment conditions. However, 1,500 hours is not a practical test duration for most models or experiments.

J.W. Kamphuis (Professor of Civil Engineering, Queen's University, Kingston, Ontario, personal communication, 1978) used a series of wave conditions replicating a year's seasonal variations and found that when using a wave in the transition region in place of either the winter or summer waves the profile reached equilibrium much less readily than when using only winter and summer waves. Kamphuis further compared two-dimensional tests with three-dimensional tests, and found that 9 to 11 yearly cycles were required to reach equilibrium with the two-dimensional setup and only 1 to 2 cycles with the three-dimensional setup.

The LEBS experiments were planned to be run until the profile developed an equilibrium shape because it was assumed that if the profile reached equilibrium, the primary source of temporal wave height variability, the changing profile reflectivity, would be eliminated or significantly reduced.

The effects of varying initial slope and wave period are discussed below. The effect of tank width on profile development is discussed in Section IV.

2. Effect of Initial Profile Slope.

Two experiments were conducted in which the only variable was the initial profile slope--0.10 in experiment 71Y-06 and 0.05 in experiment 72D-06.

The steeper initial slope in experiment 71Y-06 (Fig. 12) adjusted slowly to the waves and did not appear to have reached equilibrium along any segment of the profile after 375 hours. The foreshore retreated at a rate of 0.113 foot (3.44 centimeters) per hour between 1 and 15 hours and at a rate of 0.025 foot (0.76 centimeter) per hour thereafter. The flat shelf in the inshore zone and the steeper slope in the offshore zone developed between 200 and 220 hours.

The flatter initial slope in experiment 72D-06 (Fig. 13) adjusted more quickly to the wave attack, but also did not appear to have reached equilibrium. The foreshore retreated at a rate of 0.05 foot per hour between 5 and 125 hours, prograded seaward between 125 and 135 hours, and then stabilized for the remainder of the experiment. The inshore zone slowly grew in width and the offshore slope remained mild during the first 100 hours. After 100 hours the flat shelf in the inshore zone and the steeper slope in the offshore zone rapidly developed. Once the foreshore stabilized, the inshore zone began eroding, creating a significant depression in the profile below the forshore zone, while the offshore zone continued to prograde seaward. The K_R stopped varying during the last 25 hours (Fig. 7), indicating that equilibrium may have been near.

Although neither profile reached equilibrium, the profiles developed somewhat different shapes (Fig. 14). The differences in rates and types of profile adjustments verify the conclusions of Collins and Chesnutt (1975, 1976) that the initial profile slope can affect the final profile shape.

3. Effect of Wave Period.

Nine experiments were conducted with an initial profile slope of 0.10 and four different wave periods; the experiments are analyzed below to determine the effect of wave steepness on profile equilibrium. The deepwater wave steepness was 0.039 for the 1.50-second wave, 0.021 for the 1.90-second wave, 0.013 for the 2.35-second wave, and 0.004 for the 3.75-second wave.

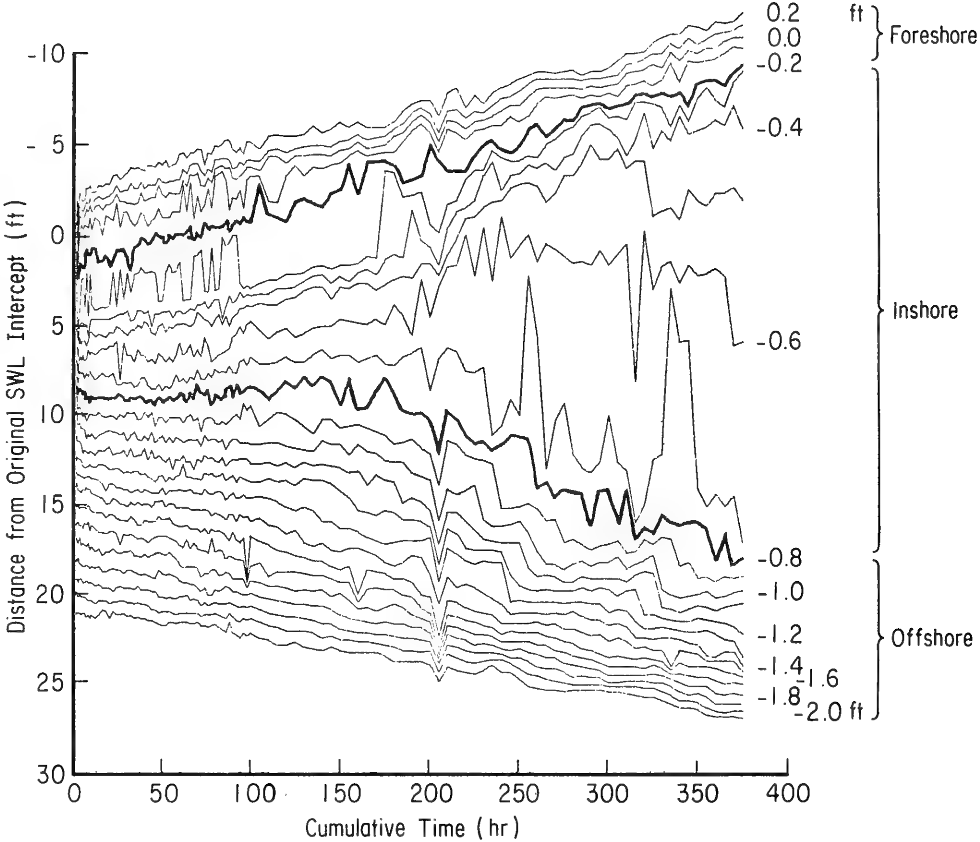


Figure 12. Contour movements along center range of experiment 71Y-06.

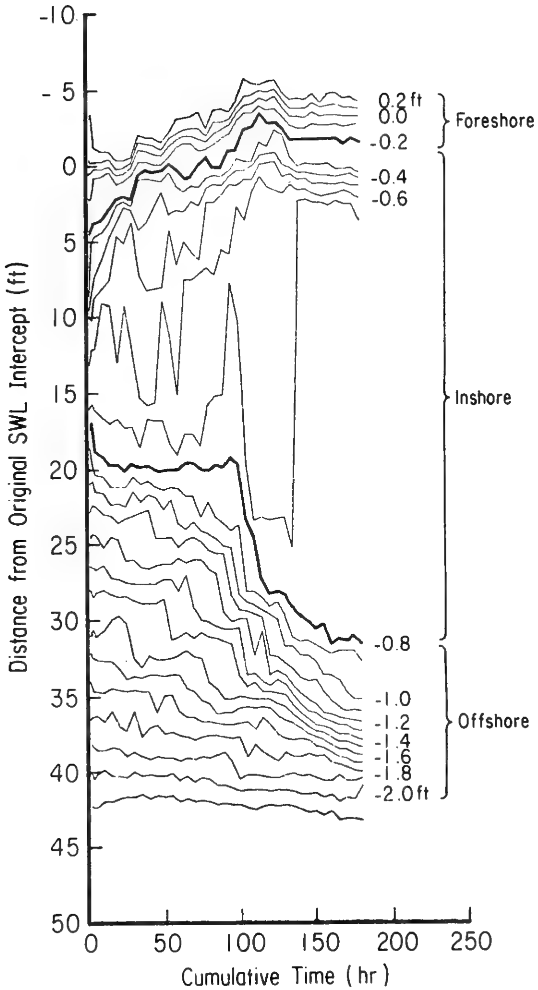


Figure 13. Contour movements along center range of experiment 72D-06.

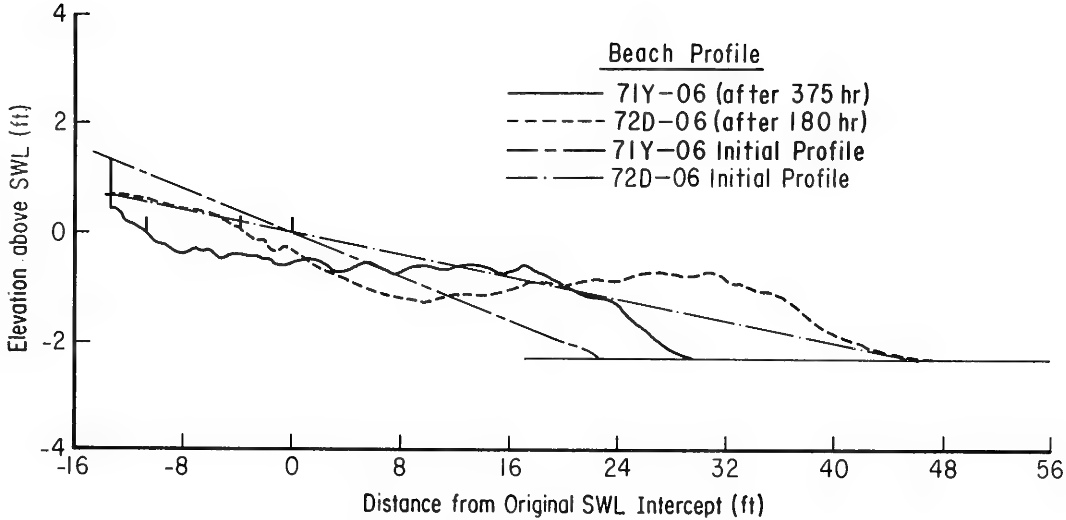


Figure 14. Comparison of final profiles with a 1.90-second wave and different initial slopes.

a. 1.50-Second Wave. The profile in the one experiment (72C-10) conducted with a wave period of 1.50 seconds appeared to be near equilibrium, as indicated by horizontal contours in the foreshore zone and most of the inshore zone in Figure 15. Erosion of the foreshore was continuing but slowing along the range 1 side of the tank and some erosion was occurring in parts of the inshore zone. Deposition continued in the offshore zone, but at a slower rate. The breaker type and position had stabilized and the K_R and its variability had decreased to small values. If this experiment had been continued, presumably it would have soon reached equilibrium. The final profile is shown in Figure 16.

b. 1.90-Second Wave. Four experiments were conducted with a wave period of 1.90 seconds and an initial slope of 0.10.

(1) Experiments 70X-06 and 70X-10. These experiments had a 7-foot longer initial test length than the other experiments in their respective tanks. Because the shoreline was stabilized by the renourishment of the backshore after 54 and 62 hours in experiments 70X-06 and 70X-10, the final profile shapes for those experiments may not have been characteristic of profiles for the 1.90-second wave. The final profiles could not have been at equilibrium because sand was still being eroded from the backshore when the experiments were stopped (see Table 10 in Vol. II). However, the nearly horizontal contour lines near the end of the experiment in the offshore in Figure 17 indicate that parts of the profile in experiment 70X-06 may have been approaching equilibrium. It is difficult to determine from Figure 18 if the profile in experiment 70X-10 was approaching equilibrium. Several of the offshore contours had stopped moving in the seaward direction and had begun to move in the shoreward direction, indicating the possible approach to some dynamic equilibrium, but the lateral variations in the shape and development of the profiles (see Vol. II and Section IV,5 in this volume) made it difficult to determine equilibrium.

Figure 19 compares the center profiles from the two experiments at 50, 100, and 175 hours, indicating that the profiles at 50 and 100 hours were nearly the same, but that at 175 hours the profile in experiment 70X-10 had built farther seaward while maintaining a similar shape. The profile development after 175 hours in experiment 70X-10 is shown in Figure 20.

(2) Experiments 71Y-06 and 71Y-10. These experiments had a shorter initial test length than the two experiments discussed above. There is no indication that either experiment 71Y-06 or 71Y-10 was near equilibrium at the end of the experiments, as shown in Figures 12 and 21; both experiments showed slow, steady development throughout.

Figure 22 compares the center profiles from the two experiments at 100, 200, and 300 hours, indicating that at 100 hours the profiles had nearly the same shape; at 200 hours the profile in experiment 71Y-10 had already developed a flat inshore shelf while the profile in experiment 71Y-6 had not, and at 300 hours the profile in experiment 71Y-06 had

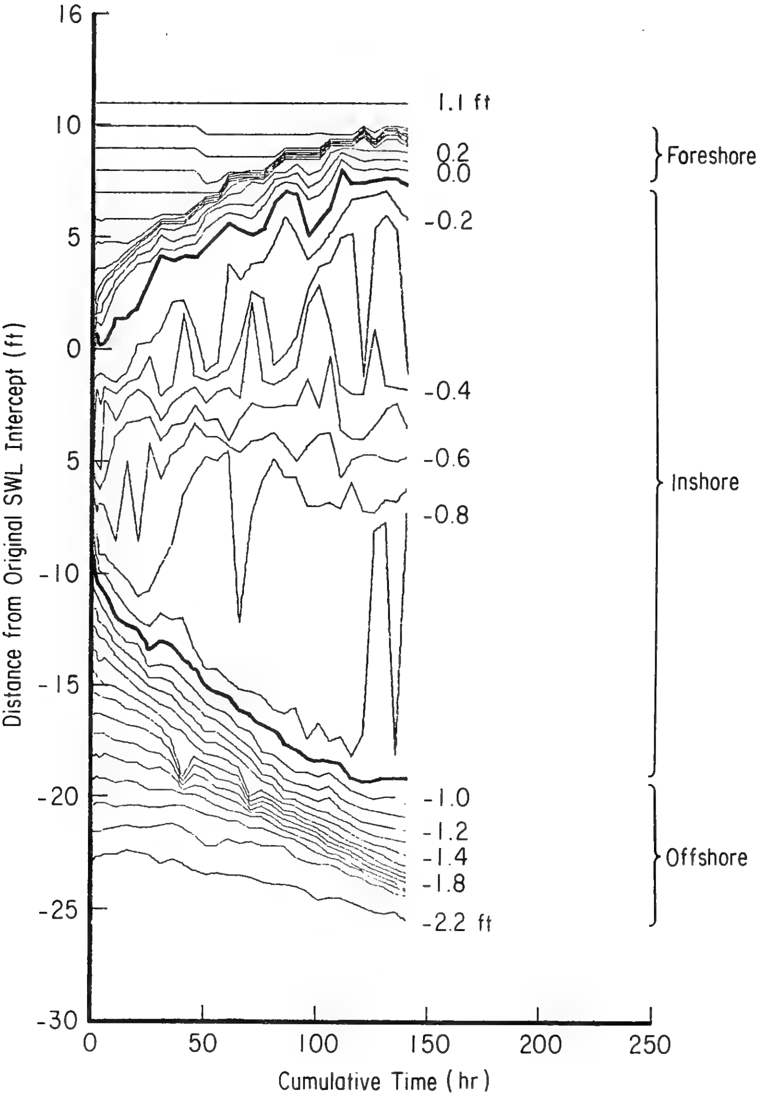


Figure 15. Contour movements along center range of experiment 72C-10.

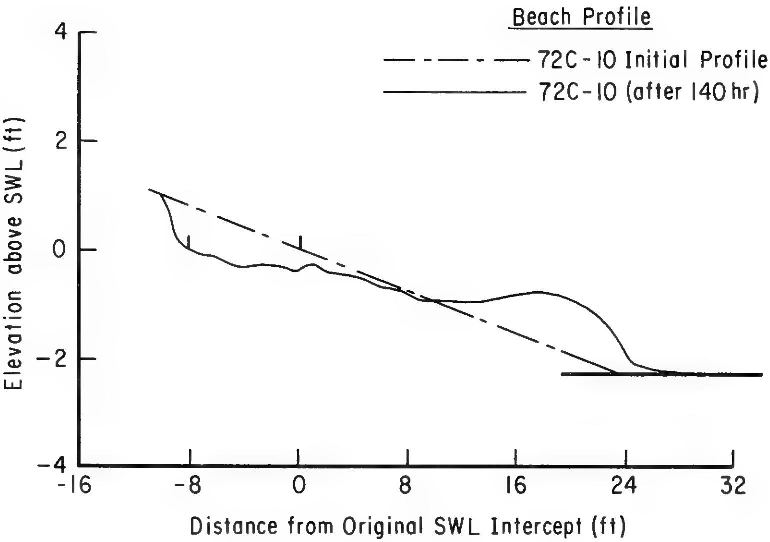


Figure 16. Equilibrium profile in experiment 72C-10, with steep "winter" wave.

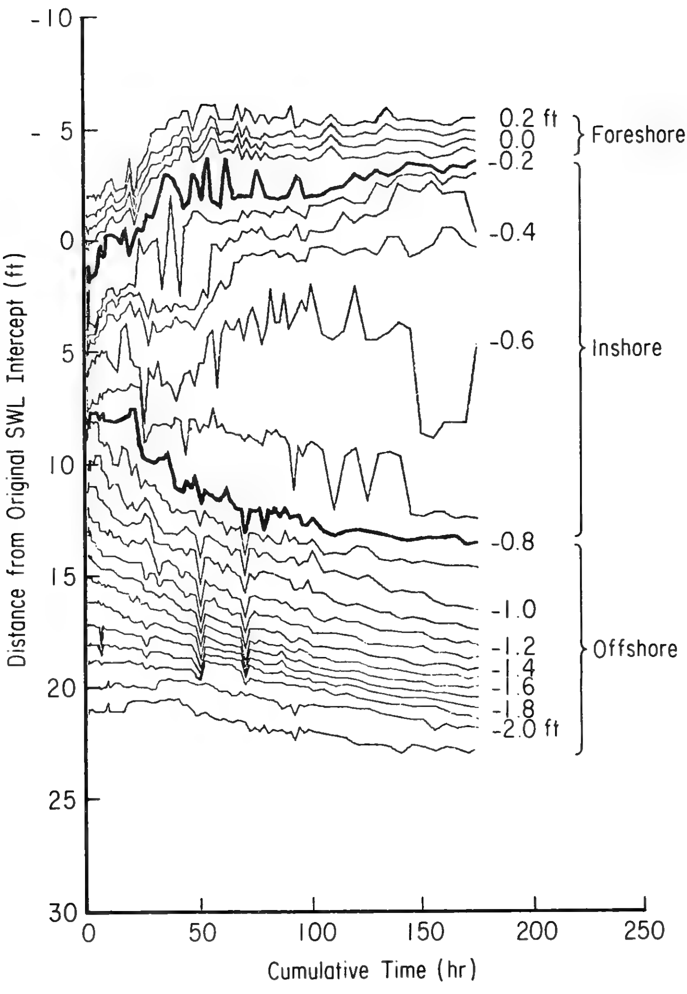


Figure 17. Contour movements along center range of experiment 70X-06.

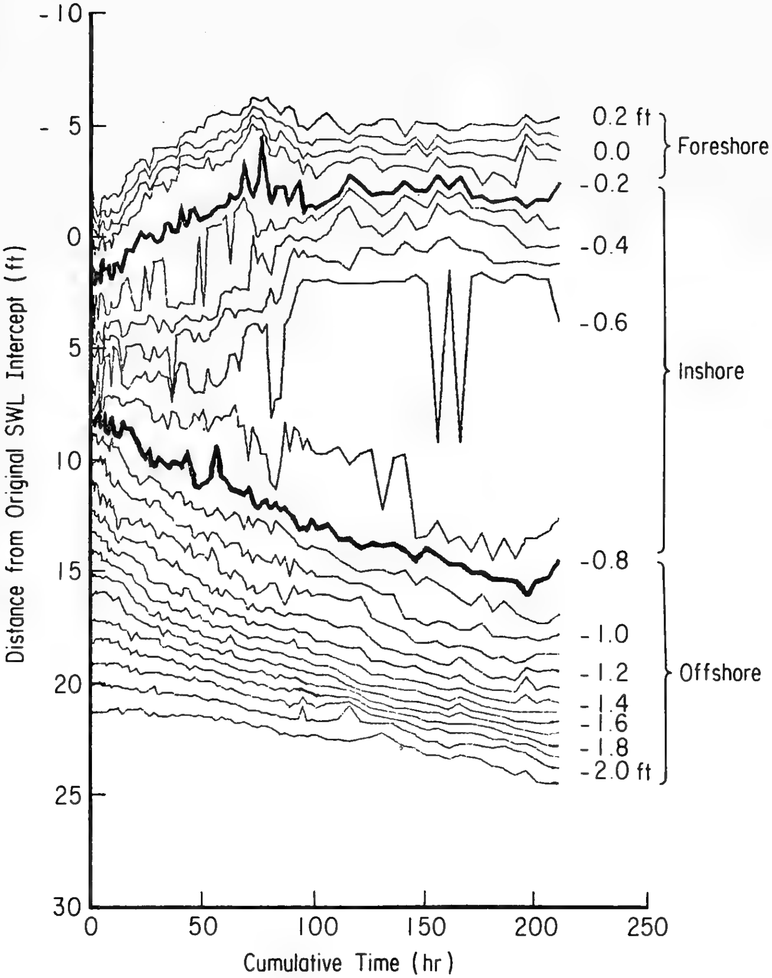


Figure 18. Contour movements along center range of experiment 70X-10.

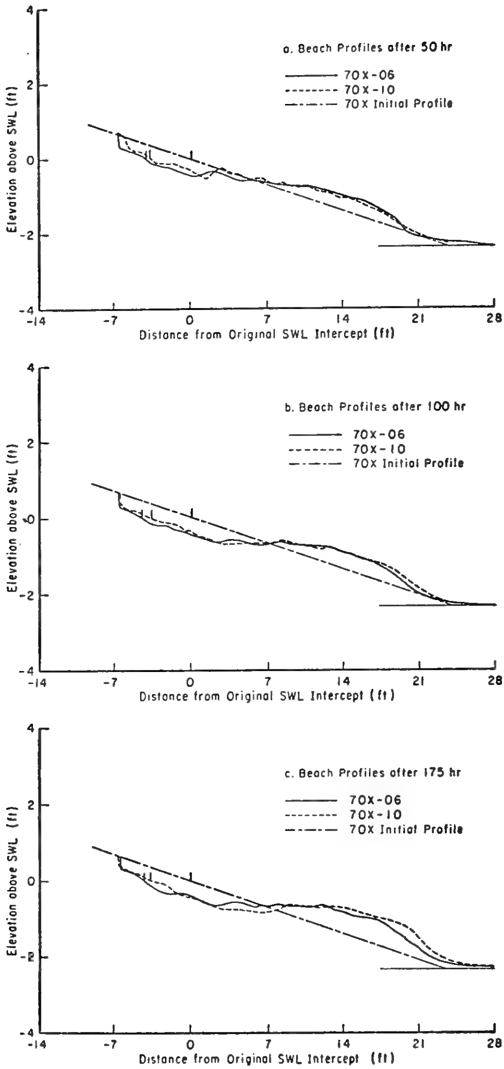


Figure 19. Greater seaward development of profile in experiment 70X-10 than in experiment 70X-06.

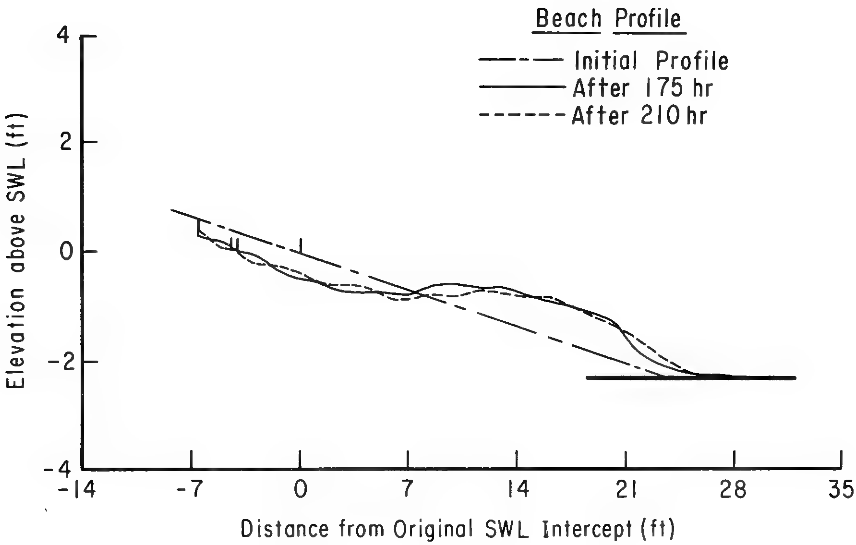


Figure 20. Profile changes in experiment 70X-10 during the last 35 hours.

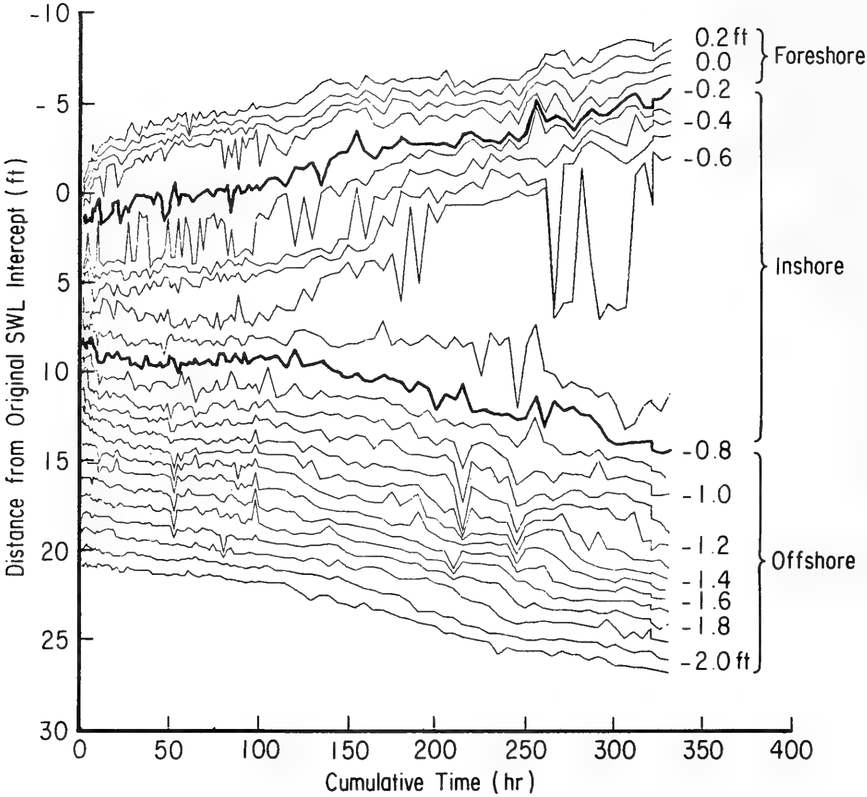


Figure 21. Contour movements along center range of experiment 71Y-10.

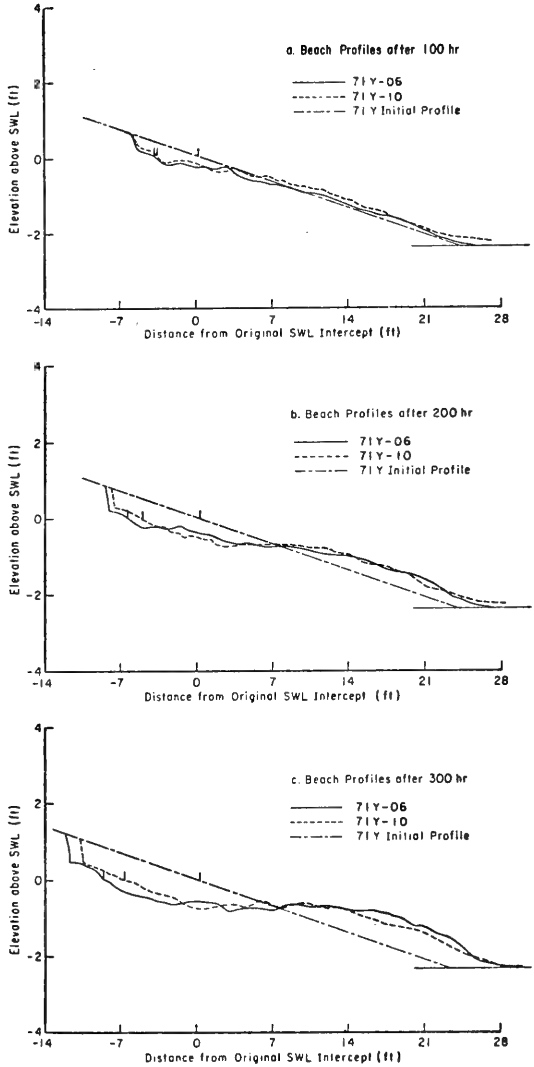


Figure 22. Greater seaward development of the profile in experiment 71Y-06 than in 71Y-10.

developed the flat inshore shelf and had surpassed experiment 71Y-10 in the progradation of the offshore zone. The comparison of the final profiles for the two experiments in Figure 23 indicates that the experiments had roughly the same shape, but that in experiment 71Y-06 the foreshore had eroded farther landward and the offshore had prograded farther seaward.

(3) Comparison of the Four Experiments. The final profiles in the experiments with the 1.90-second waves are compared in Figure 24, showing that the profile shape was similar in all four experiments, but that the longer the experiment, the farther landward the foreshore and the farther seaward the offshore. The K_R variability increased with time during each test (Figs. 3 to 6). This indicates that if an equilibrium slope can be attained for the 1.90-second period on an initial 0.10 sand slope, it is probably shaped like these four profiles with an even longer inshore zone.

c. 2.35-Second Wave. The profile in experiment 72B-06 adjusted slowly to the waves and appeared to be near equilibrium at the end of the experiment (150 hours) (Fig. 25); the profile in experiment 72B-10 adjusted more rapidly and did not appear to be near equilibrium at the end of the experiment (150 hours) (Fig. 26).

The differences in rate of profile adjustment and the differences in the shape of the offshore zone between the two experiments are shown in Figure 27. These differences may have been caused by differences in tank width and initial test length or by the transverse wave which was only generated in experiment 72B-10.

d. 3.75-Second Wave. Two experiments were conducted with a 3.75-second wave. Although the profile in the narrower tank (experiment 72A-06) did not appear close to equilibrium, the profile in the wider tank (experiment 72A-10) did, as shown by comparing Figures 28 and 29. The development and disintegration of circulation cells between antinodes of the standing wave envelope evidently prevented the profile from reaching equilibrium in experiment 72A-06 (discussed in Vol. VI). The absence of any horizontal contours in Figure 28 (narrower tank) shows this lack of equilibrium. However, in the wider tank, nearly all contours are horizontal after only 25 hours (Fig. 29).

Figure 30 compares the center profiles from the two experiments at 25, 50, and 80 hours, indicating that throughout the experiments the profile shapes were quite different in the two tanks, probably as a result of the circulation pattern in experiment 72A-06. Profile changes during the final 55 hours of experiment 72A-06 are shown in Figure 31. The offshore zone changed to a more gently sloping region.

e. Comparison of the Profiles. Although the profile in experiment 71Y-06 was not at equilibrium, it appears to well represent the shape of profile adjustment for a 1.90-second wave. The profile in experiment 72C-10 (1.50-second wave) was close to equilibrium and is assumed to be

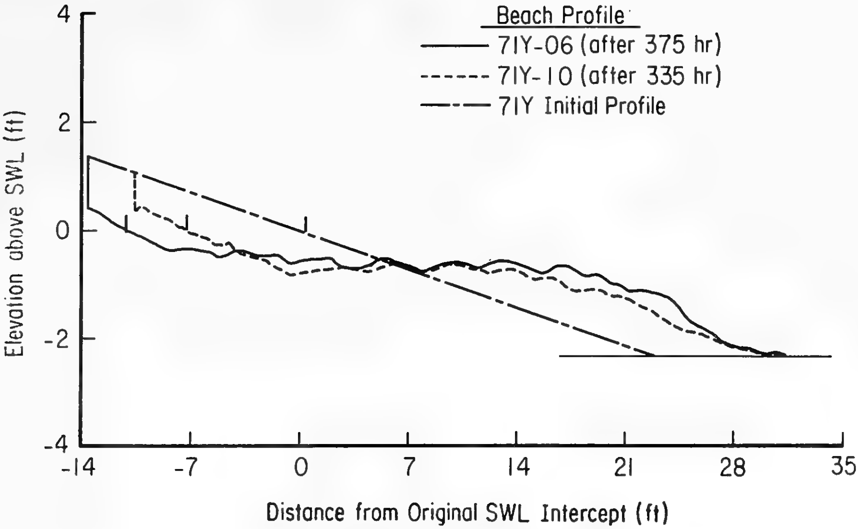


Figure 23. Final profiles in experiments 71Y-06 and 71Y-10, with the longest test durations in the series.

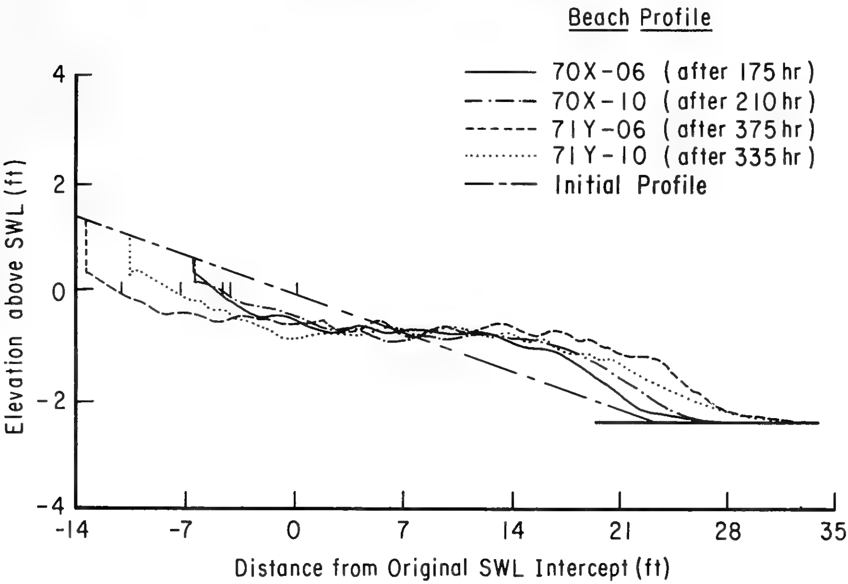


Figure 24. Comparison of final profiles with a wave period of 1.90 seconds and an initial slope of 0.10.

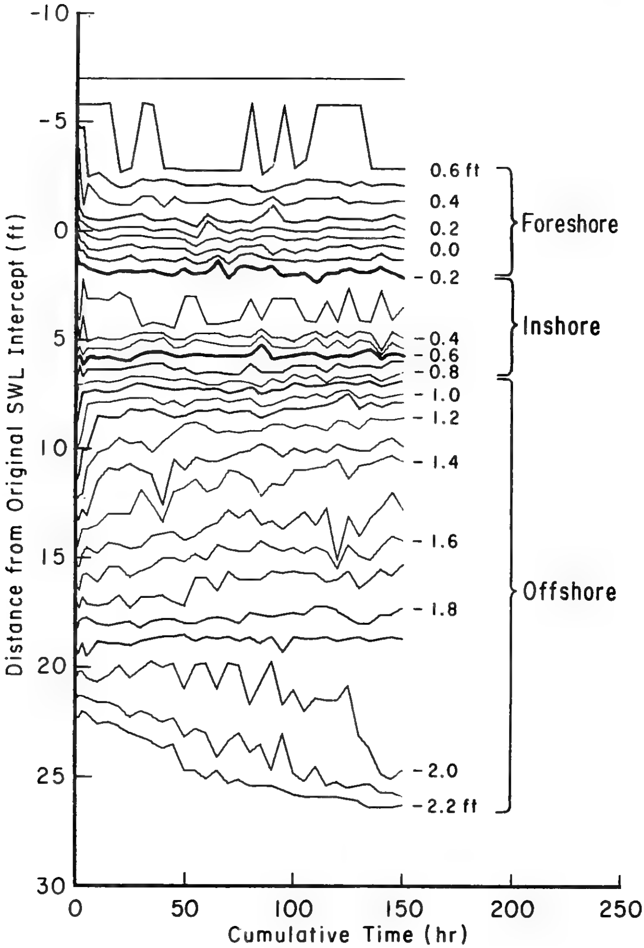


Figure 25. Contour movements along center range of experiment 72B-06.

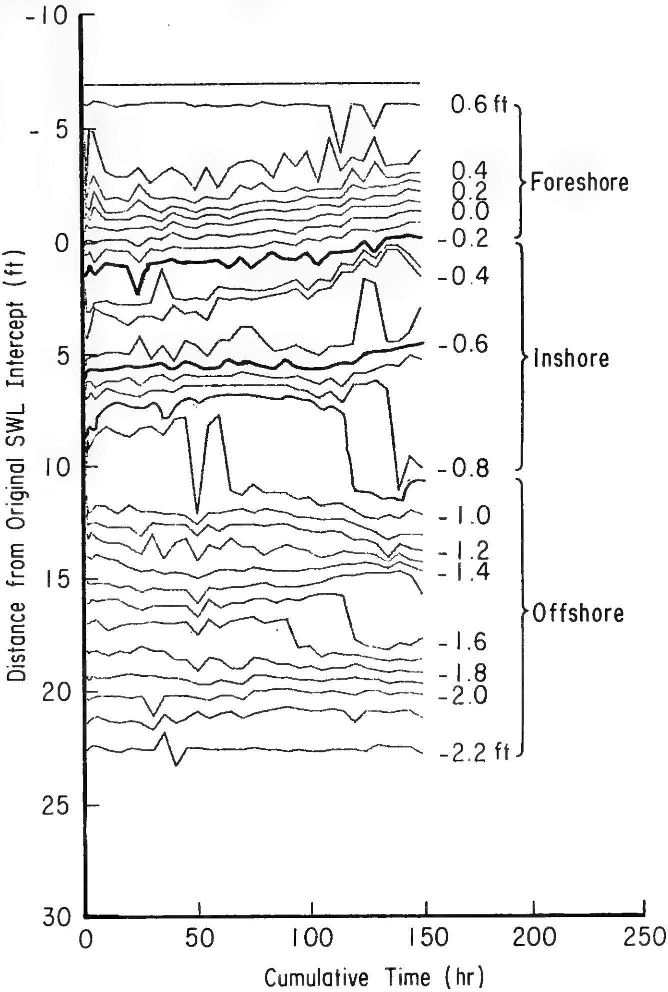


Figure 26. Contour movement along center range of experiment 72B-10.

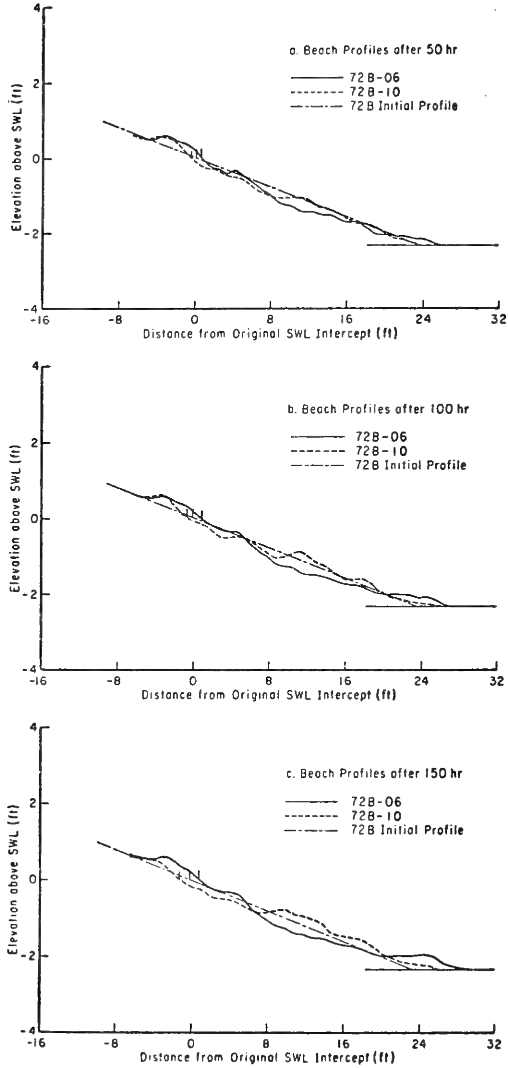


Figure 27. Development of different offshore shapes: concave upward in experiment 72B-06 and convex upward in experiment 72B-10.

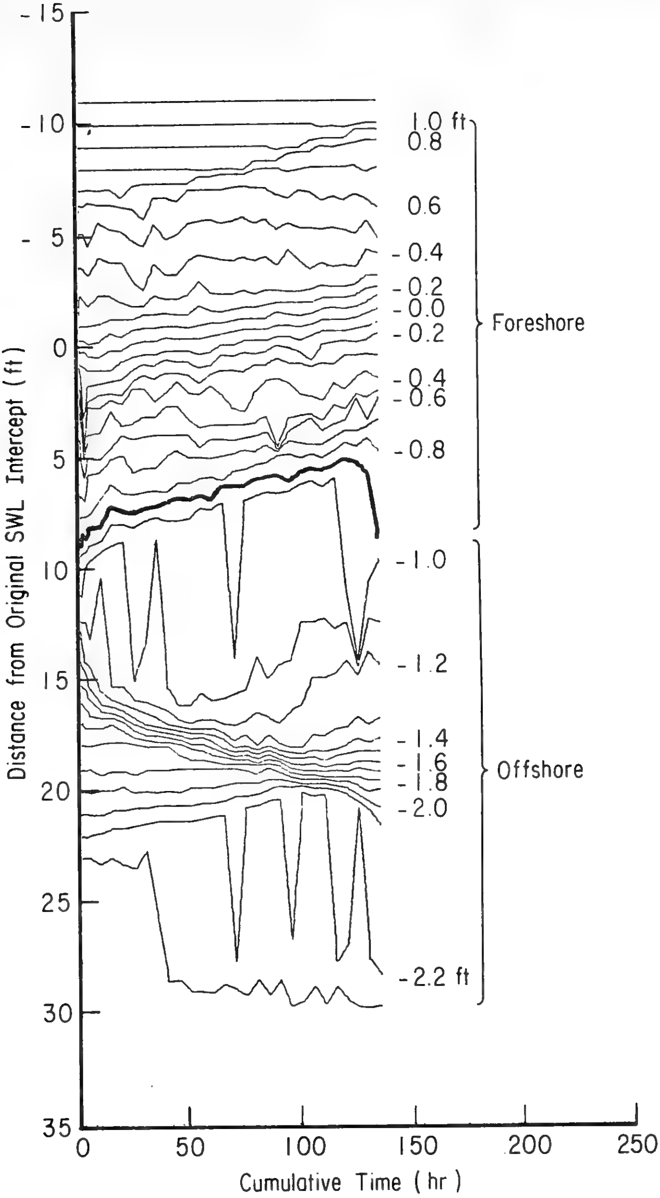


Figure 28. Contour movements along center range of experiment 72A-06.

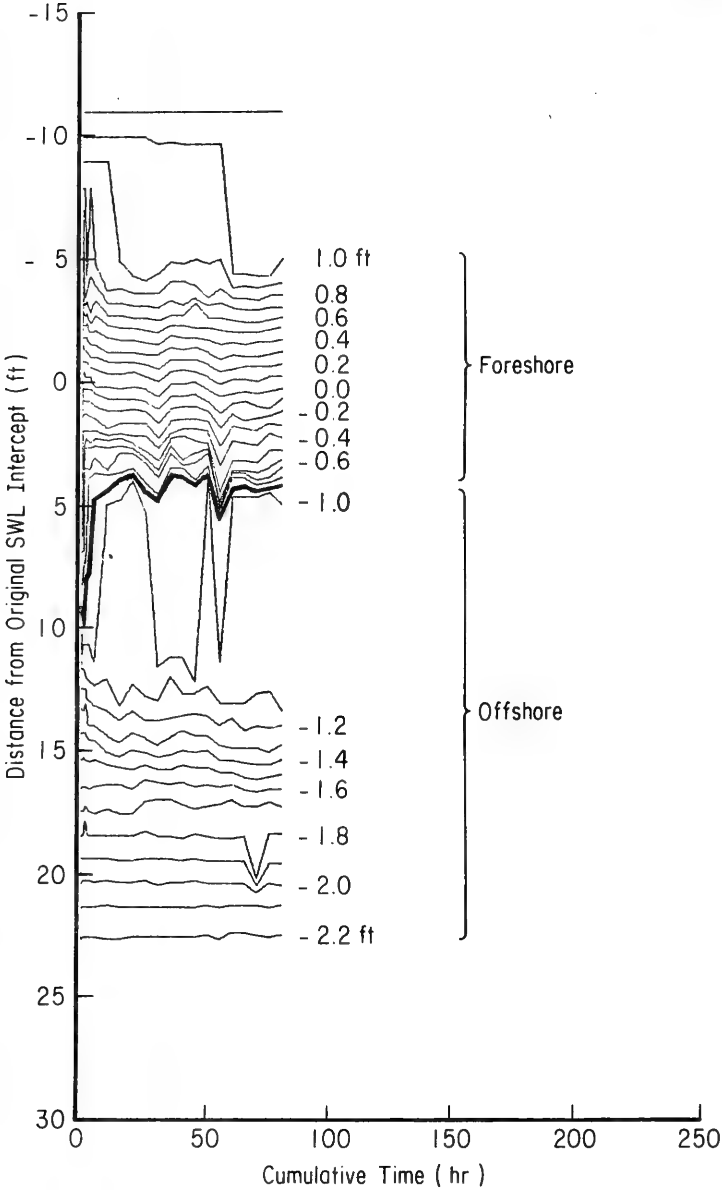


Figure 29. Contour movements along center range of experiment 72A-10.

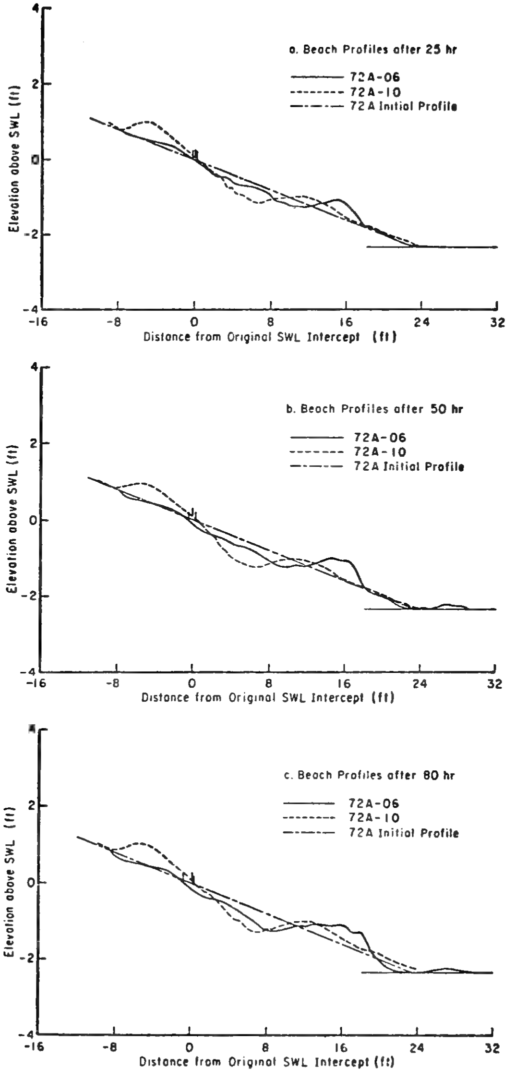


Figure 30. Development of a higher foreshore in experiment 72A-10 and a steeper offshore in experiment 72A-06.

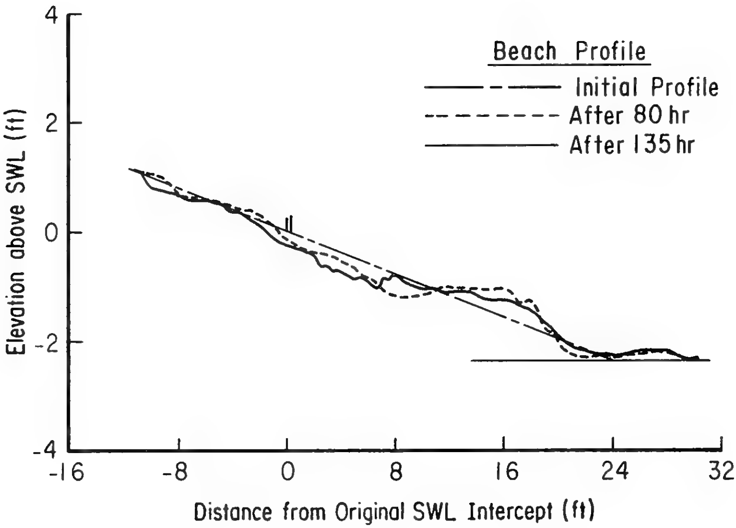


Figure 31. Profile change in experiment 72A-06 during the last 55 hours.

representative of a profile adjustment for a 1.50-second wave. The profiles in experiments 72A-10 and 72B-06 were close to or at equilibrium and are assumed to typify profile adjustment for 3.75- and 2.35-second waves. These four profiles are compared in Figure 32.

The profile from experiment 72A-10 (H_o/L_o = 0.004 at 80 hours) is typical of the step-type or summer (prograding shoreline) profile, with a high berm and a step at the toe of the foreshore zone. The profile from experiment 72B-06 (H_o/L_o = 0.013 at 150 hours) is also somewhat typical of the summer profile, except that the berm crest is lower and the lower foreshore appears to be half-bar and half-step. On both of these two profiles, some deposition occurred in the offshore zone, more in the H_o/L_o = 0.013 experiment than in the H_o/L_o = 0.004 experiment. The profile from experiment 71Y-06 (H_o/L_o = 0.021 at 375 hours) is certainly an eroding profile consisting of steep foreshore and offshore zones separated by a long shelf with several shallow bars and troughs. The profile from experiment 72C-10 (H_o/L_o = 0.039 at 140 hours) is typical of the bar-type or winter (eroding shoreline) profile with a vertical scarp, a steep foreshore, a longshore bar, and offshore deposition.

The transition zone between the two types of profiles is normally accepted to be between H_o/L_o = 0.020 and 0.025 and the profiles from the five experiments with H_o/L_o = 0.021 could certainly not be classified as either winter or summer. In fact, this was the least stable of the four conditions, with none of the five profiles close to equilibrium. With the other three wave steepnesses, at least one of the profiles appeared to be near a stable shape. This agrees with the findings of Kamphuis (personal communication, 1978) that waves in the transition region tend to take longer to develop an equilibrium profile.

The final profiles from experiments 72C-10, 71Y-10, 72B-10, and 72A-10 were averaged to develop a standard initial profile (Fig. 33) to be used in longshore transport experiments in CERC's Shore Processes Test Basin (SPTB) (P. Vitale, hydraulic engineer, CERC, personal communication, 1976). This standard profile will also be used in a study of wier jetties in the SPTB (J.R. Weggel, Chief, Evaluation Branch, CERC, personal communication, 1977).

f. Discussion of Results. The four experiments with the 1.90-second wave verify the findings of Savage (1962) and Fairchild (1970a) that an equilibrium profile is not always easily attained, even with the wave direction normal to the shoreline. The four experiments with the 3.75- and 2.35-second waves verify the findings of Collins and Chesnutt (1975, 1976) that profiles for the same wave conditions do not always have the same shape. In particular, the experiments with 3.75- and 2.35-second waves point out that the physical constraints of the laboratory facilities can affect the final profile shape. The currents in experiment 72A-06 (3.75 seconds) and the transverse wave in experiment 72B-10 (2.35 seconds) kept those from reaching equilibrium.

In judging the evidence presented here, profile equilibrium in basically two-dimensional tests does not appear to be an easily definable,

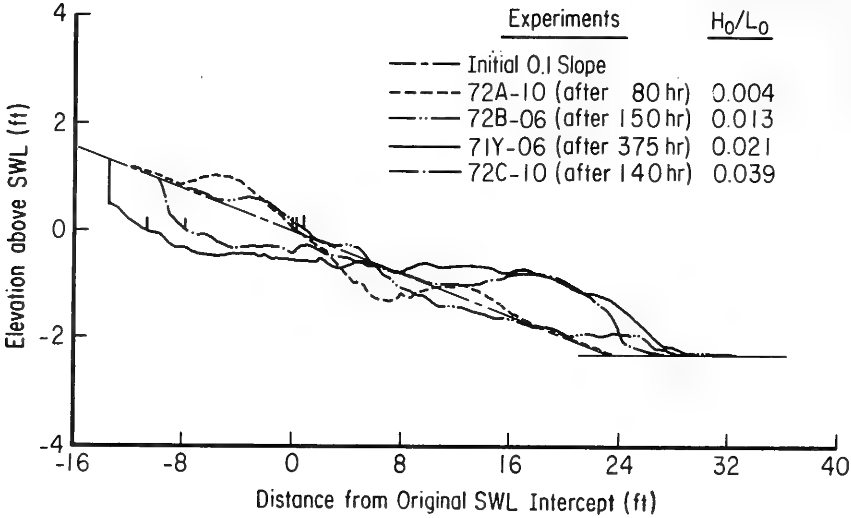


Figure 32. Comparison of the equilibrium or representative profile for each wave steepness.

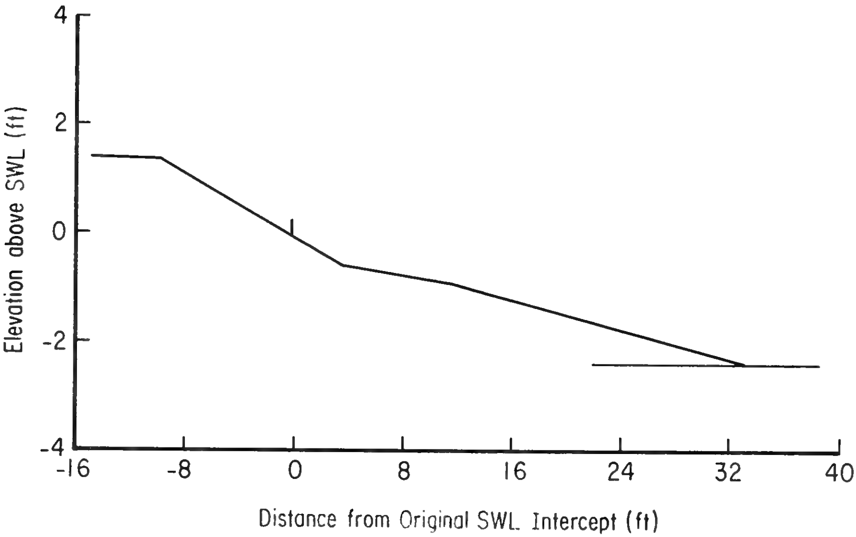


Figure 33. Preliminary beach profile of Vitale (personal communication, 1976), developed from the final profiles of experiments 72C-10, 71Y-10, 72B-10, and 72A-10.

attainable, or a useful state to be trying to reach in experiments of practical duration. Coastal engineering might be better advanced if researchers were more concerned with trying to reach some constant rate of profile change or a rate of profile change small in comparison to other variables.

IV. LABORATORY EFFECTS

1. Definitions of Terms.

Laboratory effects are the undesired differences between laboratory and prototype conditions caused by the physical constraints which exist in the laboratory, but not in the field. For example, the variations in incident wave height discussed in Section II, 3 are laboratory effects; i.e., the mechanical generator at one end of the wave tank caused a re-reflection of the wave energy propagating away from the profile that would not have occurred in nature. This project evolved from an investigation of wave height variability and equilibrium profiles into a more comprehensive examination of all laboratory effects.

This section analyzes five laboratory effects based on results from the 10 experiments. Other known laboratory effects are also identified.

2. Test Length and Initial Slope Effects.

a. Processes. Two physical processes are known to be affected by changes in initial test length: re-reflection of waves from the wave generator and secondary waves.

(1) Re-Reflection. The height of the incident wave is a function of the height of the nominal (generated) and re-reflected waves and the phase difference between the re-reflected wave and the wave generator motion. The height and phase of the re-reflected wave are functions of the height and phase of the reflected wave. The height of the reflected wave is a function of the profile reflectivity. The phase of the reflected wave with respect to the generator motion is a function of the distance between the profile and the generator. The effect of initial test length on re-reflection and incident wave height variability is discussed in Section II, 3. The effect of incident wave height variability on the profile is discussed in this section.

(2) Secondary Waves. Secondary waves cause a spatial (longitudinal) variation in wave height and a variation in the asymmetry of the velocity distribution under a wave. The degree of asymmetry obviously depends on the position along the tank. In this case the distance to the toe of the initial profile from the generator is the controlling distance.

b. Initial Test Length Effect. Four pairs of experiments are examined here. In two pairs (experiments 70X-06 and 71Y-06 and experiments

70X-10 and 71Y-10) the initial test length was the only variable; in the other two pairs (experiments 72B-06 and 72B-10 and experiments 72A-06 and 72A-10) both initial test length and tank width varied, but the effects of initial test length are distinguishable from the tank width effects.

(1) Experiments 70X-06 and 71Y-06 (1.90-Second Wave). In each experiment the effect of re-reflection on the incident wave height was the same, 0.03 foot (Table 13). However, the average incident wave height was 0.34 foot in experiment 70X-06 and 0.37 foot in experiment 71Y-06, and the difference in incident height is likely due to the difference in the phase difference as a result of the 7-foot difference in initial test length.

The profiles in the two experiments developed similar shapes (Fig. 24), with the length of the inshore shelf the only difference, due primarily to the 200-hour difference in the duration of the experiments. However, the rate of shoreline recession was quite different (Fig. 34). In experiment 70X-06 the shoreline recession rate was 0.06 foot per hour between 1 and 22 hours, 0.14 foot (4.2 centimeters) per hour between 22 and 30 hours, 0.10 foot per hour between 30 and 44 hours, and 0 thereafter. The backshore was artificially nourished after 54 hours, thus maintaining the stable shoreline after that time. In experiment 71Y-06 the rate was 0.113 foot per hour between 1 and 15 hours and 0.025 foot per hour thereafter (for 360 hours).

The differences in profile adjustment rates may have been caused by the difference in initial test length; if so, the difference was not due to re-reflection effects, since the higher recession rate was associated with the lower incident wave height. It is unlikely that secondary waves would have caused the difference in shoreline recession rates without also affecting the profile shape and such profile shape differences were not observed.

(2) Experiments 70X-10 and 71Y-10 (1.90-Second Wave). In each of these experiments the effect of re-reflection on the incident wave height was different, 0.02 foot in experiment 70X-10 and 0.06 foot in experiment 71Y-10 (Table 13). However, the average incident wave height was almost the same, 0.37 foot in experiment 70X-10 and 0.36 foot in experiment 71Y-10, even though the initial test length had a difference of 7 feet in the two experiments.

The profiles in the two experiments developed similar shapes (Fig. 24), with the length of the inshore shelf the only difference, due primarily to the 125-hour difference in the duration of the experiments. However, the rate of shoreline recession was quite different (Fig. 34). In experiment 70X-10 the shoreline recession rate was 0.08 foot per hour between 12 and 62 hours, and 0 thereafter because the backshore was renourished to maintain a stable shoreline position. In experiment 71Y-10 the rate was 0.133 foot (4.05 centimeters) per hour (uniform laterally) between 1 and 15 hours, 0.016 foot per hour (uniform laterally) between

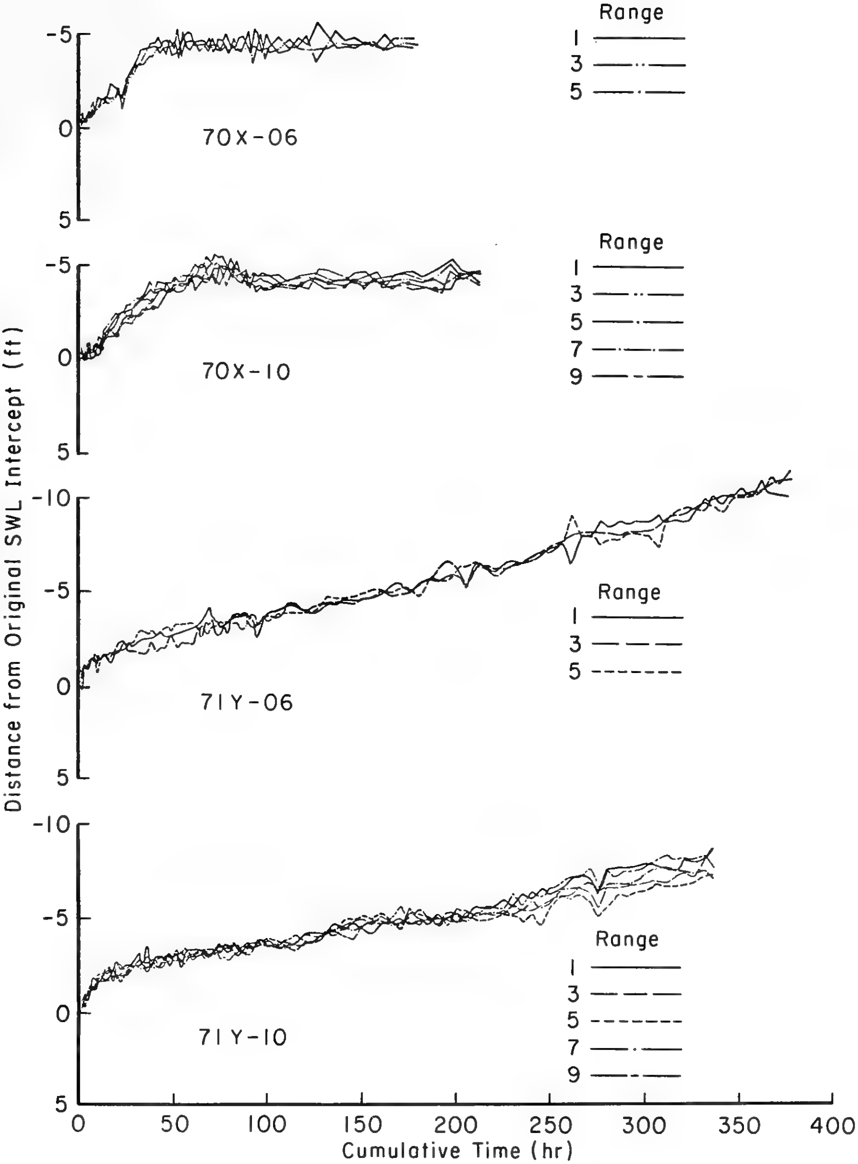


Figure 34. Comparison of shoreline movement in four experiments with a 1.90-second wave and a 0.10 initial slope.

15 and 205 hours, and varied from 0.016 foot per hour along the center of the tank to 0.025 foot per hour along the tank walls thereafter (for 130 hours).

Re-reflection is not the likely explanation for the difference in shoreline recession rates, since there was little difference in average incident wave heights and the slower recession rate was associated with the higher range of re-reflection effect within an experiment. Secondary waves are not a likely cause because there was no difference in profile shape.

(3) Experiments 72B-06 and 72B-10 (2.35-Second Wave). In these two experiments the effect of re-reflection on the incident wave height variability was slight. In experiment 72B-06 the range of incident wave heights in the movable-bed tank was only 0.01 foot greater than in the fixed-bed tank; in experiment 72B-10 the range in the movable-bed tank was less than in the fixed-bed tank (Table 13). However, there was a 0.07-foot difference in average incident wave height. The average K_R was lower in experiment 72B-06 than in experiment 72B-10, indicating that H_R and H_{RR} would have been lower in experiment 72B-06. The higher H_I in experiment 72B-06 must then have been the result of the difference in phase difference between H_I and H_{RR} as a result of the 38.3-foot (11.7 meters) difference in initial test length. Secondary waves were also present.

The profiles in the two experiments developed different profile shapes. Some of those differences were due to the differences in tank width and the presence of the transverse wave in experiment 72B-10 (discussed in the following subsection). In experiment 72B-06 the offshore zone had a concave-upward shape; in experiment 72B-10 the offshore zone had a convex-upward shape (Fig. 27,c). This significant difference could have been caused by either secondary waves or re-reflection effects, as a result of the difference in initial test length. This difference in offshore profile shape may have been a contributing cause to the lack of equilibrium in experiment 72B-10.

(4) Experiments 72A-06 and 72A-10. In each of these experiments the effect of re-reflection on the incident wave height variability was different, 0.03 foot in experiment 72A-06 and 0.08 foot in experiment 72A-10; the difference in average incident wave height between the two experiments (0.03 foot) was significant (Table 13). Thus, varying reflectivity within an experiment caused variations in H_I; and the 38.3-foot difference in initial test length affected the average H_I. Secondary waves were the most pronounced in these experiments.

The profiles in the two experiments developed different shapes (Fig. 31). Some of the differences were due to tank width effects, which are discussed in the following subsection. The differences in the shape of the outer offshore were probably due to re-reflection or secondary wave effects. In experiment 72A-06 the outer offshore had a steep segment between stations 16 and 20 and a bar at station 28. In experiment 72A-10 the outer offshore below -1.9 feet remained unchanged throughout the experiment. The differences in foreshore berm-crest elevation may have resulted from the differences in the outer offshore, but these cannot be determined.

c. Initial Slope Effect. The effect of varying the initial slope can be seen by comparing experiment 71Y-06 with an initial slope of 0.10 and experiment 72D-06 with an initial slope of 0.05. All other parameters were equal in these two experiments.

In each of these experiments the effect of re-reflection on the incident wave height variability was the same (0.03 foot), but there was a 0.02-foot difference in average incident wave height (Table 13). Re-reflection caused a higher average incident wave height in the experiment with the flatter initial slope.

The distance from the generator to the toe of the initial slope was 23 feet greater in experiment 71Y-06 (0.10 slope); thus, the velocity distribution at the toe of the slope may have been different in the two experiments.

The offshore profiles in these two experiments developed similar shapes (Fig. 14), but the inshore zone developed somewhat differently. In experiment 72D-06 (0.05 initial slope) the flat shelf in the inshore zone developed during the first 100 hours and a trough was scoured in the zone after the foreshore stabilized at 135 hours. In experiment 71Y-06 (0.10 initial slope) the flat shelf in the inshore zone developed between 200 and 220 hours and then continued to widen as the foreshore and offshore separated.

It is not possible to ascertain whether re-reflection, secondary waves, or some other phenomena caused the profiles to develop such different inshores, but it was probably the result of the difference in initial slope.

3. Tank Width Effects.

When the wavelength, L, is much larger than the tank width, W, then the wave tank is "narrow" and the result of wave action on the sand bed is expected to be two dimensional; i.e., without lateral variations in profile shape. When L is much smaller than W, then the wave tank is essentially a "basin" and the result of wave action on the sand bed, even when wave direction is normal to the initial shoreline, is expected to be three dimensional; i.e., with lateral variations in profile shape. In the intermediate case, when the tank width and wavelength are nearly the same ($L/W \simeq 1$), the wave tank is wide enough for the lateral variations to begin to occur, but the tank walls confine the third dimension of current patterns and sediment movement to an unknown extent. In the 10 LEBS experiments, L had values that ranged from equal to W to several times larger than W, so the point at which a wave tank becomes narrow can be examined.

The confining effect of the tank walls on flow in the longshore direction is complicated by other tank width effects. There are critical wavelengths for each tank width which can generate tank oscillations or unique circulation patterns (see Sec. II). Cross waves were observed over a limited segment of the profile for a short period of time in experiment 72B-06 (Vol. VII), but neither the cross waves nor their effect on the profile were measured. Transverse waves were observed and measured throughout experiment 72B-10 (Vol. VII) and their effect on the profile determined. Circulation currents between the antinodes of the standing wave, along with their effects, were measured in experiment 72A-06 (Vol. VI). These three special cases of tank width effects are assumed to produce special effects on the sand beds. Tank width effects in all 10 experiments from lowest to highest wave period tested are discussed below.

a. <u>1.50-Second Wave (L/W = 1.03, Experiment 72C-10)</u>. The foreshore and inshore zones had significant lateral variations. The shoreline station along the five ranges varied as much as 2.5 feet (0.76 meter) at any given time (Fig. 35). Specific instances of this variation are illustrated by the two photos in Figure 36. At 50 hours (Fig. 36,a) the shoreline and scarp on the near side (ranges 1 and 3) are farther landward than the shoreline along the far side (ranges 7 and 9). At this time the backshore was apparently eroding along ranges 1 and 3, and the sand moved alongshore to range 7 where it caused the shoreline to protrude into the inshore zone. At 85 hours (Fig. 36,b) the scarp was uniform in position across the tank, but the position of the shoreline was seawardmost on the near side (range 1) and landwardmost in the middle (range 5). At this time the backshore was apparently eroding in the middle of the tank, and the sand moved alongshore to range 1 where it moved out into the inshore zone. At other times the erosion of the backshore occurred only along ranges 7 and 9 and the sand was transported alongshore to range 1 before moving into the inshore.

Considerable lateral variation also occurred in the inshore zone of this experiment (Fig. 37 compares movements of the -0.3-, -0.4-, -0.5-, -0.7-, and -0.8-foot (-9.1, -12.2, -15.2, -21.3, and -24.4 centimeters) contours). The lateral variations were particularly great just below the foreshore (elevation -0.3 foot) and the amount of variation decreased moving in the seaward direction. No lateral variation occurred in the offshore zone (Fig. 38 compares movements of the -0.9-, -1.4-, and -1.9-foot (-27.4, -42.7, and -57.9 centimeters) contours). Erosion of a trough near station 10 started first along the tank walls and progressed toward the center (discussed in Vol. V).

The three dimensionality of the profile shape is shown in Figure 39, which is a contour map of the sand bed at the end of the experiment. The foreshore and offshore topographies are skewed in the same direction and the inshore topography is approximately symmetric about the tank centerlines. The symmetric development of the inshore is illustrated by the depressions along the tank walls near stations 3 and 13. The tank walls obviously constrained the shape that did develop, but that shape does have a significant variation in the third (longshore) dimension.

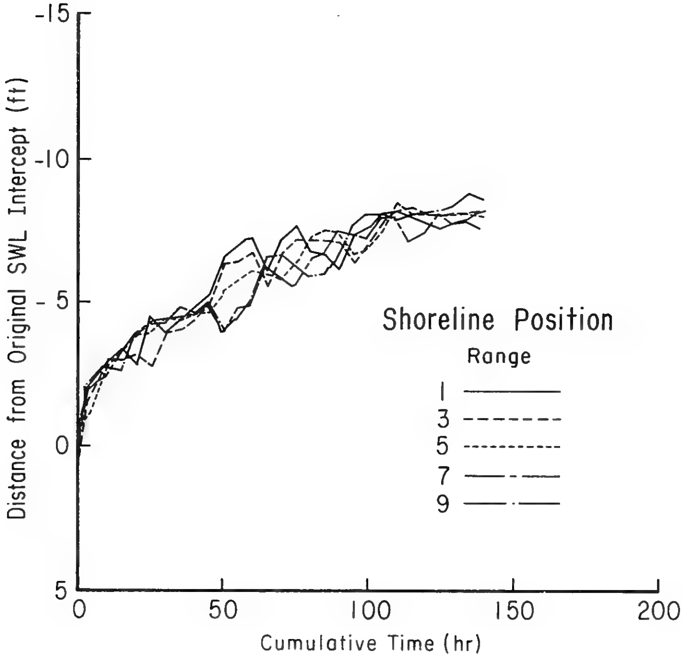
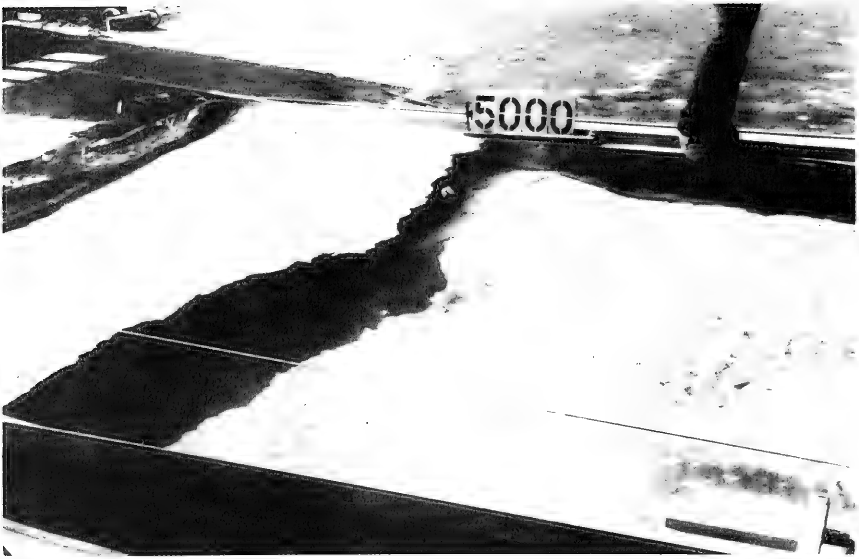


Figure 35. Shoreline movement of five ranges in experiment 72C-10 (L/W = 1.03).



a. At 50 hr

b. At 85 hr

Figure 36. Foreshore variability over 35-hour period in experiment 72C-10 (L/W = 1.03).

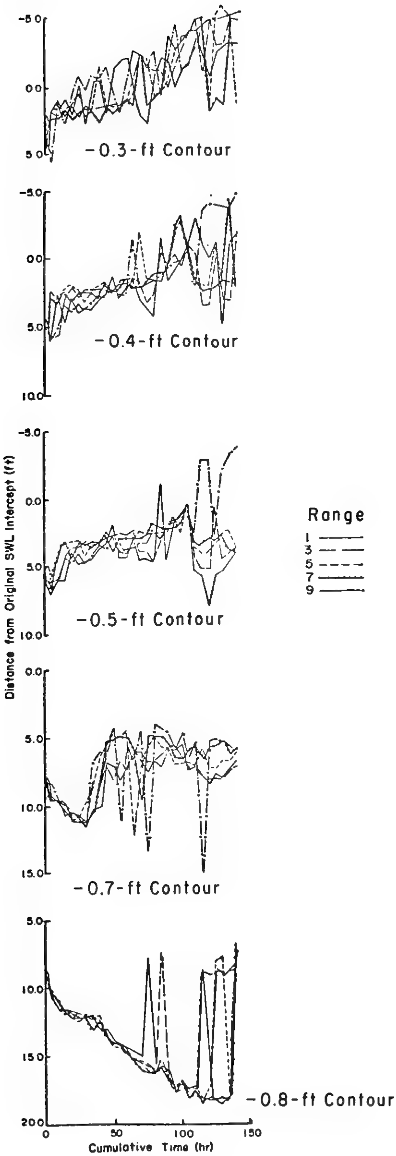


Figure 37. Lateral variations in movement of inshore zone contours in experiment 72C-10 (L/W = 1.03).

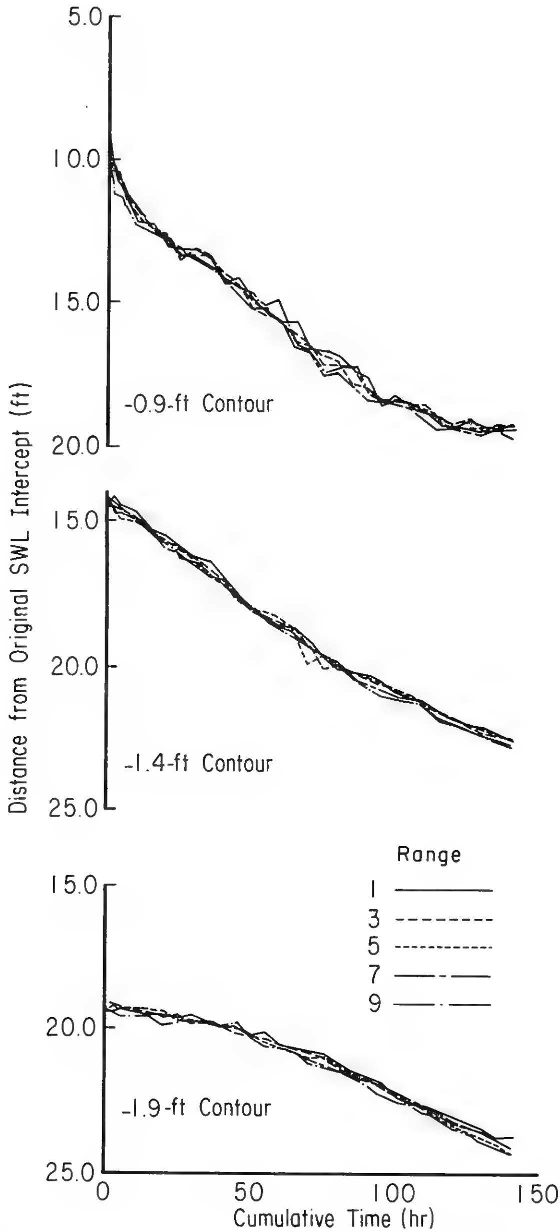


Figure 38. Lack of lateral variations in movement of offshore zone contours in experiment 72C-10 (L/W = 1.03).

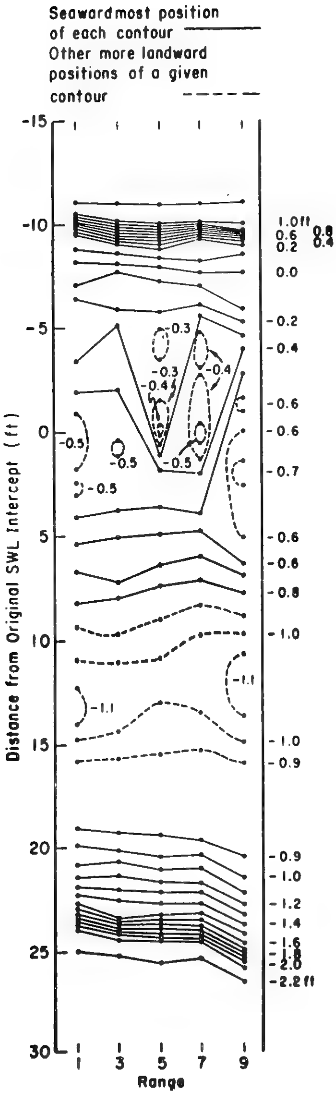


Figure 39. Profile shape at end (140 hours) of experiment 72C-10 (L/W = 1.03).

b. 1.90-Second Wave.

(1) L/W = 1.43 (Experiments 70X-10 and 71Y-10). Although the foreshore had some lateral variations, the inshore zones had greater lateral variations, particularly in the development of the flat shelf in the inshore in experiments 70X-10 and 71Y-10, the experiments with the next highest value of L/W.

In both experiments with L/W = 1.43, the slope of the foreshore and position of the shoreline varied with range at any one time and with time at any one range. The slope varied from 0.04 to 0.60 in experiment 70X-10 and from 0.08 to 0.56 in experiment 71Y-10. The shoreline position at any one time varied up to 1.6 feet (48.8 centimeters) in experiment 70X-10 and 2.0 feet in experiment 71Y-10 (Fig. 40) (compared to up to 2.5 feet with L/W = 1.03). The most important profile change in all of the experiments with the 1.90-second wave was the development of the long flat shelf within the inshore zone. In experiment 70X-10 the shelf development began at 15 hours along range 1 and at 95 hours along range 9, as indicated by the initial upward movements of the -0.6-foot contour positions in Figure 41. In experiment 71Y-10 (Fig. 41) the shelf development began at 210 hours along range 1 and 110 hours along range 9. The 80-hour difference in experiment 70X-10 and the 100-hour difference in experiment 71Y-10 are significant--that this variation occurred in both experiments in the same tank and that the development started on one side in one experiment and on the other side in the other experiment indicates that the variation was not due to a unique external influence or some misalinement in the tank.

The three dimensionality of the profile shape at the end of the experiments is shown in Figure 42. The offshore zones are skewed seaward along ranges 7 and 9 in both experiments, just as in experiment 72C-10.

(2) L/W = 2.38 (Experiments 70X-06, 71Y-06, and 72D-06). In three experiments with a 1.90-second wave conducted in the narrower tank, the profile shape usually had less lateral variation, as would be expected from the higher value of L/W.

In these experiments, lateral variations in slope and position occurred on the foreshore. The foreshore slope varied from 0.10 to 0.36 in experiment 70X-06, from 0.08 to 0.52 in experiment 71Y-06, and from 0.02 to 0.50 in experiment 72D-06 (the experiment with a 0.05 initial slope). The shoreline position varied as much as 2.0 feet in experiment 70X-06, 2.3 feet (70.1 centimeters) in experiment 71Y-06, and 1.9 feet in experiment 72D-06 (Fig. 43). The foreshore variations are not less than those with L/W = 1.43 (compare Fig. 43 with Fig. 40), especially since the tank was narrower.

The inshore in experiment 70X-06 developed the flat shelf with little lateral variation in time of development, but after the shelf developed lateral variations occurred, as indicated by the -0.6-foot contour movements in Figure 44. The same holds for experiment 71Y-06 (Fig. 44). In

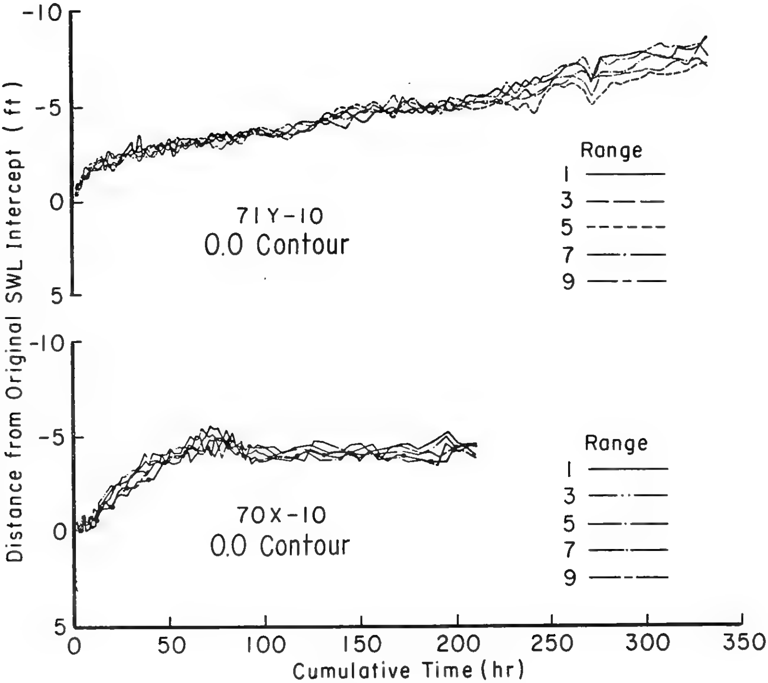


Figure 40. Shoreline movement in experiments 70X-10 and 71Y-10 (L/W = 1.43).

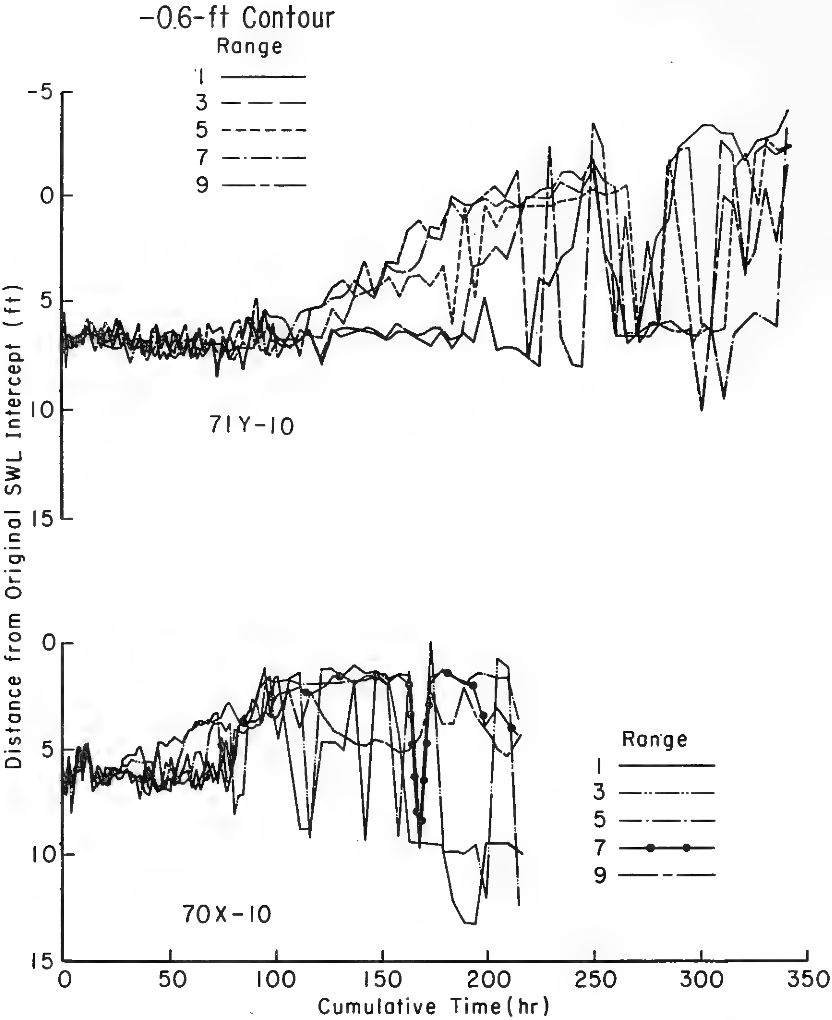


Figure 41. Comparison of the movements of the -0.6-foot contour in experiments 70X-10 and 71Y-10 (L/W = 1.43). Compare with Figure 37.

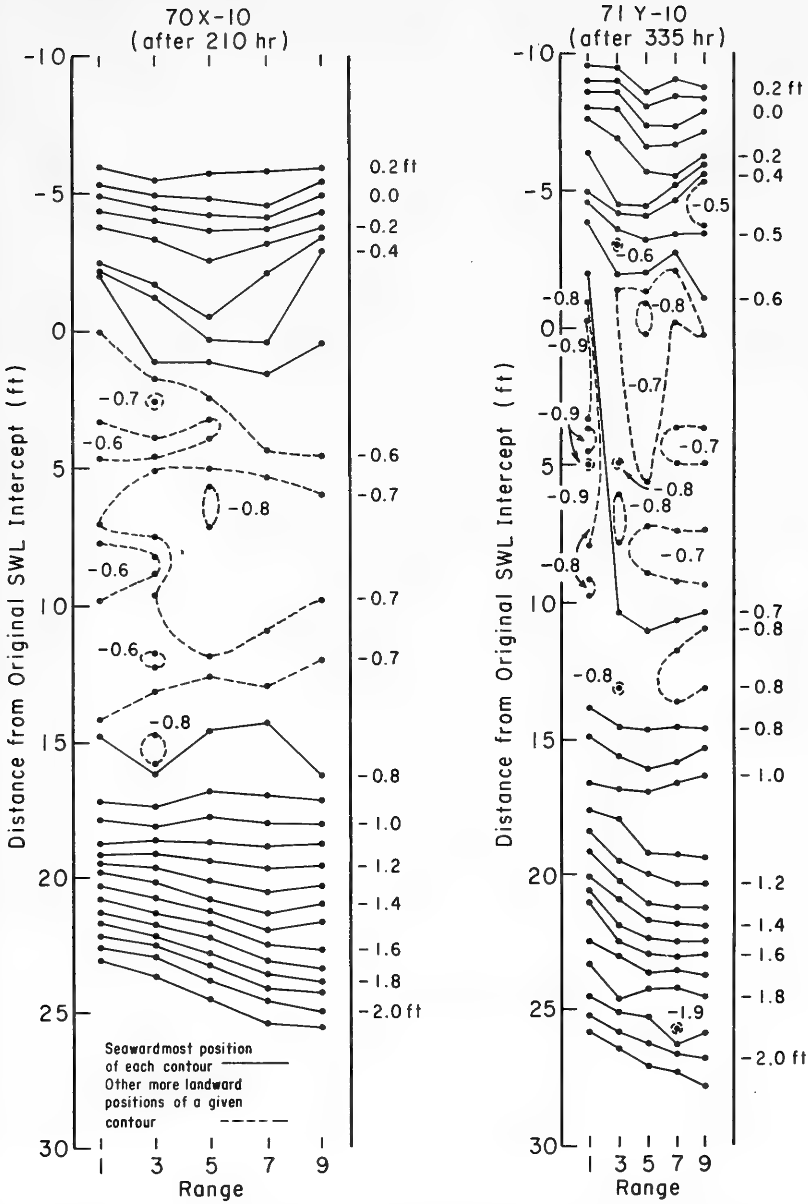


Figure 42. Profile shape at end of experiments 70X-10 and 71Y-10 (L/W = 1.43). Compare with Figure 39.

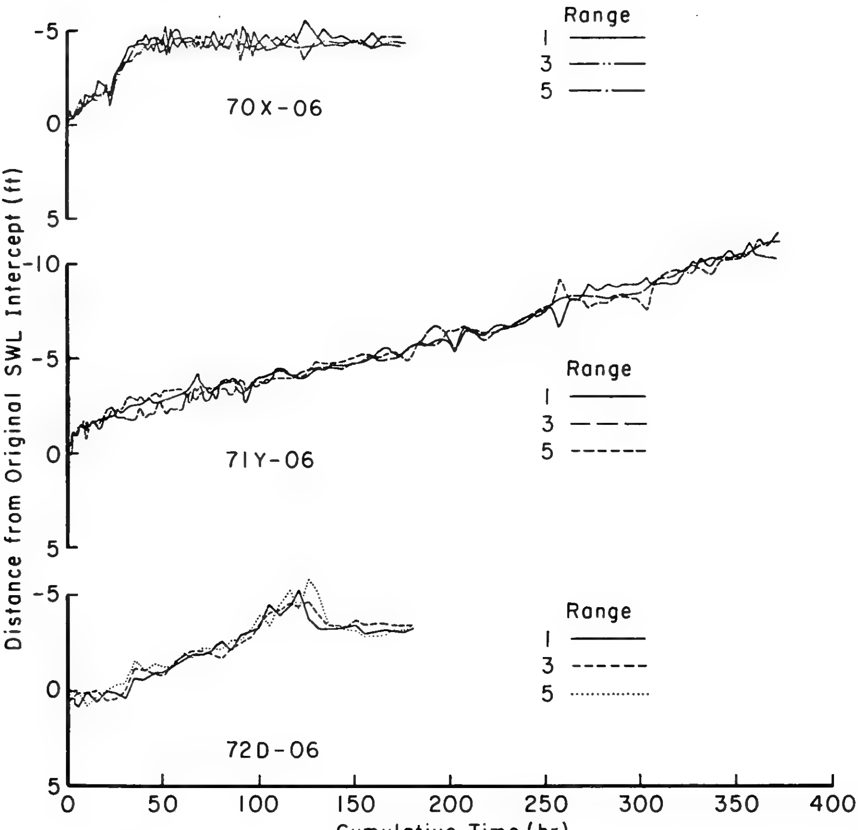


Figure 43. Shoreline movement in experiments 70X-06, 71Y-06, and 72D-06 (L/W = 2.38). Compare with Figure 40.

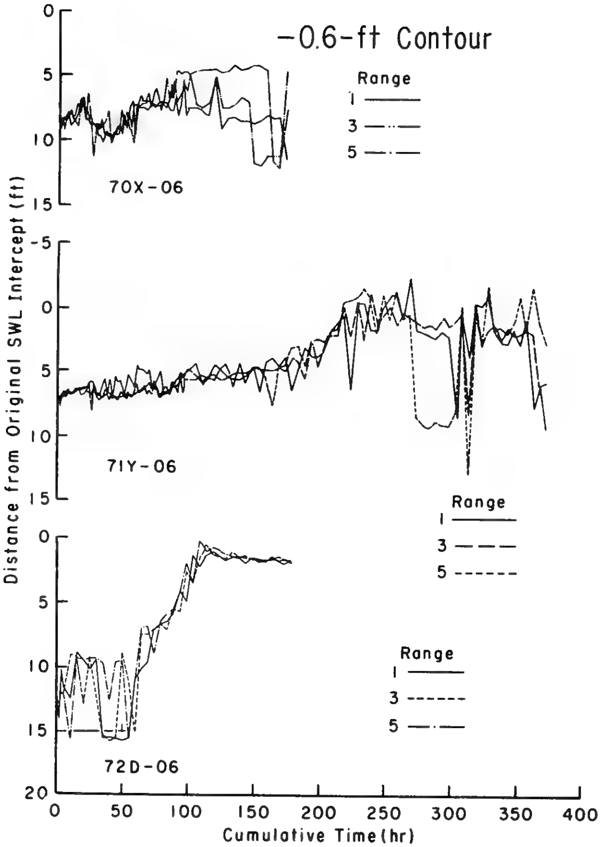


Figure 44. Comparison of the -0.6-foot contour movements in experiments 70X-06, 71Y-06, and 72D-06 (L/W = 2.38). Compare with Figure 41.

experiment 72D-06 the flat inshore developed quickly and then a large trough was scoured at the shoreward end of the inshore. In contrast to experiments 70X-06 and 71Y-06, the lateral variations in the position of the -0.6-foot contour in experiment 72D-06 (Fig. 44) occurred while the inshore was a flat shelf, perhaps because of the differences in initial slope.

Contour maps of the final profile shape for the three experiments are in Figure 45. The profile shape obviously varied laterally, particularly in the foreshore and inshore, but in the offshore zone the variations were less than in the wider tank.

c. 2.35-Second Wave.

(1) L/W = 1.86 (Experiment 72B-10). In experiment 72B-10, the L/W ratio was less than the three experiments in the 6-foot tank with the shorter 1.90-second wave. The profile in this experiment was affected by the transverse wave, generated by the gap at the end of the generator blade. Thus, the width effects identified here are the result of the "generator gap effect," which is another special case of width effects.

The foreshore slope and position varied laterally and with time, as a result of the three-dimensional swash movement. The slope varied from 0.10 to 0.54. During the first 100 hours and between 130 and 150 hours, the shoreline position was skewed across the tank, with up to a 1.2-foot difference in shoreline position between range 1 (seawardmost) and range 9 (landwardmost) (Fig. 46). Between 100 and 130 hours the shoreline position was not skewed.

In the inshore a longshore bar developed near station 2 and later eroded, and a flat area developed near station 5 and later developed into a bar. The above changes occurred at different times along each range, as shown by the variation in movement of the different contours in Figure 47, and as discussed in Volume VII.

Flat areas developed in the offshore zone near stations 8 and 16, but in each case the elevation of this flat area increased from the range 1 side to the range 9 side. Sand deposited at the toe of the slope along ranges 1 and 3, but not along ranges 5, 7, and 9. The lateral variation of contours in each of the three areas is shown in Figure 48.

The final profile shape is shown in Figure 49 with lateral variations in the areas discussed above.

(2) L/W = 3.10 (Experiment 72B-06). In experiment 72B-06 the lateral variations in profile shape were minimal. The foreshore slope varied from 0.10 to 0.46 as a result of lateral variations in swash movement, but the shoreline position varied as much as 0.5 foot only once and was generally uniform (Fig. 50).

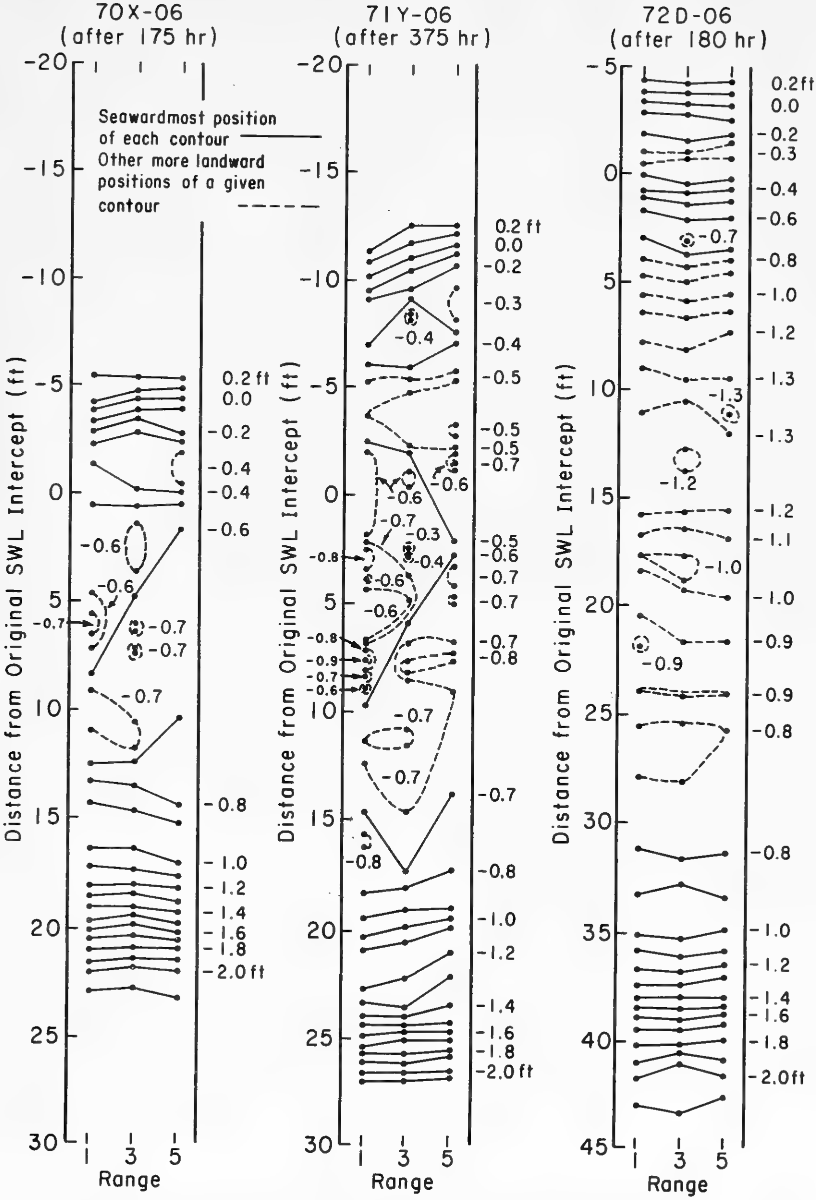


Figure 45. Profile shape at end of experiments 70X-06, 71Y-06, and 72D-06 (L/W = 2.38). Compare with Figure 42.

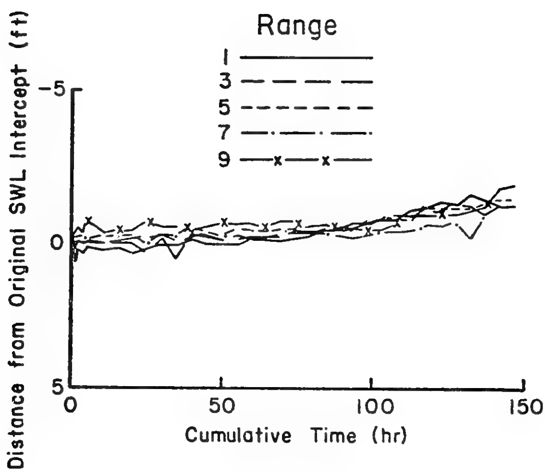


Figure 46. Shoreline movement in experiment 72B-10 (L/W = 1.86). Compare with Figure 40.

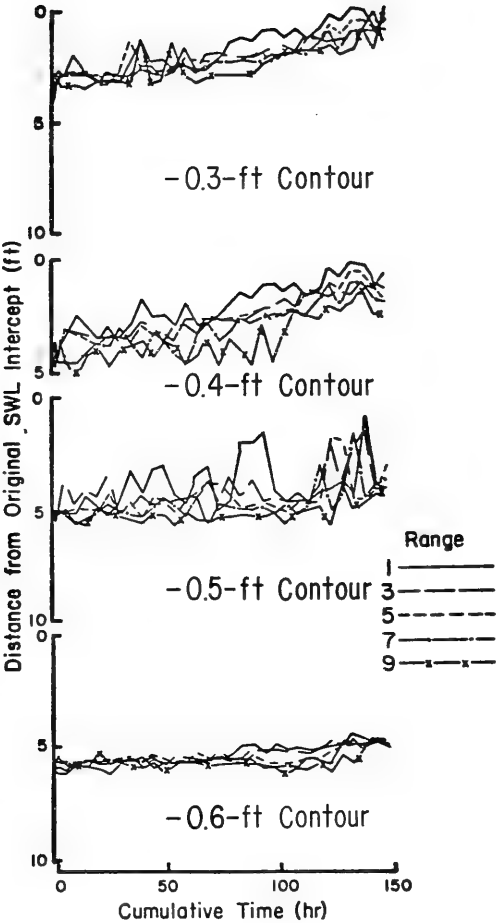


Figure 47. Lateral variations in the movements of inshore zone contours in experiment 72B-10 (L/W = 1.86). Compare with Figure 41.

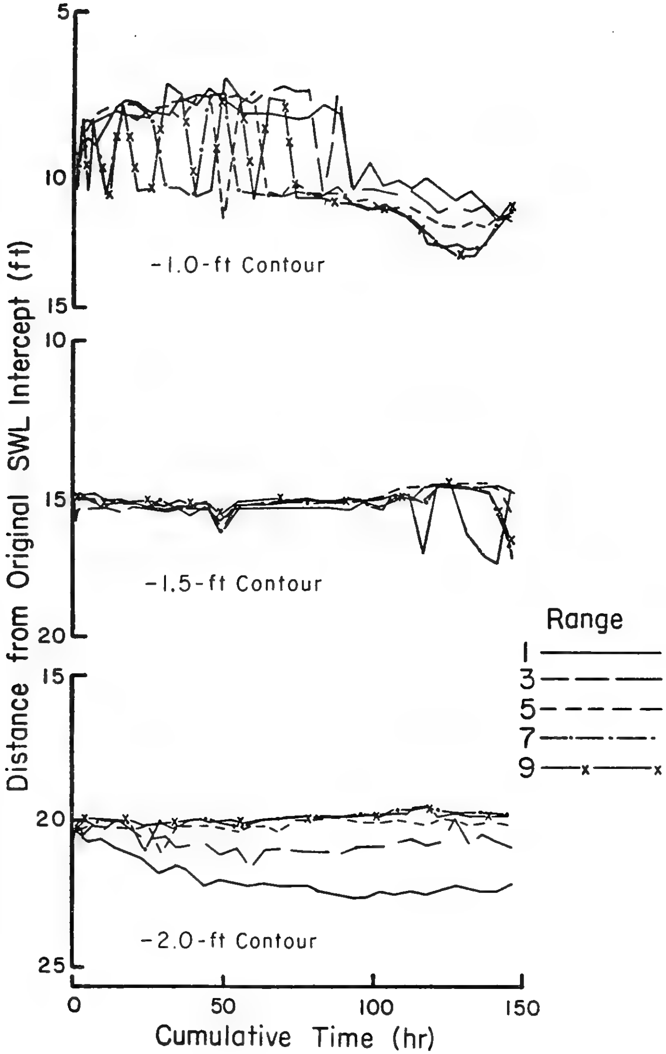


Figure 48. Lateral variations in the movements of offshore zone contours in experiment 72B-10 (L/W = 1.86). Compare with Figure 38.

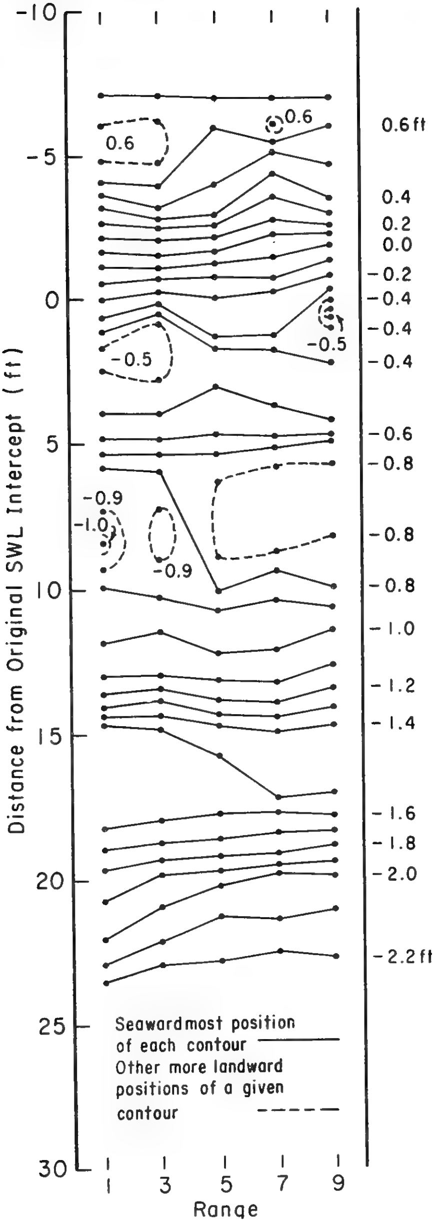


Figure 49. Profile shape at end (150 hours) of experiment 72B-10 (L/W = 1.86). Compare with Figure 42.

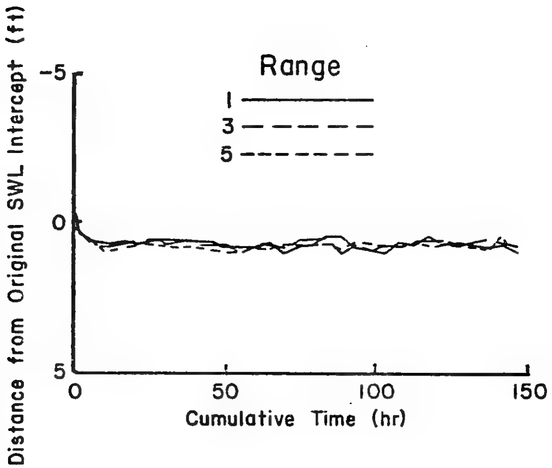


Figure 50. Shoreline movement in experiment 72B-06 (L/W = 3.10). Compare with Figure 43.

In the inshore, little significant lateral variation occurred at elevations -0.4, -0.5, and -0.6 foot; only a random variation in the times at which the longshore bar crest reached elevation -0.3 foot (Fig. 51).

Large lateral variations occurred in position of particular contours in the offshore (Fig. 52), indicating that the crest elevation of the seaward bar reached -2.0 feet at different times, but the variations had no pattern.

At the end of the experiment the only significant lateral variation was the slope of the foreshore (Fig. 53).

d. 3.75-Second Wave.

(1) L/W = 3.14 (Experiment 72A-10). Experiment 72A-10 had a longer wavelength in a wider tank than experiment 72B-06 discussed above, with the result that the L/W ratio was nearly the same (3.14 versus 3.10). As expected, this experiment also had little significant lateral variation.

The foreshore slope was steeper along the middle ranges (3, 5, and 7), varying from 0.14 to 0.36 with an average of 0.20, and flatter along the outside ranges (1 and 9), varying from 0.12 to 0.30 with an average of 0.18. The shoreline position varied laterally during the first 25 hours as it prograded first along the outside ranges (Fig. 54). Between 30 and 50 hours the shoreline position also varied laterally. At other times the shoreline position was quite uniform.

The only lateral variations in the offshore zone were differences in the bar-crest elevation along the different ranges (Fig. 55), but this was a fairly minor variation in elevation.

A contour map of the profile at the end of the experiment in Figure 56 shows how little the lateral variations were.

(2) L/W = 5.23 (Experiment 72A-06). In experiment 72A-06, with the highest L/W value, the lateral variations in profile shape were quite large, contrary to what was expected.

In the foreshore, a strong counterclockwise circulation caused the foreshore slope to be steeper (0.20) along range 5 and flatter (0.12) along range 1, but only at 115 hours was there a large (1.3 feet) lateral difference in shoreline position (Fig. 57).

In the inner offshore zone, a clockwise circulation developed between the antinodes in the foreshore and near station 18 during the first 70 hours, and then began disintegrating. The wavelength in this area was approximately 24 feet (7.3 meters), or four times the tank width, which suggests that the circulation was the result of some resonance unique to a laboratory wave tank. This is apparently another special tank width

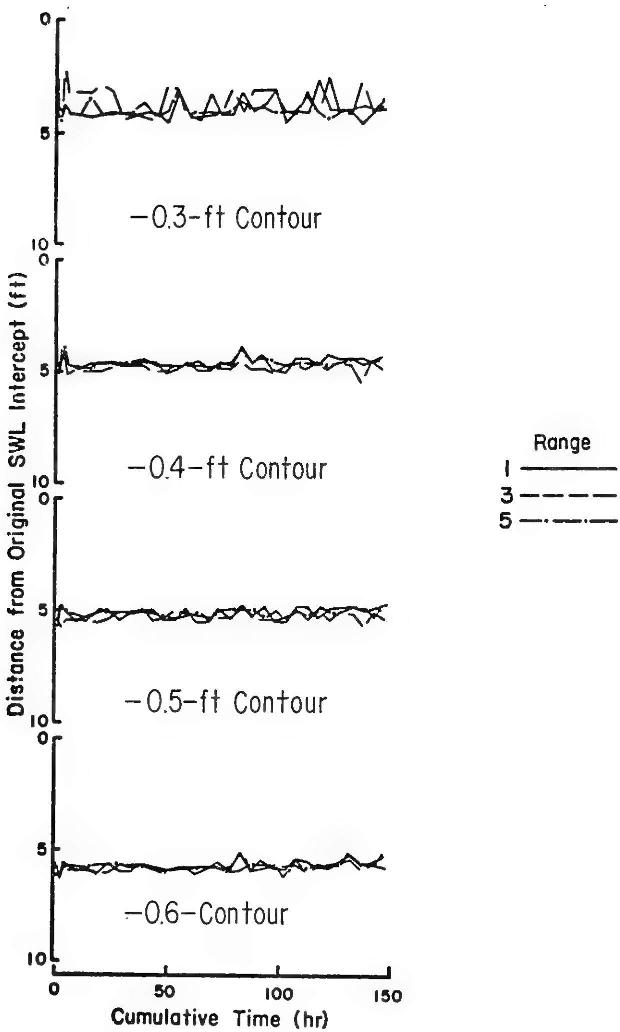


Figure 51. Comparison of the movements of inshore zone contours in experiment 72B-06 (L/W = 3.10). Compare with Figure 44.

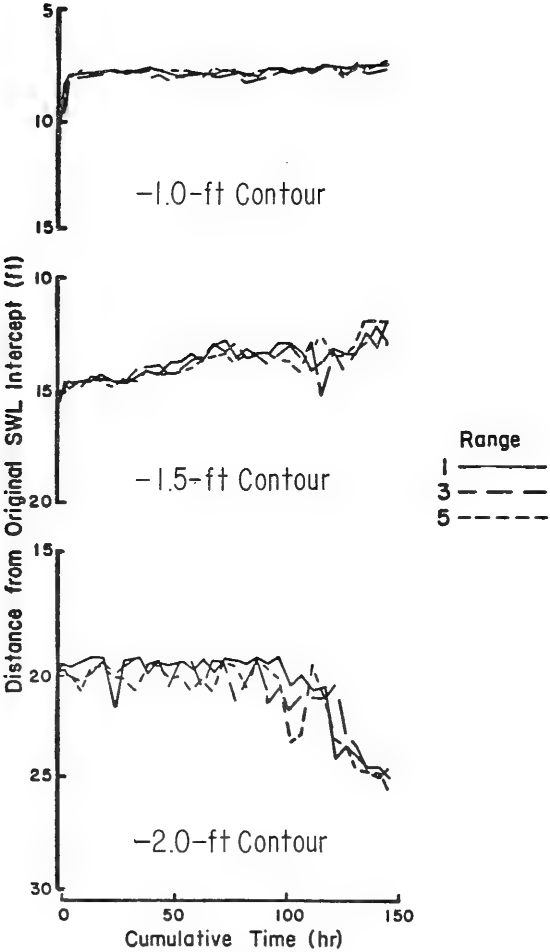


Figure 52. Comparison of the movements of offshore zone contours in experiment 72B-06 (L/W = 3.10). Compare with Figure 48.

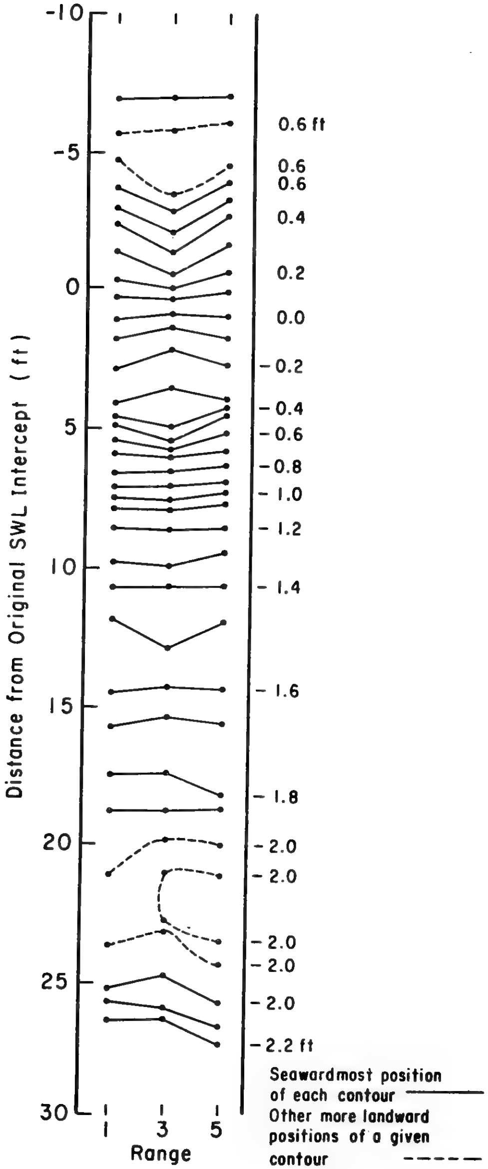


Figure 53. Profile shape at end (150 hours) of experiment 72B-06 (L/W = 3.10). Compare with Figure 45.

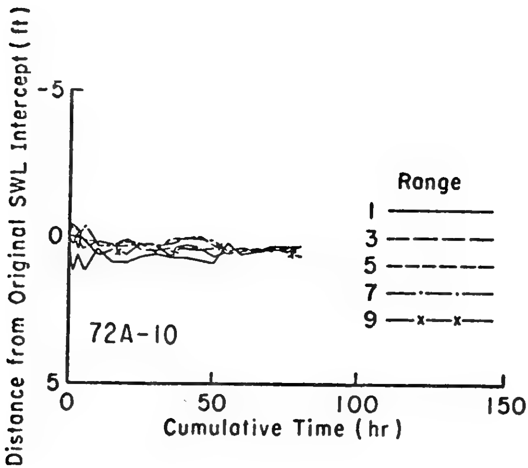


Figure 54. Shoreline movement in experiment 72A-10 (L/W = 3.14). Compare with Figure 50.

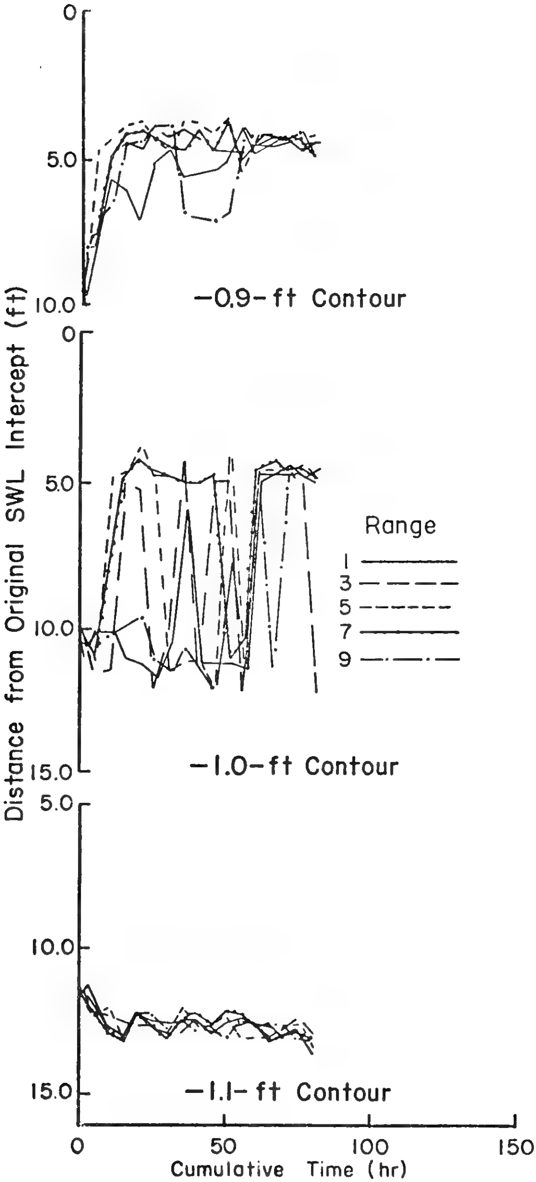


Figure 55. Comparison of the movements of offshore zone contours in experiment 72A-10 (L/W = 3.14). Compare with Figure 51.

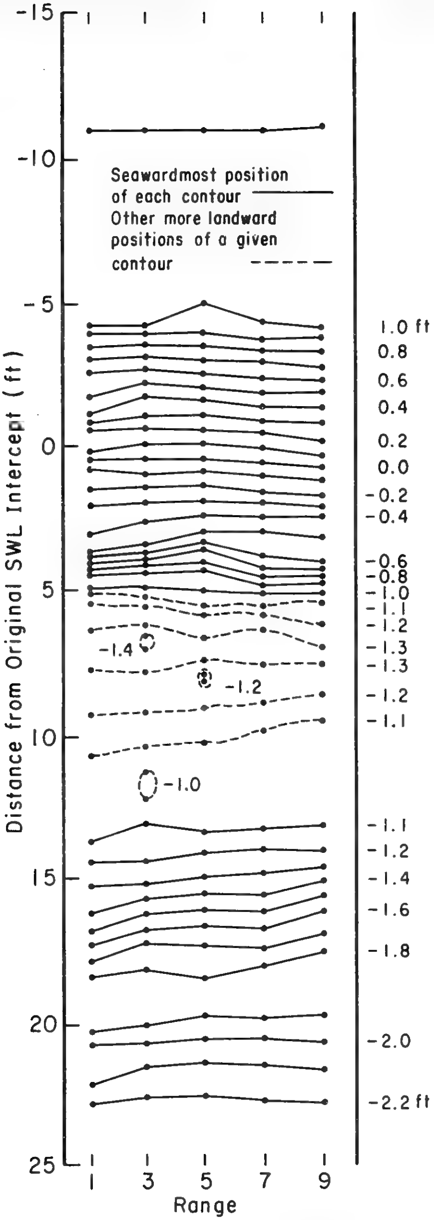


Figure 56. Profile shape at end (80 hours) of experiment 72A-10 (L/W = 3.14). Compare with Figure 51.

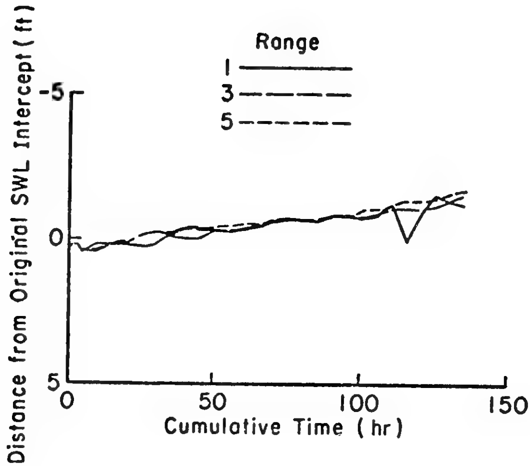


Figure 57. Shoreline movement in experiment 72A-06 (L/W = 5.23). Compare with Figure 54.

effect, since this effect was not seen for this wavelength in the wider tank. Lateral variations in the position of contours in the inner offshore are shown in Figure 58.

Lateral variations at the toe of the profile are shown in Figure 59, which compares the movement of selected contours, and in Figure 60, which is a contour map of the final profile.

4. Water Temperature Effects.

a. Processes. Since the 10 LEBS experiments were conducted in an outdoor basin, water temperature was an uncontrolled variable, varying from 4° to 31° Celsius, the dynamic viscosity varying from 3.30×10^{-5} to 1.64×10^{-5} pounds-second per square foot (1.61×10^{-5} to 0.80×10^{-5} grams-second per square centimeter) (Daily and Harleman, 1966). Viscosity is known to affect the fall velocity of sediment particles in settling tubes: as the viscosity of water increases, the fall velocity decreases (see Fig. 4-31 in U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). Since viscosity has been shown to have several effects on sediment transport in unidirectional flow (American Society of Civil Engineers, 1975), it is likely that water temperature and viscosity would affect sediment suspension and transport in oscillatory flow. For example, the erosion of beaches in the winter months may not be the result of increased wave steepness alone, but perhaps due to the decrease in water temperature as well.

A greater knowledge of temperature-viscosity effects on sediment transport in oscillatory flow is needed for at least three purposes: (a) to understand the effects of temperature on erosion and accretion in nature, (b) to understand the scale effects in the laboratory when relating laboratory results obtained with one temperature history to prototype localities with another temperature history, and (c) to understand the laboratory effects when attempting to compare results from a series of research experiments with one another when the water temperature was not controlled. The lack of knowledge on this last point has made it difficult to prove that the lack of profile equilibrium in several of these experiments was not due to a constantly decreasing water temperature.

The important effects of temperature-viscosity on sediment transport in unidirectional flow and the results on the effect of temperature-viscosity on shoreline recession and profile development in the LEBS experiments are discussed below.

b. Literature Review--Unidirectional Flow. Colby and Scott (1965) found three effects of water temperature on sediment discharge: (a) Viscosity changes cause changes in the thickness of the laminar sublayer which affect the relationship between mean velocity and effective bed shear. (b) The vertical distribution of suspended sediment depends on the ratio between the fall velocity of sediment particles in a turbulent sediment-water mixture and the effective turbulence of the flow for sus-

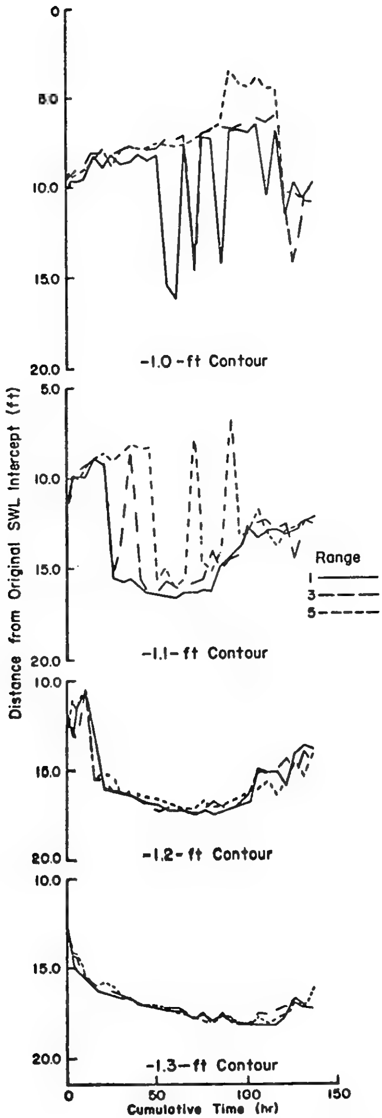


Figure 58. Comparison of the movements of upper offshore zone contours in experiment 72A-06 (L/W = 5.23). Compare with Figure 55.

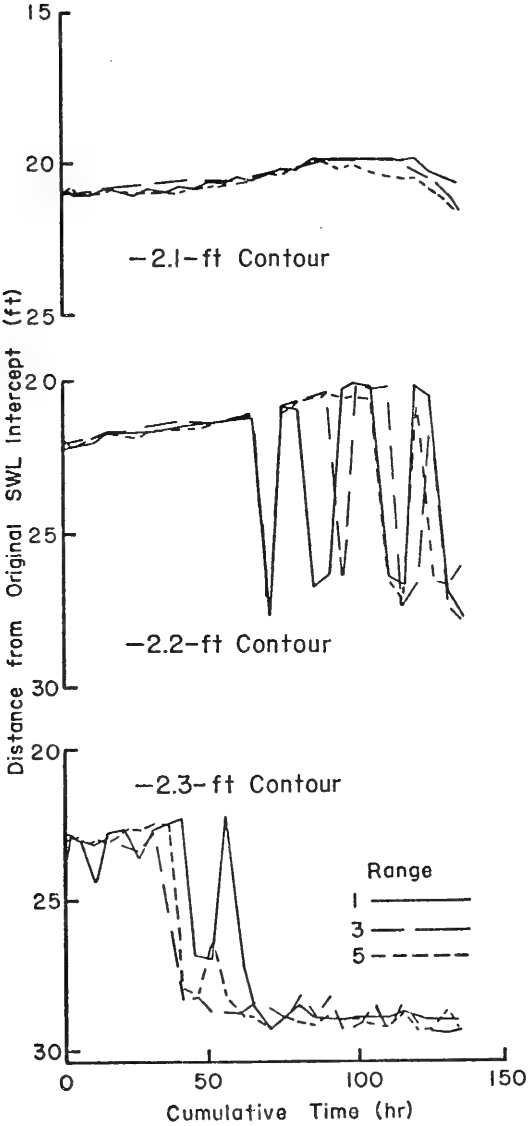


Figure 59. Comparison of the movements of lower offshore zone contours in experiment 72A-06 (L/W = 5.23). Compare with Figure 52.

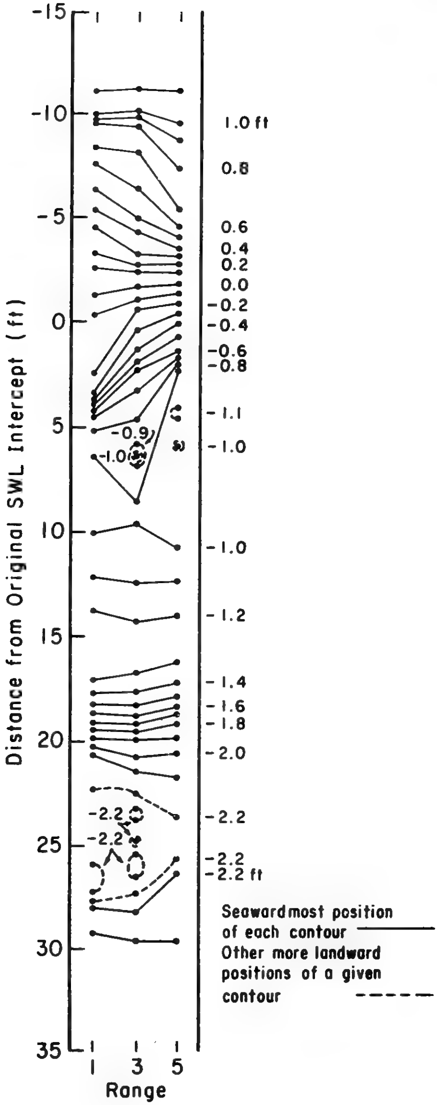


Figure 60. Profile shape at end (135 hours) of experiment 72A-06 (L/W = 5.23). Compare with Figure 56.

pending sediment. The effective turbulence of the flow is evidently not affected by viscosity changes, but the fall velocity of sand in turbulent water (nearly the same as the fall velocity in still water) is directly related to viscosity. The temperature effect is greatest for particle sizes between 0.25 and 0.5 millimeter and next greatest for the 0.125- to 0.25-millimeter range, and the effect increased with increasing depth. (The sediment used in the LEBS experiments had a d_{50} of 0.22 to 0.23 millimeter.) (c) Changes in viscosity affected the fall velocity which changed the d_{50} of the bedload and thus the bed forms. (The size distribution of the SPTB sand was narrow, so this effect would be negligible.) Changes in bed form change the resistance to flow and thus the sediment discharge. Temperature effects in both directions were found; i.e., sediment discharge both increased and decreased with increasing temperature.

Taylor and Vanoni (1972a, 1972b) examined temperature effects in both low- and high-transport flows, and they also found temperature effects in both directions in each case.

For low-transport flow, Taylor and Vanoni found that the direction of the effect was related to position on the Shields curve (Fig. 2.45 in American Society of Civil Engineers, 1975; shear stress versus boundary Reynolds number) where the Shields curve slopes down, increasing temperature caused increasing sediment discharge; where the Shields curve slopes up, increasing temperature caused decreasing sediment discharge; and where the Shields curve is flat, increasing temperature caused no change in discharge.

For high-transport flows, they found that the effect was related to particle size: for the particles finer than 0.135 millimeter, suspended-sediment concentrations at all depths increased with increasing temperature; for particles coarser than 0.135 millimeter, the concentrations at all depths decreased with increasing temperature; but for particles with a d_{50} of 0.135 millimeter, concentrations at the higher elevations increased with increasing temperature and at the lower elevations decreased with increasing temperature.

c. <u>LEBS Results--Oscillatory Flow</u>. Those results for unidirectional flow point out the complexity of the temperature effect, so it is not unreasonable to expect a complex temperature-viscosity effect on sediment transport in oscillatory flow. These experiments were obviously not designed to study temperature effects since temperature was uncontrolled, but they do indicate the potential for temperature effects. Temperature changes are compared to the shoreline recession rate and volume erosion rate in the discussions that follow. Because the backshore slope was not flat the volume erosion and profile development rates were proportional to the square of the shoreline recession rate in these tests.

(1) <u>1.50-Second Wave</u>. In experiment 72C-10 (Fig. 61) the shoreline recession rate was decreasing, which means that the volume erosion rate was decreasing or near constant, while the temperature was gradually falling.

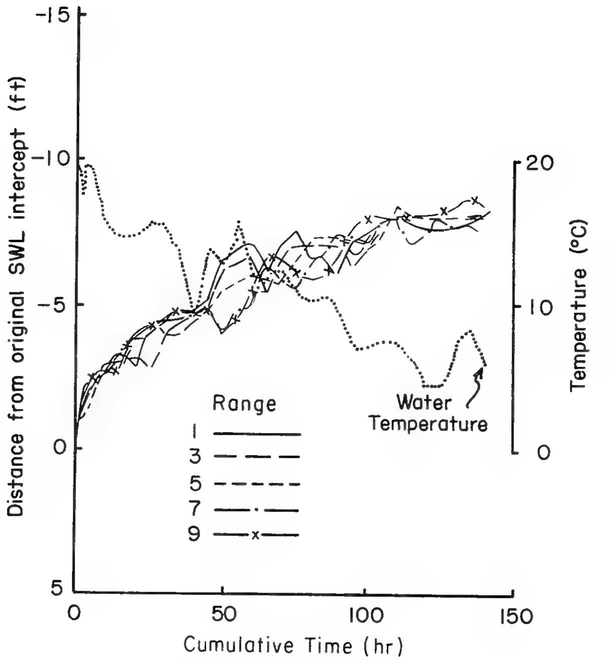


Figure 61. Comparison of daily mean water temperatures and shoreline positions in experiment 72C-10.

(2) 1.90-Second Wave. The most dramatic evidence for a temperature effect was in experiment 70X-06. At 22 hours the water temperature dropped from 28° to 18° Celsius and the shoreline recession rate increased from 0.06 to 0.14 foot per hour (Fig. 62,a). (After sand feeding was begun the experiments had little value to this analysis.) In experiment 70X-10 (Fig. 62,b) temperature data collection did not begin until 38 hours and the comparison of shoreline recession and temperature between 38 and 62 hours is not very conclusive. The temperature was fairly high (25° to 30° Celsius) and the shoreline recession rate was 0.08 foot per hour.

In experiments 71Y-06 and 71Y-10 (Fig. 63) the shoreline recession rates were high during the first few hours (0.113 foot per hour in experiment 71Y-06 and 0.133 foot per hour in experiment 71Y-10). However, the shoreline recession rate soon decreased to 0.025 foot per hour in experiment 71Y-06 and 0.016 foot per hour in experiment 71Y-10, although the temperature remained at a high value. The recession rate remained constant throughout the remainder of the experiments, even though the temperature dropped sharply several times, which tends to disprove the effect suggested by experiment 70X-06. However, the mutual agreement between experiments 70X-06 and 71Y-06 is important. Between 10 and 50 hours the recession rate was quite high in experiment 70X-06 while the temperature dropped and the recession rate was much lower in experiment 71Y-06 while the temperature remained high.

In experiment 72D-06 the shoreline retreated at a rate of 0.05 foot per hour, which means that the volume rate of erosion was continually increasing, while the temperature decreased from 20° to 6° Celsius (Fig. 64). The erosion of the trough in the inshore zone after the shoreline recession stopped occurred when the temperature was at its lowest values.

(3) 2.35-Second Wave. In experiment 72B-06 (Fig. 65,a) the shoreline was stable and the profile was at equilibrium, even though the temperature took two 8° drops. In experiment 72B-10 (Fig. 65,b) the shoreline retreated at a very slow rate, which varied between 0.004 and 0.018 foot (0.12 and 0.55 centimeter) per hour, while the temperature varied between 30° and 20° Celsius, with drops of 5° and 9°. Compared to the 1.90-second experiments (Figs. 62, 63, and 64), the temperature remained fairly high and the recession rate was small.

(4) 3.75-Second Wave. In experiment 72A-06 (Fig. 66,a) the shoreline recession rate was constant, meaning that the volume erosion rate was increasing, while the water temperature increased. In experiment 72A-10 (Fig. 66,b) the shoreline was stable as the profile was at or near equilibrium and the temperature rose initially and then remained fairly constant.

(5) Discussion. Experiment 70X-06 supports the hypothesis that decreasing water temperature causes increasing erosion. Although the shoreline recession rate did not respond to sharp drops in temperature in experiments 71Y-06, 71Y-10, 72D-06, 72B-06, and 72B-10, the comparison of those experiments with 70X-06 supports the general hypothesis that the

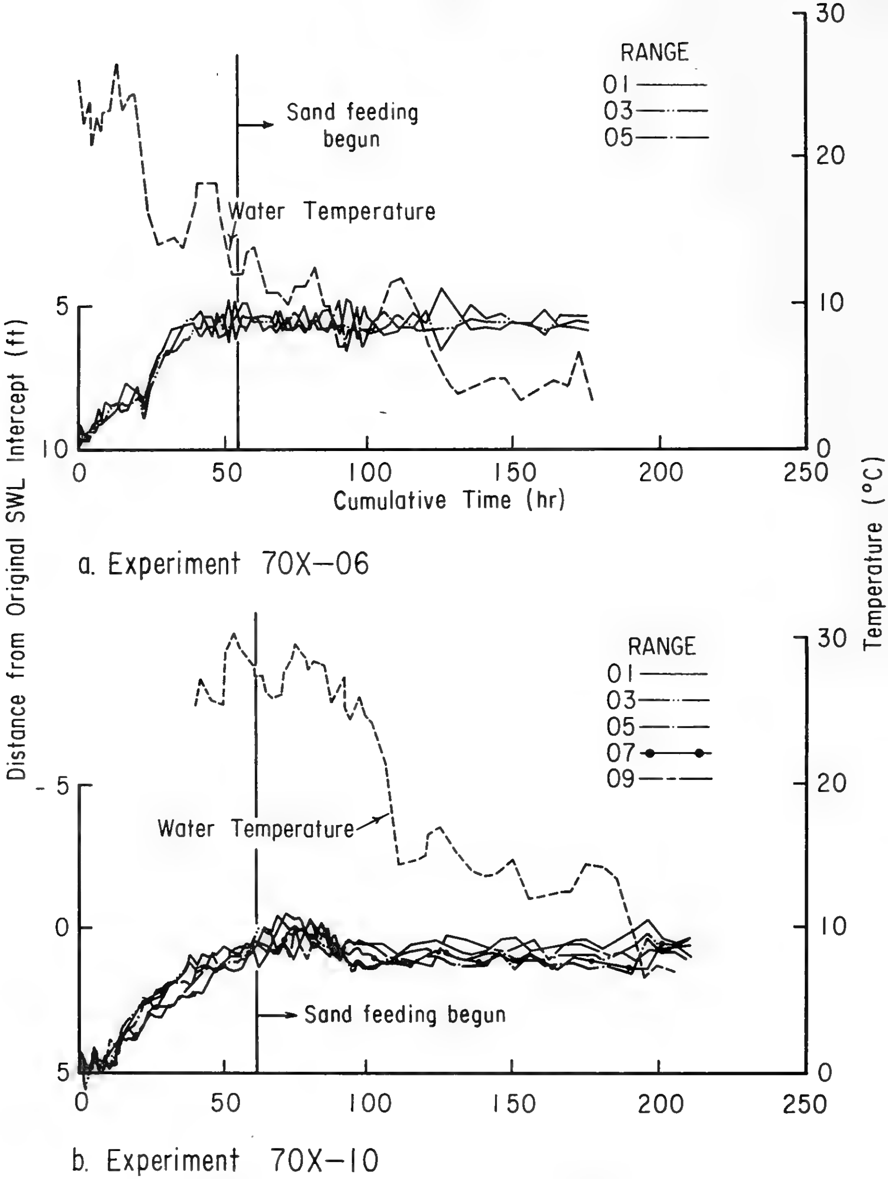


Figure 62. Comparison of daily mean water temperatures and shoreline positions in experiments 70X-06 and 70X-10.

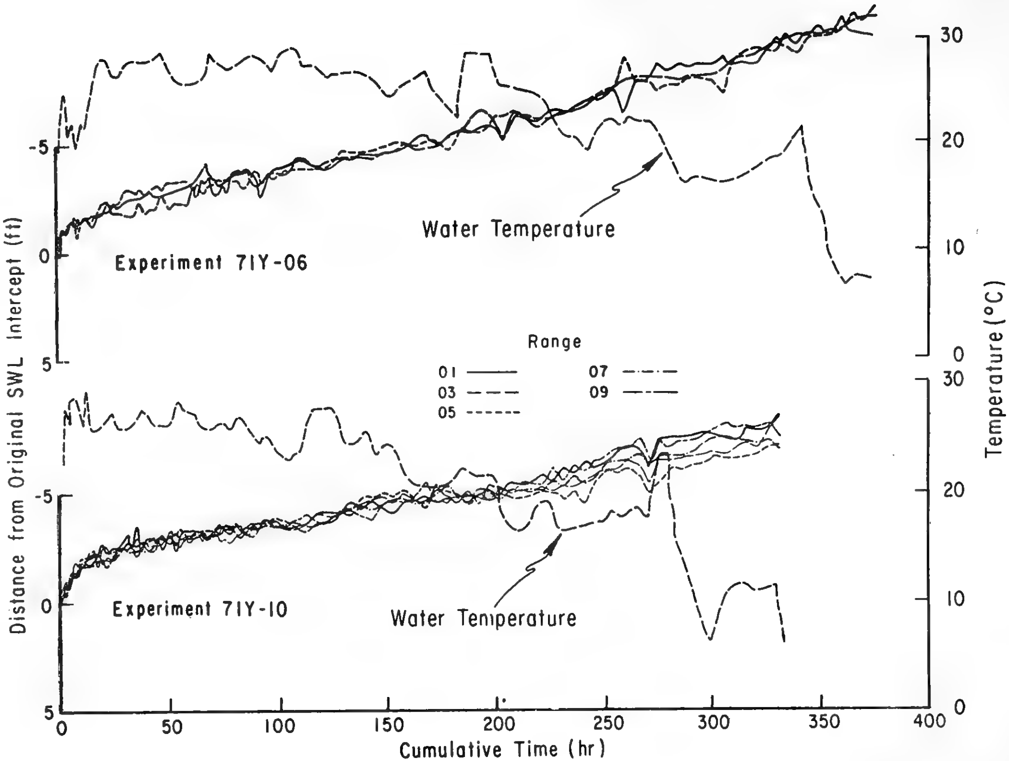


Figure 63. Comparison of daily mean water temperatures and shoreline positions in experiments 71Y-06 and 71Y-10.

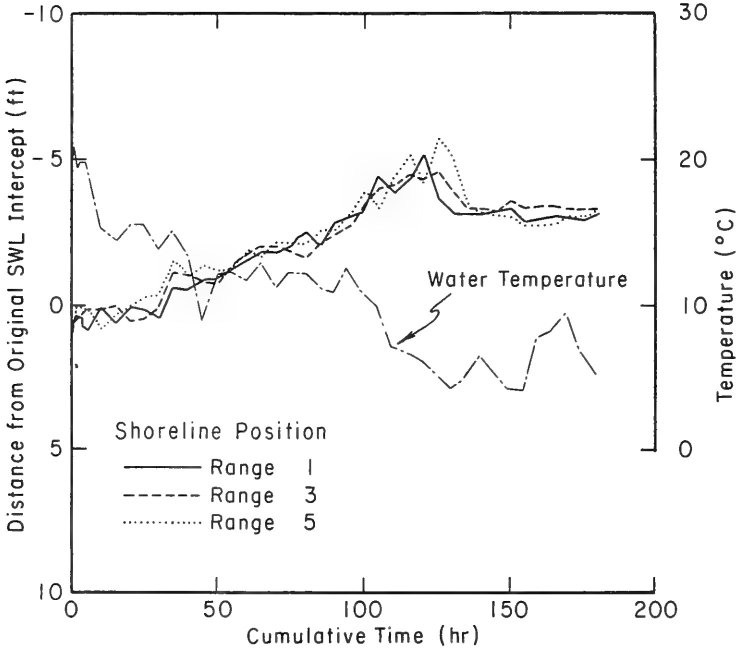
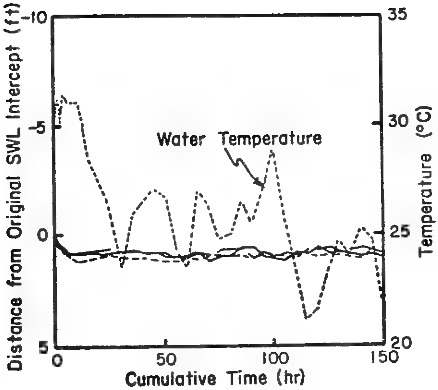
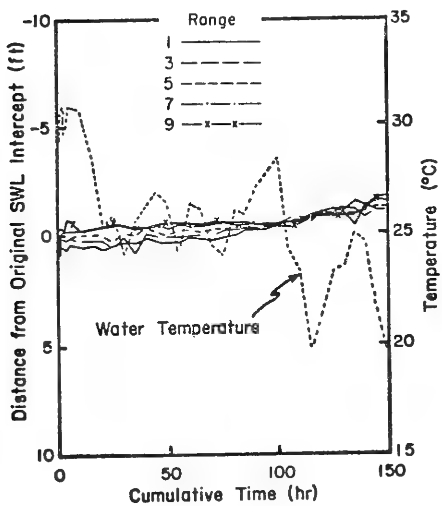


Figure 64. Comparison of daily mean water temperatures and shoreline positions in experiment 72D-06.



a. Experiment 72B-06



b. Experiment 72B-10

Figure 65. Comparison of daily mean water temperatures and shoreline positions in experiments 72B-06 and 72B-10.

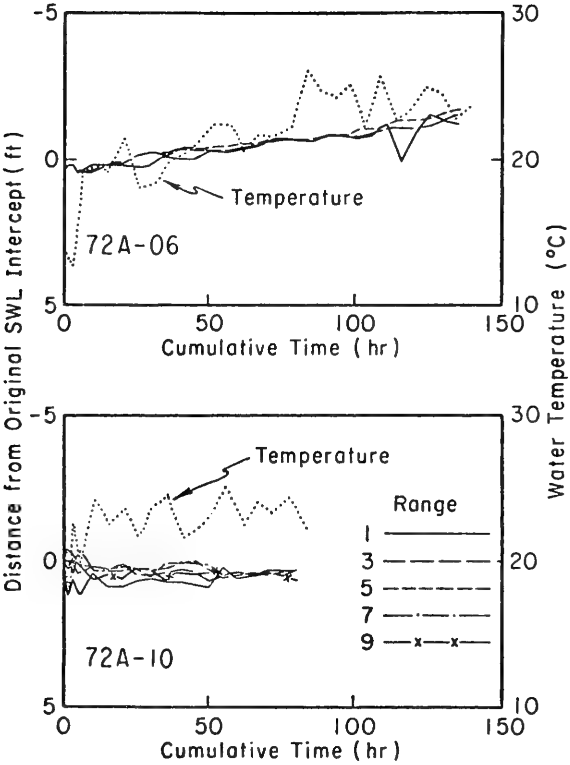


Figure 66. Comparison of daily mean water temperatures and shoreline positions in experiments 72A-06 and 72A-10.

higher the temperature the lower the recession rate. Too little useful data are available in experiment 70X-10 to be of any value to the comparison.

Experiment 72A-06 supports the opposite hypothesis that an increasing water temperature causes an increasing erosion. Experiment 72C-10 supports this hypothesis or perhaps tends to disprove the other hypothesis in that a decreasing water temperature coincided with a decreasing erosion rate.

Experiment 72A-10 supports either hypothesis since the temperature and the shoreline were both stable.

5. Other Laboratory Effects.

The known causes of laboratory effects are summarized in Table 14, classified by physical constraint and by phenomena or parameter affected. The effects of re-reflection, wavelength-to-tank width ratio, transverse waves, and circulation between antinodes were discussed earlier in this section. Secondary waves were observed on the wave records and their effect in a few of the experiments was discussed. Hulsbergen (1974) provides a detailed description of the effects of secondary waves on profile shape. Water temperature was measured and some of the possible effects of changing viscosity were measured, but the results are inconclusive. Cross waves were observed for a short period of time but their effect could not be measured.

Four other phenomena can cause laboratory effects, depending on the physical constraints of the individual experiment or facility designs.

When conducting experiments in a wave basin with training walls and with the waves approaching the shoreline obliquely, the waves reflected from the profile can re-reflect from the down-drift sidewall, then from the generator, from the up-drift sidewall, and then reattack the profile from an entirely different angle. In similar experiments without training walls, re-reflection problems are minimal but diffraction effects and basin resonance become significant sources of variations. Fairchild (1970b) discussed these three interrelated phenomena and their effects.

Another effect is the difference between a profile shaped by monochromatic waves and a profile shaped by irregular waves. Watts (1954) and Watts and Dearduff (1954) examined the effect of varying wave period and water level. The effect of periodic waves could be examined by repeating these experiments with a set of irregular waves having the same energy density.

V. CONCLUSIONS

1. Wave Height Variability.

(a) Variation in reflection from the profile was found to be the major source of wave height variability in 10 movable-bed experiments. The varying phase difference between the wave re-reflected from the

Table 14. Known laboratory effects.

Physical constraint	Phenomenon or parameter affected
1. Tank length a. Distance to initial SWL intercept b. Initial profile slope	1. Secondary waves from generator motion[1] 2. Re-reflection from wave generator[2]
2. Tank width	3. Wavelength-to-tank width ratio[2] 4. Transverse waves[2] 5. Cross waves[3] 6. Circulation between antinodes of standing wave[2]
3. Water temperature	7. Viscosity[1]
4. Wave basin (waves approaching obliquely with training walls)	8. Sidewall re-reflection
5. Wave basin (waves approaching obliquely without training walls)	9. Diffraction 10. Basin resonance
6. Periodic wave	11. Simulation of real waves

[1]Phenomenon observed and effects measured to a limited extent in LEBS study.

[2]Phenomenon observed and effects measured.

[3]Phenomenon observed, but effects not measured.

generator and the generator motion caused a varying average incident wave height. Transverse, cross, and secondary waves also contributed to the spatial variability of the incident wave height.

(b) The reflection coefficient variation ranged from moderate to significant in the movable-bed tanks, ranging from 0.02 to 0.12 in experiment 72C-10 and from 0.04 to 0.27 in experiment 72D-06. In the fixed-bed tanks, which is an indication of the measurement accuracy in the movable-bed tanks, K_R ranged from 0.01 to 0.02 in experiment 72C-10 and from 0.02 to 0.09 in experiment 72B-10.

(c) Waves are reflected by the runup on the foreshore, a plunging-type breaker, and any segment of the submerged profile where the depth change is significant. Variations in the steepness and top elevation of any submerged slope can cause significant variations in K_R. The distance between two reflecting zones can affect the phase difference between waves reflected from the two zones and thus affect the K_R measurement seaward of the profile. The important source of K_R variability in any one experiment did not appear to be a function of the wave period. The steepness of the submerged slope was an important source of variability in all experiments except 72A-10, and the increasing foreshore berm elevation was the primary source of variability in only experiment 72A-10. Variations in the elevations of the top of the submerged slope caused significant K_R variability in experiments 71Y-06, 72D-06, and 72A-06. The increasing distance between the foreshore and submerged slopes caused some K_R variability in all experiments with the 1.90-second wave and was the primary source in experiment 72C-10 with the 1.50-second wave. As the shelf length varied in each experiment, the K_R varied correspondingly.

(d) The average K_R from profiles which developed from an initial 0.10 slope increased with increasing wavelength (or wave period).

(e) The average K_R of the 1.90-second wave increased, rather than decreased, as the initial profile steepness decreased.

(f) Reflection coefficient variation was less than 0.05 during the last 25 hours of the three experiments which appeared to be at or very near equilibrium, but this does not conclusively prove that K_R variability is eliminated on an equilibrium profile.

(g) In all experiments except 72C-10 the K_R tended to increase during the experiment indicating that the profile adjustment tended toward reflecting, rather than absorbing, energy.

(h) Incident wave height, H_I, measurements in the fixed-bed tanks were indicative of the measurement errors in the movable-bed tank. H_I range in the fixed-bed tanks was as little as 0.03 foot in five experiments, and as much as 0.07 foot in experiment 72A-06.

(i) The effect of varying re-reflection on the incident wave height in each experiment was calculated by subtracting the range of heights in the fixed-bed tanks from the range of heights in the movable-bed tanks. In the 6-foot tank, this effect ranged from 0.01 foot in experiment 72B-06 to 0.03 foot in the other four experiments. In the 10-foot tank, this effect ranged from 0 in experiment 72B-10 to 0.08 foot in experiment 72A-10. This implies that the wider tank may amplify this re-reflection effect.

(j) The importance of phase difference between the reflected wave and the generator motion to the incident wave height variability is seen best by comparing experiments 72B-06 and 72B-10. The average K_R in experiment 72B-06 was 0.08 and in experiment 72B-10 was 0.17, which means that the reflected wave height was greater in the 10-foot tank. However, the average incident wave height was 0.38 foot in 72B-06 and only 0.31 foot in experiment 72B-10. Since the difference in reflected wave height would not have caused that difference, only the phase-difference effect resulting from the difference in initial test length can account for the difference.

2. Profile Equilibrium.

(a) In two experiments with all parameters the same except the initial slope (0.05 and 0.10), the final profiles had quite different slopes, although neither reached equilibrium. This further verifies the conclusion of Collins and Chesnutt (1975, 1976) that the initial profile influences the final stable profile shape.

(b) In two pairs of experiments with the same wave condition but different tank width and initial test length, one experiment in each pair reached equilibrium; the other experiment in each pair developed a different shape which continued to adjust. Laboratory effects are the apparent causes for the differences.

(c) Profile equilibrium is not easily attained. Two of four summer profiles and the one winter profile reached equilibrium, but none of the five profiles in the transition category ($0.020 < H_o/L_o < 0.025$) reached equilibrium, indicating that profiles for waves in the transition region are more unstable.

3. Laboratory Effects.

(a) The initial profile slope affects the profile development at least partially as a result of differences in the phase of secondary waves at the toe of the profile.

(b) The initial distance from the generator to the shoreline is an important experimental parameter. Differences in this distance affect the phase difference between the reflected wave and the generator motion and thus affect the incident wave height. The effect of varying incident wave height on profile shape is opposite to intuition; in experiments with the same wave condition and different initial distance to the shoreline developed, the higher erosion rate was associated with the lower average H_I. Differences in this distance also affect the phase of secondary waves at the toe of the profile. The effect of secondary waves was shown by differences in the shape of the offshore zone in two pairs of experiments.

(c) Three special and one general tank width effects were observed. Strong circulation currents developed over the profile between antinodes of the standing wave for a wavelength four times the tank width, which affected the profile development and reflectivity. Cross waves occurred over a short segment of the profile for a brief time in one experiment, but the effect was not measured. Transverse waves generated by the gap at the end of the generator blade caused significant lateral variations in one experiment, but were not observed in the experiment with the same wave period but different tank width and initial test length and without a gap. In general, as the wavelength-to-tank width ratio increased from 1, the amount of lateral variation in profile development decreased.

(d) Two different effects of water temperature variation were observed. Six experiments support, to varying extents, the hypothesis that the higher the water temperature, the lower the recession rate. Two experiments support the opposite effect, that the higher the water temperature, the higher the recession rate. Another experiment supports either hypothesis.

VI. RECOMMENDATIONS FOR CONDUCTING MOVABLE-BED COASTAL EXPERIMENTS

1. Modeling Criterion.

Equilibrium profiles are not often found in the prototype, and thus they may not be necessary to replicate. Also, equilibrium profiles are difficult to attain in the laboratory and may not be repeatable when they are reached. Therefore, it is recommended that some other criteria be selected as the prototype condition for replication in the laboratory, such as constant rate of shoreline recession or volume erosion.

2. Tank Setup and Test Conditions.

(a) The initial distance from the generator to the shoreline must be held constant when attempting to perform repeatable profile experiments.

(b) The initial slope can affect the profile development and should be held constant to assure test repeatability.

(c) To eliminate lateral variations in profile shape due to too short a crest length, wavelengths greater than three times the tank width should be chosen. However, two-dimensional tests may distort a three-dimensional problem to an unknown extent.

(d) The water temperature should be kept within a 5° Celsius range to assure test repeatability.

(e) Cross waves in the constant-depth section and transverse waves can be avoided by careful selection of wave period and water depth for each tank width (Barnard and Pritchard, 1972; Madsen, 1974).

(f) Secondary waves in the constant depth section can be eliminated by programing the generator motion with elliptic functions or by the use of sills placed at the proper location along the tank for each wave period (Hulsbergen, 1974).

(g) Variability in profile reflectivity, generation of secondary waves over a shelf, and generation of cross waves over profile segments are phenomena which cannot be avoided or eliminated, but the experimenters should be aware of the potential of these phenomena to affect profile development.

(h) As a minimum the experimental conditions discussed in this series of reports should be documented in each movable-bed coastal engineering experiment and model study.

3. Future Investigation.

(a) The hypotheses on sources of profile reflectivity variability should be examined one-by-one in fixed-bed experiments.

(b) More research is needed to quantify the effect of the initial profile slope on the final profile shape.

(c) More research is needed on how wide a tank must be to assure that the tank walls do not affect a significant part of the profile.

(d) More basic research is needed on the effect of water temperature on sediment transport in oscillatory flow.

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