1969

Major Environmental Variables Affecting Grain Size Distribution in the Shoaling-Wave Zone Under Storm Conditions at Virginia Beach, Virginia

Dunnie Richard Tuck
College of William and Mary - Virginia Institute of Marine Science

Recommended Citation

Tuck, Dunnie Richard, "Major Environmental Variables Affecting Grain Size Distribution in the Shoaling-Wave Zone Under Storm Conditions at Virginia Beach, Virginia" (1969). *Dissertations, Theses, and Masters Projects.* Paper 1539617414.
https://dx.doi.org/doi:10.25773/v5-j7vx-6144

PUEBLO OCEANOGRAPHER—Dunnie Richard Tuck, one of two oceanographers aboard the U.S. Navy intelligence ship Pueblo captured last week by North Korea, is shown during 1965 when he was a graduate student at Virginia Institute of Marine Science. His research included work on erosion problems at Virginia Beach. Tuck, 30, is a native of South Boston. His parents, Mr. and Mrs. D. R. Tuck Sr., live in Richmond.

Civilian No Spy, Mother Declares

Washington Post 1/28/68

RICHMOND, Va., Jan. 27 (AP)—The mother of Dunnie Richard Tuck, one of two civilians aboard the captured Navy intelligence ship Pueblo, said today he is not a spy, as claimed by the North Koreans.

"I know he is not a spy. He's an oceanographer," said Mrs. Dunnie R. Tuck of Richmond.

The North Koreans earlier this week cited an alleged statement by the Pueblo's captain, Cmdr. Lloyd M. Bucher, as identifying Tuck and the other civilian aboard, Harry Iredale, as "espionage agents."

Mrs. Tuck said her son was employed two years by the Naval Oceanographic Laboratory in Washington before going to the Pueblo as a civilian oceanographer. He is a graduate of Virginia Military Institute and of the Virginia Institute of Marine Science.

MAJOR ENVIRONMENTAL VARIABLES AFFECTING GRAIN SIZE DISTRIBUTION IN THE SHOALING-WAVE ZONE UNDER STORM CONDITIONS AT VIRGINIA BEACH, VIRGINIA

A Thesis
Presented to
Virginia Institute of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Master of Arts in Marine Science

By
D. Richard Tuck, Jr.
1969

APPROVAL SHEET

This thesis is submitted in partial fulfillment of
the requirements for the degree of
Master of Arts in Marine Science

D. Richard Tuck, Jr.

D. Richard Tuck, Jr.

Approved, August 1969

Maynard M. Nichols

Maynard M. Nichols, Ph.D.

John J. Norcross

John J. Norcross, M.S.

E. P. Ruzecki

Evon P. Ruzecki, M.S.

ACKNOWLEDGMENTS

The author wishes to thank professors M. Nichols and W. Harrison for their assistance and guidance throughout the study. Grateful acknowledgments are extended to Dr. W. C. Krumbein, Northwestern University, for his suggestions in analyzing the data; and to Mrs. B. Benson who made the necessary modifications of the "whirlpool" program for data analysis on the IBM 7090 computer at Northwestern University. The author is grateful to the Physics Department at the College of William and Mary for making the IBM 1620 computer available for the initial phase of the data analysis. The study was financed by U.S. Army Corps of Engineers Contract No. DA-49-055-CIV-ENG-65-5.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

ABSTRACT

Temporal variations of ten major environmental variables occurring during a storm were studied in relation to mean grain size distribution in the shoaling-wave zone of an oceanic beach. A similar study had been conducted earlier on the same beach by Harrison and Krumbein (1964) during relatively calm to moderate weather conditions. By augmenting their data with the "storm-condition" data and performing the same type of multiregression analysis, an evaluation could be made of the influence that storm conditions exerted upon the mean grain size distribution on this beach. Environmental variables studied included those related to beach geometry, local water properties, local wind conditions, tidal fluctuations and wave characteristics. The effect of these variables on the beach response was investigated by sequential linear multiregression analysis utilizing high speed computers.

The most influential sets of four-variable combinations, in a least squares sense, were found to suffice in "explaining" the observed variability in mean grain size distribution. Analysis of the effects of combined storm and non-storm values indicated that the "average" mean grain size (referring to the average of several sediment samples collected simultaneously in the study zone) was most dependent upon the variables manifested 4-8 hours prior to measurement of the beach response. The most influential four-variable combination consisted of: sigma-t, still-water depth, tidal-current speed and wind speed offshore. Sigma-t was found to be the most influential single variable when examined in four-variable combinations. The influence of mean bottom slope angle, which was the major influential variable during calm to moderate conditions (Harrison and Krumbein, 1964), became less prominent in the analysis of the combined non-storm and storm data. The recent study suggested that a reversal in the bottom-slope-grain size relationship occurred under the storm conditions. (Generally, mean bottom slope and average mean grain size are inversely related in the shoaling-wave zone.) With the decreased effect of bottom slope angle, wave-drift currents and tidal currents became more influential on average mean grain size distribution, according to the multiregression analysis.

MAJOR ENVIRONMENTAL VARIABLES AFFECTING GRAIN SIZE DISTRIBUTION IN THE SHOALING-WAVE ZONE UNDER STORM CONDITIONS AT VIRGINIA BEACH, VIRGINIA

INTRODUCTION

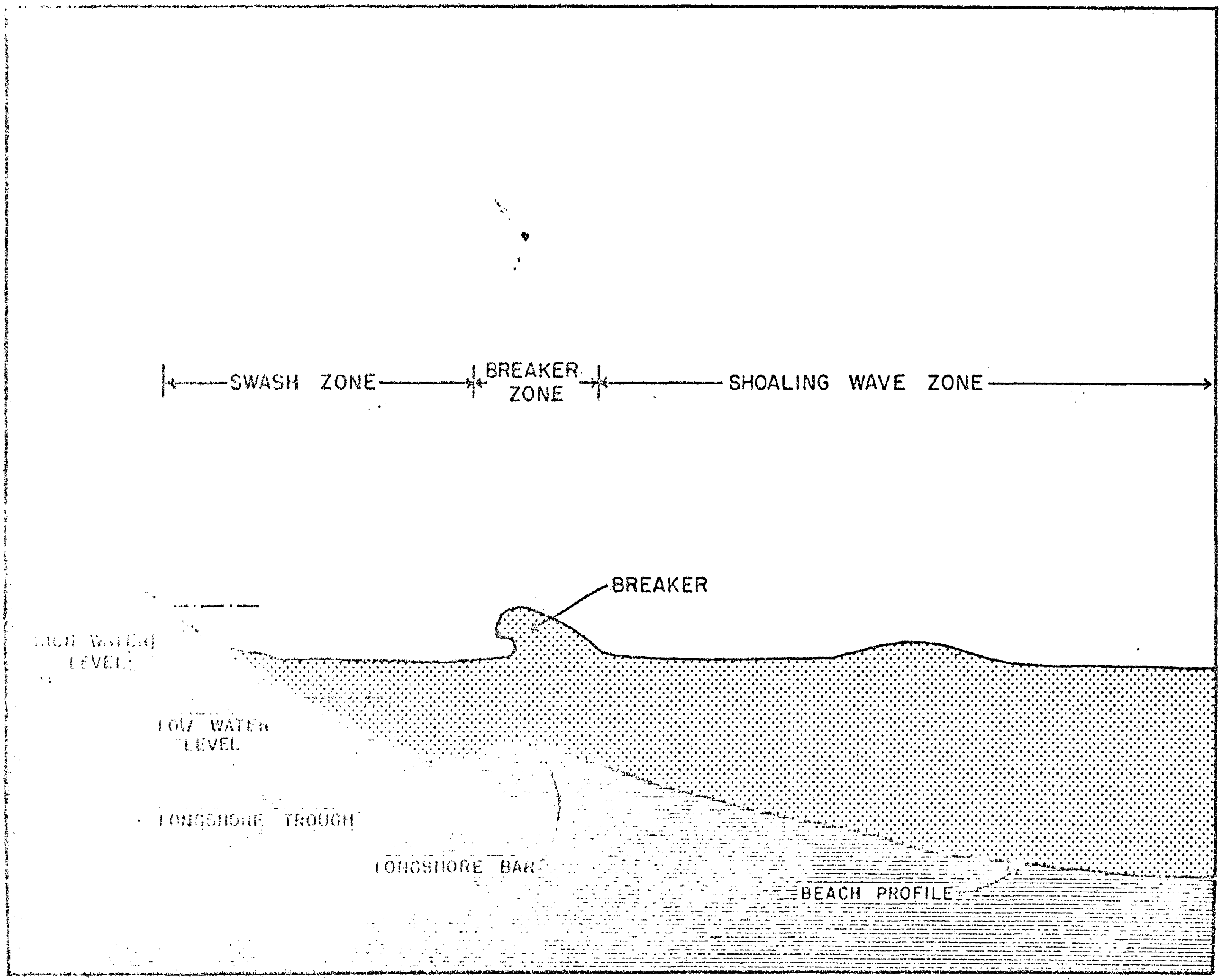
On a natural oceanic beach mean grain size varies significantly from one of the several beach zones to another (Fig. 1) and periodically within each of the given zones. This study was concerned with determining what environmental variables, acting during a storm period, are significant in affecting the distribution of average mean grain size (referring to the average of several sediment samples) with respect to time in the shoaling-wave zone of an oceanic beach.

Many variables of the beach-ocean-atmosphere system participate in affecting mean grain size. To elide unnecessary complications in the analysis, ten of the major environmental variables (Table 1) were selected for observation of their effects upon average mean grain size distribution.

An approach to the defined problem of average mean grain size distribution entailed three sequential phases. First, field measurements of selected "causal" elements in conjunction with measurements of the related "effect" element had to be obtained during storm conditions. Second, correlations between the environmental causal factors and distribution of average mean grain size were determined by sequential linear multiregression, a least squares search procedure, which will be discussed later. The final phase involved the evaluation of the correlations.

Harrison and Krumbein (1964) conducted a similar study on the

Figure 1.--Schematic diagram showing boundaries of the various beach zones.


SWASH ZONE
BREAKER ZONE
SHOALING WAVE ZONE
BREAKER
HIGH WATER LEVEL
LOW WATER LEVEL
LONGSHORE TROUGH
LONGSHORE BAR
BEACH PROFILE

same oceanic beach under calm to moderate weather conditions. Some comparisons between related results of the two projects have been included in this study.

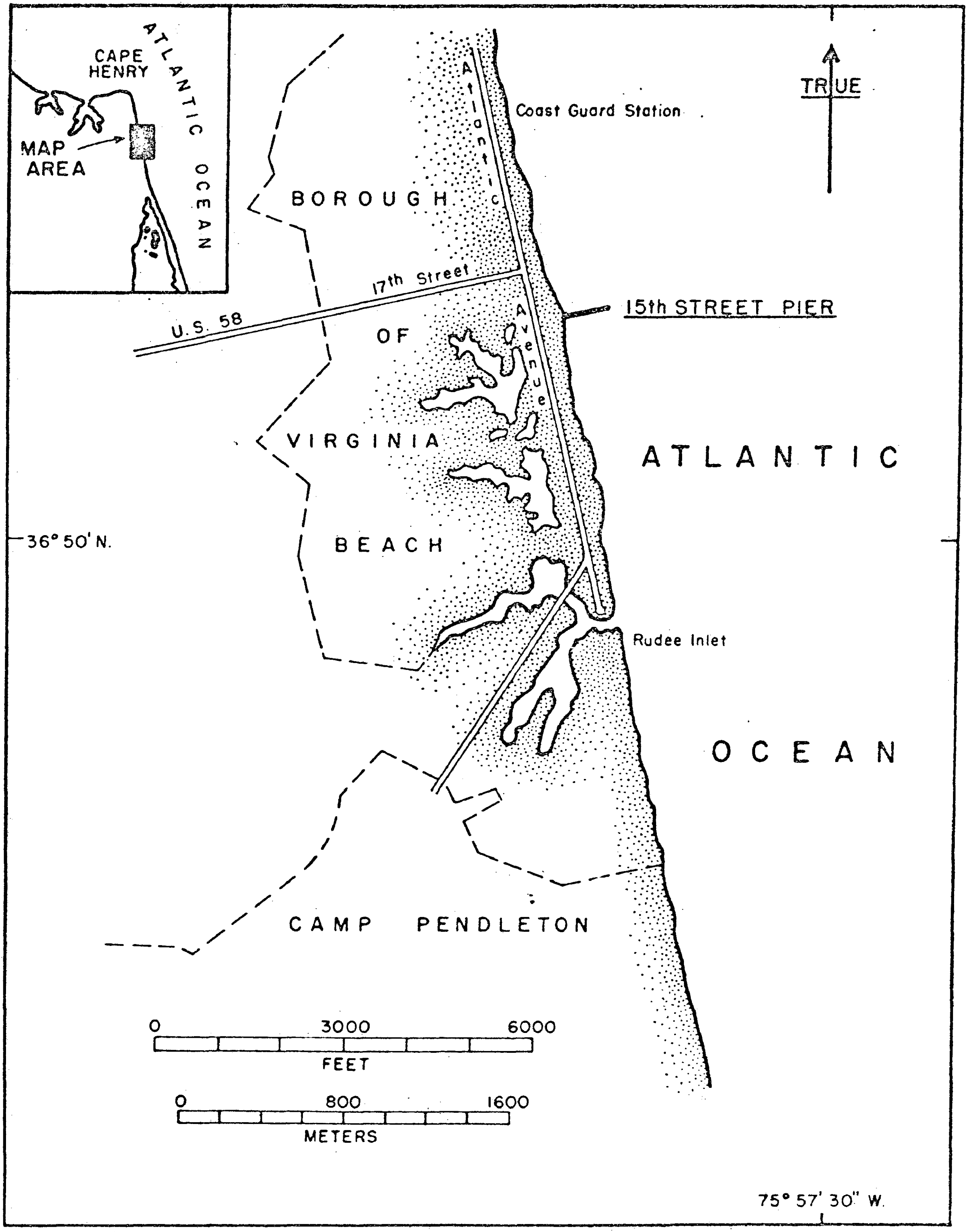
AREA OF INVESTIGATION

The beach selected for this study is located at Virginia Beach, Virginia, an oceanic beach situated immediately south of the entrance to Chesapeake Bay (Fig. 2). The area of the shoaling-wave zone examined was centered along the north side of the 15th Street pier (Fig. 3) which is about 10 km south of Cape Henry. The 15th Street pier, from which certain measurements were taken, extends seaward for a distance of 260 m from the shoreline and terminates at approximately the 6-m contour.

The site of investigation in the nearshore shoaling-wave zone was limited to a 30.5 x 4.6 m area roughly between 61.0 and 91.5 m seaward of the normal breaker zone under calm conditions. Generally, the area of investigation had an average water depth ranging between 3.3 and 4.3 m. In surveys conducted by the U. S. Army Corps of Engineers (U. S. Congress, 1953, p. 13), it was found that the beach slopes, beyond the breaker zone to the 6-m contour, ranged between 1:50 and 1:60. In the same survey studies, the Corps of Engineers found that the beach face was experiencing a long-term net erosion, while a slight accretion of beach material was occurring in the region seaward of the breaker zone and extending to the 6-m contour.

The beach material throughout the area is composed of quartz sand particles that exhibit an average Corey Shape Factor of 0.7 (Harrison and Morales-Alamo, 1964). The Corey Shape Factor for

Figure 2.--Maps showing general area of investigation.


CAPE HENRY
ATLANTIC OCEAN
MAP AREA
Coast Guard Station
TRUE
BOROUGH OF VIRGINIA BEACH
Atlantic Avenue
17th Street
U.S. 58
15th STREET PIER
ATLANTIC OCEAN
36° 50' N.
Rudee Inlet
CAMP PENDLETON
0
3000
6000
FEET
0
800
1600
METERS
75° 57' 30" W.

a sand particle is defined by:

$$S.\ F. = \frac{c}{\sqrt{a.b}}$$

where a, b, and c are the orthogonal long, intermediate, and short axes, respectively. Observations suggested that the average mean grain sizes in the study area generally range from 0.250 to 0.400 mm. In the shoaling-wave zone, there is a gradual decrease in mean grain size with increasing water depth.

A review of wind and swell records (U. S. Congress, 1953, plates 5 and 6) indicates that the higher wind velocities and total wind movements are greater from the northern quadrants and the dominant medium and high swells are from the northeastern quadrant. These high swells and wind velocities occur normally in the fall and winter and tend to erode the beach slightly, regardless of artificial nourishment. During the summer, the low swells approach from the southeast and the prevailing winds are from the southwest. These relatively milder conditions in the summer tend to nourish the beach naturally. More details of beach profile modifications in the area of investigation are presented by Harrison and Wagner (1964).

Surf conditions over a three-year period have been compiled by Helle (1958), as observed at the Virginia Beach Life Boat Station approximately 800 m north of the 15th Street pier. Results show that the surf is 1.2 m or higher 10% of the year, 0.9 m or higher 50% of the year, and 0.6 m or higher 95% of the year. The surf tends to be highest in the fall and early winter. The average period of the surf tends to be greatest in late spring and early summer (around 6.0 seconds).

Semi-diurnal tides occur at Virginia Beach which have a mean range of 0.9 m. The tidal currents are mainly of the reversing type and are generally parallel to shore. This reversing current is associated with the strong ebb and strong flood tidal currents exhibited at the entrance to Chesapeake Bay.

DATA COLLECTION AND COMPILATION

Field observations of the environmental variables occurring during the storm period were conducted between November 27, 1964 and December 5, 1964, inclusively. This period contained a 3-day storm with strong winds initially out of the northeast and eventually out of the northwest from November 29 to December 1. The methods of data collection performed during the storm period were similar to those used by Harrison and Krumbein (1964) during relatively calm conditions.

Bottom sediment samples were collected twice daily at 0600 and 1800 hours from November 28 through December 4. The causal variable measurements (the independent variables of Table 1) were either taken or determined from other data-collecting sources daily at 0200, 0600, 1000, 1400, 1800, and 2200 hours. Because a given beach element does not respond immediately to the operating forces of a given set of causal variables, it was necessary to investigate the time lag in the beach response adjustment. For this reason, measurement of causal variables began one day prior to initial sampling of the bottom sediment.

Four-hour lag periods, extending through the previous 20 hours, were arbitrarily established for the analysis in order to determine how readily the beach element responded to the environmental variables. For example, the beach response element observed at 0600 hours was assigned five lag periods terminating at 0200, 2200, 1800, 1400 and

Table 1.--The Ten Major Independent Variables Used in Determining Relative Influence on the Distribution of Average Mean Grain Size [$(\overline{M}_z)s$] in the Shoaling-Wave Zone at Virginia Beach.

Number	Symbol	Dimensions	Description
1.	$\overline{S}_s$	0	Mean angle of slope in shoaling-wave zone
2.	T	T	Wave period
3.	H	L	Wave height
4.	$\overline{U}_{on}$	LT^{-1}	Mean wind speed in an onshore direction
5.	$\overline{U}_{of}$	LT^{-1}	Mean wind speed in an offshore direction
6.	$\overline{U}_p$	LT^{-1}	Mean wind speed parallel to shore
7.	α	0	Angle of wave approach
8.	h	L	Still-water depth
9.	σ_t	0	Sigma-t
10.	C	LT^{-1}	Speed of tidal current

1000 hours respectively. Similarly, for the beach response element observed at 1800 hours, the five lag periods terminated at 1400, 1000, 0600, 0200 and 2200 hours respectively.

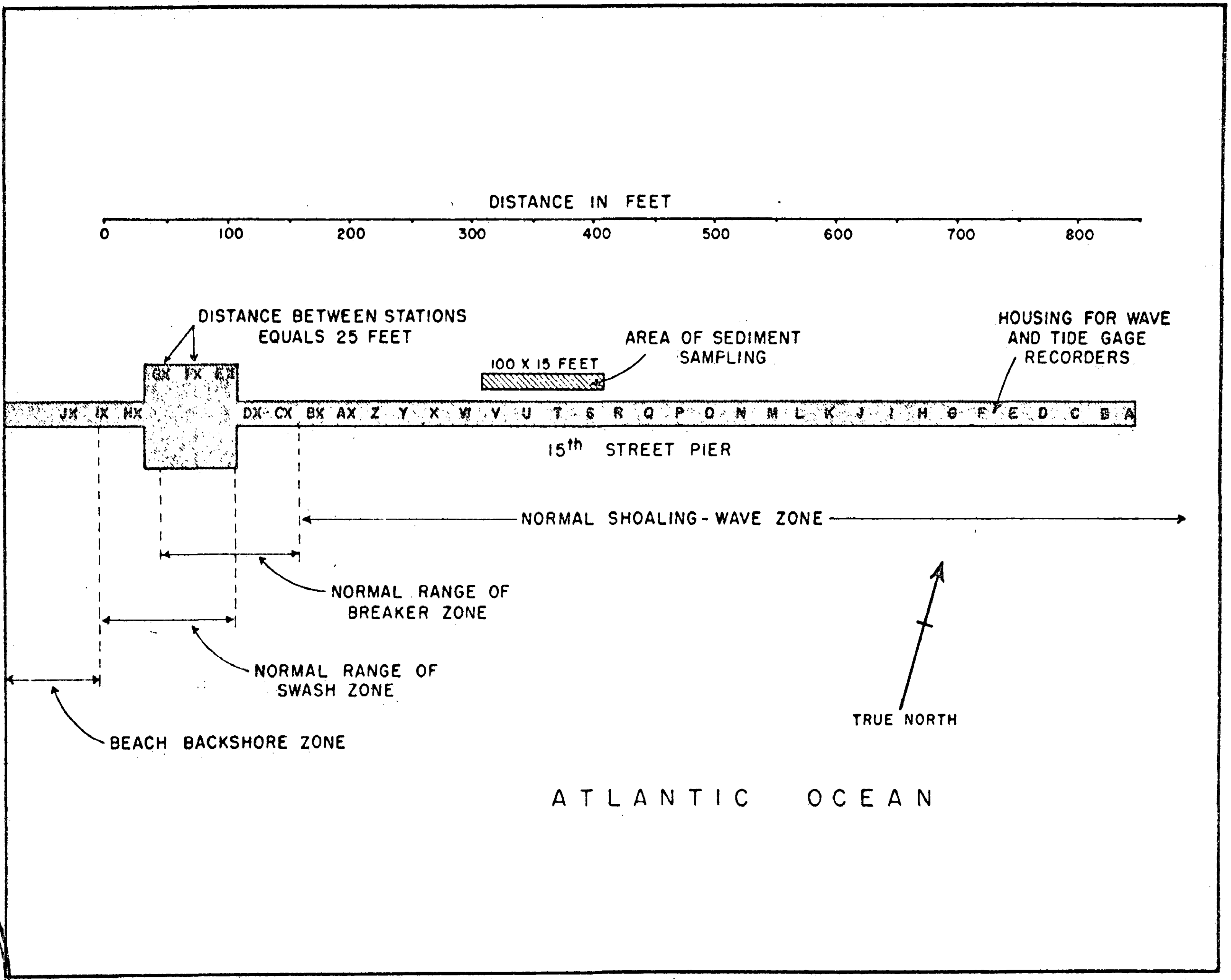
Sand samples were collected from the surface layer of the sediment bed with a pipe dredge, 4 cm in diameter. Sampling depths ranged from 0.5 to 2 cm below the sediment surface. The dredge was normally drawn along a transect approximately 4.6 m perpendicular to the pier. As mentioned earlier, the length of the study zone (Fig. 3) was 30.5 m, thus making the actual size of the zone 30.5 x 4.6 m. Samples were taken from four fixed stations (designated by S. T. U. and V., Fig. 3), and the average value of the analyzed mean grain sizes (which is termed "average mean grain size" in this study) of the four stations was employed in the multiregression analysis. Mean grain size of each sample was determined using a Woods Hole Rapid Sand Analyzer (Zeigler, Whitney, and Hayes, 1960), and the procedure outlined in Harrison and Morales-Alamo (1964). The statistic used to estimate the mean nominal diameter was

$$\overline{M}_z = \frac{P_{10} + P_{30} + P_{50} + P_{70} + P_{90}}{5}$$

where P are percentiles determined in the analysis.

The angle of bottom slope was determined from soundings off the pier at the same four fixed stations where the sand samples were taken and one additional station at each end of the study area (7.6 m between each station). These soundings along with tidal records were used in determining the still-water depth. The angle of wave approach was measured with a pelorus mounted at the end of the pier. Various littoral current speeds and

Figure 3.--Schematic diagram of the 15th Street pier and the general area of sediment sampling.


DISTANCE IN FEET
0
100
200
300
400
500
600
700
800
DISTANCE BETWEEN STATIONS
EQUALS 25 FEET
100 X 15 FEET
AREA OF SEDIMENT
SAMPLING
HOUSING FOR WAVE
AND TIDE GAGE
RECORDERS
GX FX EX
JX IX HX DX CX BX AX Z Y X W V U T S R Q P O N M L K J I H G F E D C B A
15th STREET PIER
NORMAL SHOALING-WAVE ZONE
NORMAL RANGE OF
BREAKER ZONE
NORMAL RANGE OF
SWASH ZONE
BEACH BACKSHORE ZONE
TRUE NORTH
ATLANTIC OCEAN

directions (designated as "tidal" currents) one meter above the bottom were measured with a Savonius rotor and vane installed on the pier immediately seaward of the study area. Sigma-t was determined from salinity-temperature observations. Surface water samples for salinity and temperature measurements were taken at four-hour intervals. Temperatures were read directly from a bucket thermometer. Salinities were determined by titration with silver nitrate.

The U. S. Coast and Geodetic Survey Bureau maintains a tide gage near the seaward end of 15th Street pier, and the U. S. Army Corps of Engineers has a relay-type wave gage unit on the same pier (Fig. 3). Tidal elevations with respect to time and wave data (i.e., wave height and wave period) were acquired from these two agencies. The U. S. Weather Bureau has a regional station at Cape Henry, approximately 10 km miles north of the study area. This agency supplied information on wind direction and wind speed for each hour.

METHOD OF ANALYSIS

The distribution of sand grains of various sizes is controlled by the interaction of many beach process elements. It would be a difficult task to measure all the possible process variables and correlate them with average mean grain size distribution. In this comparative study the process elements were limited, presumably, to the ten most influential variables.

A sequential linear multiregression analysis was selected for determining the relationship between the ten variables and average mean grain size. In the first step of the analysis, the linear relation between average mean grain size and each of the process variables was determined from regression coefficients calculated by the least squares method. At this initial stage the most influential variables affecting average mean grain size normally become apparent. Next, the relation between average mean grain size and all possible pairs of the process variables were computed. From the most influential pair of process variables, the second most influential single variable could be identified. Sequential steps of analyzing combinations of three, four, or more variables at a time served the two-fold purpose of ranking the process variables in their mathematical order to physical significance as well as acquiring the most influential set of variables in the various multiple combinations. Thus, the variable combinations are referred to as "strong" or "weak" in terms of the least squares search results.

The multiregression analysis, as reviewed by Krumbein (1959 and 1961), was performed on an IBM 1620 computer for the initial steps, and for more time-consuming steps, an IBM 7090 computer was used. Data prepared for the multiregression analysis are presented in Appendix A.

In the first step, when the process variables are being considered one at a time, the complete order of importance cannot accurately be determined by the amount in which each variable reduces the percent sum of squares of the response variable. Because there are many complex interrelations among the various process variables, an individual analysis may be misleading as to their true control when acting in combination. Some of the process variables may be redundant because their relation to the response variable is partially influenced by their interaction with other process variables. This is shown by the fact that the addition of the sum of squares reduction values is greater than 100 percent when the variables are computed individually. Most pairs and sequential combinations of the stronger variables will have a smaller effect on the sum of squares reduction than the total of the sum of squares reduction of all the involved process variables when computed individually. These progressive combinations tend to reduce redundancy and possibly approach the true statistical relationship between any combination of the process variables and the response variable.

In arranging the data for analysis, the distribution of average mean grain size was considered as a function of bottom slope angle, local wave period, local wave height, wind speed onshore, wind speed offshore, wind speed parallel to shore, angle of wave approach, still-water depth, sigma-t, and tidal-current speed (Table 1) over five 4-hour lag periods (t 1-5).

Thus:

$$(\overline{M}_z)s = f\ (\overline{S}_s,\ T,\ H,\ \overline{U}on,\ \overline{U}of,\ \overline{U}p,\ \alpha,\ h,\ \sigma_t,\ C)_{t1-5}$$

For consistency, the data in this study were analyzed in the same way the data in the study of Harrison and Krumbein (1964) were analyzed. A brief review of the multiregression technique is present in Appendix B.

OBSERVED STORM CONDITIONS

Virginia Beach is subjected to frequent "northeaster" storms (referring to wind velocities $>$ 11 m/s) of varying intensity throughout the winter. For two days before the observed storm occurred, the winds, which were blowing primarily from the northeast, gradually increased in intensity. As the wind speeds increased, the direction of approach swung to the north (blowing parallel to shore), and, after three days, to the northwest (blowing out to sea). Wind speeds reached a maximum of 18.8 m/s during the height of the storm and maintained an average speed slightly over 11 m/s during the storm period. After the storm subsided, the winds blew mainly from the south (parallel to shore). The angle of wave approach changed with the shifting wind directions; from the northeast before and during the storm and from the southeast after the storm. The salinity of the local water was not significantly affected by the variable winds; however, the local water temperatures during the storm decreased over 4.5°C below the mean water temperatures observed the day before and the day after the storm.

The mean local wave height observed before the storm was 0.6 m and the mean wave period averaged 7 seconds. During the storm the local wave height ranged from 1.2 to 3.95 m, which was relatively high considering that most of the waves had broken at least once on storm-built sandbars before reaching the study zone. The wave period in the early stages of the storm averaged between 5 and 6 seconds, and as the disturbance continued, the period and height increased slightly. Immediately after the storm the local wave height and period decreased substantially. Throughout the storm, the mean tidal-current speeds were 1.3 times greater than the speeds observed before and after the storm. Before and during the initial impact of the storm, the shoaling-wave zone mean bottom slope in the sampling area was approximately 1:50, containing sand grains ranging between 0.320 and 0.370 mm in average mean grain size. As the storm intensified, the mean slope steadily increased and the sand grains varied between 0.250 and 0.300 mm in average mean grain size. After the storm the mean slope was found to be approximately 1:30, containing sand grains ranging between 0.320 and 0.370 mm in average mean grain size. Deposition, averaging about 0.5 m, occurred within the study zone during the storm. Hence, the still-water depth, which averaged 3.2 m before the storm, was found to be approximately 2.7 m immediately after the storm.

COMPUTED RESULTS AND COMPARISONS

Table 2 contains the results of the sequential linear multi-regression analysis of the initial phase in the present study. As shown, the results indicated that the beach-ocean-atmosphere conditions manifested in lag period 2 (4-8 hours prior to beach response sampling) had the greatest influence on average mean grain size distribution. Additional results of the analysis (Tables 3-7, storm data) indicated that the strongest four-variable combination in the most dominant lag period (Table 4B) consisted of wind speed offshore, still-water depth, sigma-t, and tidal-current speed. In considering the three strongest sets of four-variable combinations in all of the five lag periods (Table 8, storm data), the dominant variables are wave height, still-water depth, sigma-t and tidal current speed. The weakest variable was found to be angle of wave approach.

By way of comparison, the earlier study (Harrison and Krumbein, 1964) found that beach-ocean-atmosphere conditions in lag period 3 (Table 2), occurring 8-12 hours prior to sediment sampling, had the most significant influence on beach response. Results of four-variable combinations for each of the five lag periods in the earlier work are presented in Tables 3-7, non-storm data: From the earlier work, it was found that the strongest four-variable combination in the most dominant lag period (Table 5A) consisted of bottom slope, wave period, angle of wave approach and tidal-current

Table 2.--Percent Reduction in Average Mean Grain Size (Shoaling-wave Zone) Sum of Squares Attributable to Ten Independent Variables, Taken Individually, for Lag Periods 1-5, Including Both the Non-storm (Harrison and Krumbein, 1964), shown in parentheses, and the Storm Weather Conditions.

Variable	Percent Reduction in SS by Lag Periods				
	Period 1	Period 2	Period 3	Period 4	Period 5
Total % SS Reduction	77.66 (82.59)	86.95 (81.99)	54.87 (96.20)	72.50 (93.95)	70.03 (91.48)
Mean Grain Size Shoaling-wave Zone	----- ------	----- ------	----- ------	----- ------	----- ------
Slope Angle Shoaling-wave Zone	4.36 (63.20)	4.15 (60.33)	2.94 (58.74)	2.50 (48.69)	1.79 (42.09)
Wave Period	2.55 (1.59)	0.30 (2.49)	1.16 (1.29)	2.89 (2.08)	0.80 (1.91)
Wave Height	15.84 (1.27)	8.34 (9.06)	11.17 (0.72)	8.56 (11.58)	7.22 (16.82)
Wind Velocity(Onshore)	2.95 (8.94)	2.46 (4.93)	5.06 (15.60)	0.92 (1.06)	0.65 (0.03)
Wind Velocity (Offshore)	2.05 (1.19)	5.89 (12.51)	0.14 (0.02)	0.31 (0.07)	0.02 (1.41)
Wind Velocity (Parallel to Shore)	11.74 (5.09)	21.13 (24.24)	5.26 (0.81)	6.63 (8.27)	5.37 (4.00)
Angle of Wave Approach	3.65 (16.77)	11.92 (33.23)	4.43 (15.78)	0.10 (6.34)	0.09 (2.94)
Still-water Depth	8.26 (1.89)	25.64 (0.10)	10.34 (14.86)	9.53 (0.33)	28.22 (1.66)
Sigma-t	28.57 (31.60)	26.02 (26.07)	23.80 (22.48)	20.52 (18.53)	18.09 (14.38)
Tidal-current Velocity	4.44 (7.71)	7.05 (24.34)	0.03 (5.23)	15.84 (28.41)	12.01 (49.58)

Table 3A.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 1 (Excluding Storm Data).

Independent Variable Combinations										Percent Reduction in SS
1						7		9	10	78.72
1			4					9	10	77.61
1				5				9	10	77.46

Table 3B.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 1 (Including Storm Data).

Independent Variable Combinations										Percent Reduction in SS
		3		5				9	10	69.14
	2	3						9	10	68.05
		3	4					9	10	64.67

Explanation of Variable Numbers

X1 - Slope

X2 - Wave Period

X3 - Wave Height

X4 - Wind Velocity (Onshore)

X5 - Wind Velocity (Offshore)

X6 - Wind Velocity (Parallel to Shore)

X7 - Angle of Wave Approach

X8 - Still-water Depth

X9 - Sigma-t

X10 - Tidal-current Velocity

Table 4A.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 2 (Excluding Storm Data).

Independent Variable Combinations						Percent Reduction in SS
1		5		9	10	72.42
		5	7	9	10	71.83
	4	5		9	10	71.25

Table 4B.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 2 (Including Storm Data).

Independent Variable Combinations							Percent Reduction in SS
		5		8	9	10	78.11
1	3	5		8			75.55
			7	8	9	10	75.30

Explanation of Variable Numbers

X1 - Slope Angle
X2 - Wave Period
X3 - Wave Height
X4 - Wind Velocity (Onshore)
X5 - Wind Velocity (Offshore)
X6 - Wind Velocity (Parallel to Shore)
X7 - Angle of Wave Approach
X8 - Still-water Depth
X9 - Sigma-t
X10 - Tidal-current Velocity

Table 5A.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 3 (Excluding Storm Data).

Independent Variable Combinations	Percent Reduction in SS
1 2 7 10	82.75
1 2 3 10	82.69
1 2 8 10	81.24

Table 5B.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 3 (Including Storm Data).

Independent Variable Combinations	Percent Reduction in SS
1 3 5 8	52.10
1 3 6 8	49.06
1 3 4 8	48.90

Explanation of Variable Numbers

X1 - Slope Angle

X2 - Wave Period

X3 - Wave Height

X4 - Wind Velocity (Onshore)

X5 - Wind Velocity (Offshore)

X6 - Wind Velocity (Parallel to Shore)

X7 - Angle of Wave Approach

X8 - Still-water Depth

X9 - Sigma-t

X10 - Tidal-current Velocity

Table 6A.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 4 (Excluding Storm Data).

Independent Variable Combinations										Percent Reduction in SS
1	2			5					10	89.53
1			4	5					10	89.47
1		3		5					10	89.46

Table 6B.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 4 (Including Storm Data).

Independent Variable Combination										Percent Reduction in SS
	2	3						9	10	67.68
1		3						9	10	61.00
		3			6			9	10	60.93

Explanation of Variable Numbers

X1 - Slope Angle
X2 - Wave Period
X3 - Wave Height
X4 - Wind Velocity (Onshore)
X5 - Wind Velocity (Offshore)
X6 - Wind Velocity (Parallel to Shore)
X7 - Angle of Wave Approach
X8 - Still-water Depth
X9 - Sigma-t
X10 - Tidal-current Velocity

Table 7A.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 5 (Excluding Storm Data).

Independent Variable Combinations								Percent Reduction in SS
	3			7		9	10	81.12
1	3	5					10	78.90
1		5	6				10	77.79

Table 7B.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 5 (Including Storm Data).

Independent Variable Combinations						Percent Reduction in SS
1			8	9	10	67.15
	3		8	9	10	66.18
		5	8	9	10	66.03

Explanation of Variable Numbers

X1 - Slope Angle
X2 - Wave Period
X3 - Wave Height
X4 - Wind Velocity (Onshore)
X5 - Wind Velocity (Offshore)
X6 - Wind Velocity (Parallel to Shore)
X7 - Angle of Wave Approach
X8 - Still-water Depth
X9 - Sigma-t
X10 - Tidal-current Velocity

speed. However, in compiling the three strongest sets of four-variable combinations in all of the five lag periods (Table 8, non-storm data), the results suggested that the dominant variables were bottom slope, wind speed offshore, sigma-t and tidal-current speed. The weakest variable was still-water depth. Table 9 shows a comparison of the range of values of the environmental variables observed during both the earlier and the more recent study.

Table 8.--Variable Frequency of Occurrence in the Three Strongest Combinations for Four Xs at a Time in All Five Lag Periods Under Non-storm and Storm Conditions.

Variable	Occurrence Under Non-storm Conditions	Occurrence Under Storm Conditions
Slope Angle	12	6
Wave Period	4	2
Wave Height	4	11
Wind Speed Onshore	3	2
Wind Speed Offshore	9	5
Wind Speed Parallel to Shore	1	2
Angle of Wave Approach	4	1
Still-water Depth	1	9
Sigma-t	7	11
Tidal-current Speed	15	11

Table 9.--Comparative Table of the Observed Range of Values of the Environmental Variables Under Non-storm and Storm Conditions.

Variable	Range of Values Under Non-storm Conditions	Range of Values Under Storm Conditions
Grain Size	0.234-0.843 mm	0.237-0.384 mm
Slope Angle	0.45-2.22°	0.54-1.75°
Wave Period	3-13.9 s	3-12 s
Wave Height	0.15-1.95 m	0.3-3.9 m
Wind Speed Onshore	0-11.9 m/s	0-16.6 m/s
Wind Speed Offshore	0-15.2 m/s	0-17.8 m/s
Wind Speed Parallel to Shore	0-14.8 m/s	0-18.8 m/s
Angle of Wave Approach	20-125°	20-75°
Still-water Depth	2.4-4.9 m	3.3-4.3 m
Sigma-t	13.6-25.0	19.6-24.9
Tidal-current Speed	0-21.3 cm/s	0-35.6 cm/s

DISCUSSION

In the earlier study, Harrison and Krumbein (1964, pp. 45-48) found a strong inverse correlation existing between mean bottom slope and average mean grain size in the shoaling-wave zone under non-storm conditions (Fig. 4, inset). Because of this strong "bottom slope-grain size" relationship, bottom slope appeared as the dominant independent variable influencing average mean grain size distribution (Table 2, period 3, data in parentheses) when all the independent variables observed during the non-storm period were analyzed individually. Under storm conditions, the data suggested that a position correlation of bottom-slope-grain size existed in the same area of investigation (Fig. 4). With the increased turbulence along the water-sediment interface, a quasi-fluidization of the bed surface developed (cf. Shepard, 1963; Scheidegger, 1961), and presumably the bottom slope or lack of a rigid slope greatly modified the influence of the slope angle on the average mean grain size.

Generally, storm waves develop two, three, and sometimes more breaker zones with accompanying "breaker" sandbars and "breaker" troughs. Such was the case in the zone of investigation during and after the storm (Fig. 5). The seaward edge of the study zone (Fig. 3) contained the second breaker bar and trough, and the remaining shoreward portion contained a "pseudo-foreshore" slope. As mentioned earlier, there was a positive relationship between

Figure 4.--Graphic representation of mean bottom slope-average mean grain size relationship during the storm period.

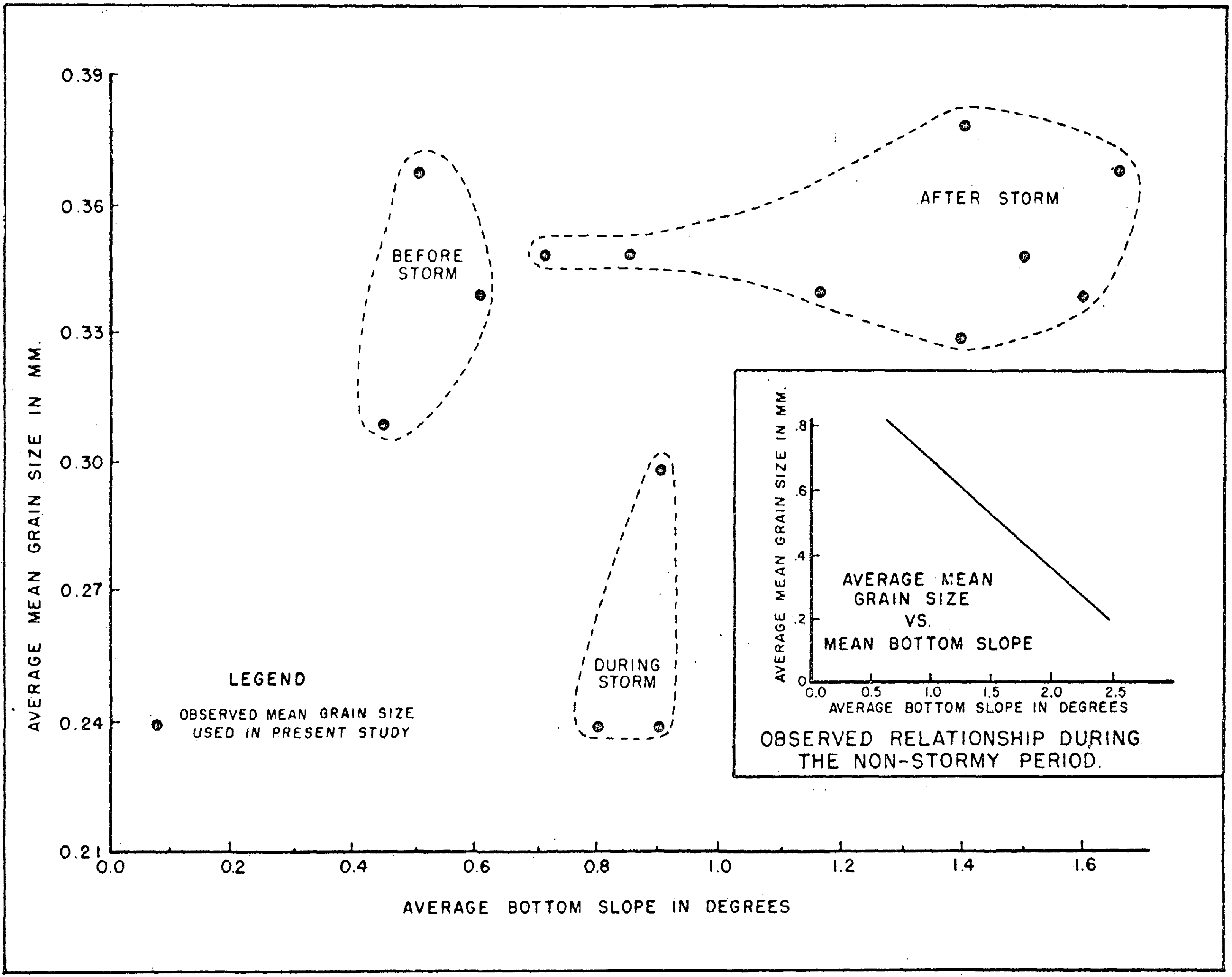
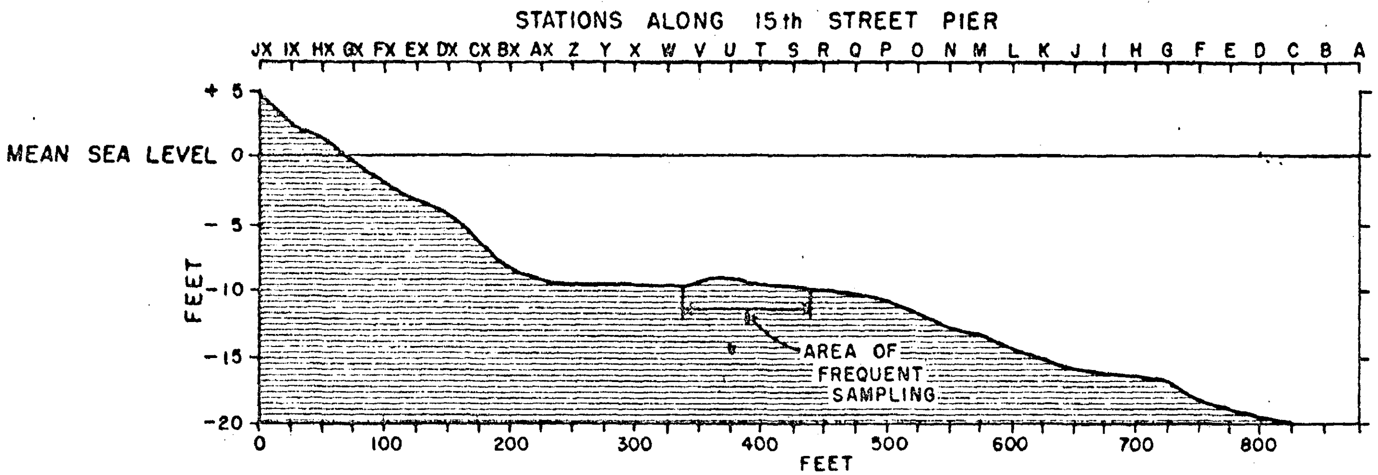
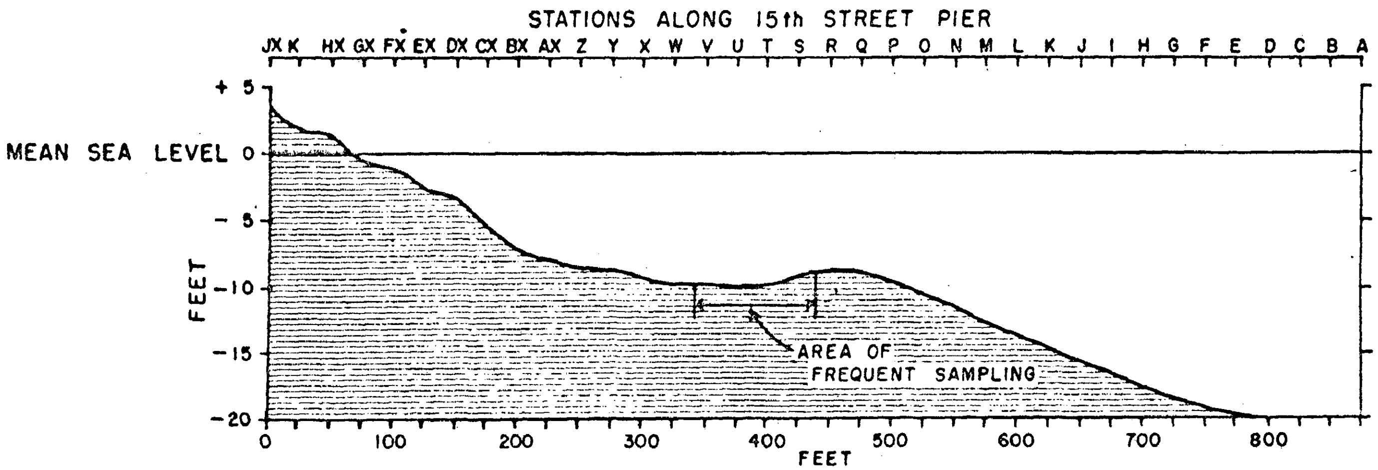

0.39
0.36
0.33
0.30
0.27
0.24
0.21
AVERAGE MEAN GRAIN SIZE IN MM.
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
AVERAGE BOTTOM SLOPE IN DEGREES
BEFORE STORM
AFTER STORM
DURING STORM
LEGEND
OBSERVED MEAN GRAIN SIZE USED IN PRESENT STUDY
AVERAGE MEAN GRAIN SIZE IN MM.
.8
.6
.4
.2
0
0.0
0.5
1.0
1.5
2.0
2.5
AVERAGE BOTTOM SLOPE IN DEGREES
AVERAGE MEAN GRAIN SIZE VS. MEAN BOTTOM SLOPE
OBSERVED RELATIONSHIP DURING THE NON-STORMY PERIOD.

Figure 5.--Schematic diagram of beach profiles at 15th Street pier before and after storm.



BEACH PROFILE BEFORE STORM
28 NOVEMBER 1964



BEACH PROFILE AFTER STORM
4 DECEMBER 1964

bottom slope and grain size, which is the case on a true foreshore (Bascom, 1951). The observed change of the original study zone, from one exhibiting bottom slope-grain size characteristics similar to a near-shore shoaling-wave zone to one having bottom slope-grain size characteristics similar to a foreshore, altered the observed strong inter-relationship between bottom slope angle and average mean grain size distribution exhibited in the earlier analysis.

Waves have two basic methods in initiating movement of sand grains; one involves the orbital movement of water particles, and the other involves the unidirectional flow of water induced by the passing wave front (Arlman, Santema, and Svasek, 1958). Both of these methods are directly related to wave height (Shepard, 1963). As the local wave height increases, within limits, the size of the sand grains which are set in motion increases. However, smaller sand grains were measured in the area during the actual storm; the grains ranged from 0.250 to 0.300 mm. Previous studies (cf. Eagleson, Glenne, and Dracup, 1961, p. 45) have shown that waves with steepness less than 0.025 build up a beach shoreward of the breaker zone and waves with steepness greater than 0.025 erode a beach shoreward of the breaker zone. (Wave steepness is defined as $^{H}/_{L}$, where H is wave height and L is wave length.) Further observations suggest that the steeper waves not only erode the foreshore slope, but deposit relatively smaller sand grains in the offshore region via significantly strong rip currents that may be induced by a storm. This phenomenon possibly occurred in the study zone since the average mean grain sizes observed during the storm were smaller than the average mean grain sizes observed for the earlier non-storm period. The newer analysis indicated that the steepness characteristic of waves during storms has a strong relationship with average mean grain size. Most all of the waves during the storm had a steepness greater than 0.025, which set up conditions for a seaward movement of sand grains into the near-shore shoaling-wave zone.

In reviewing the data (Table 8), the strong winds during the storm were not from the northeast, but were dominantly from the north and northwest. Winds blowing from the latter two directions were parallel to shore and "offshore," respectively. Pore (1964) observed that extratropical storm surges, such as existed during the observed storm, are more dependent on the winds blowing parallel to shore than on the onshore winds. Results suggested that the induced currents generated by the observed northerly winds parallel to shore were refracted toward the shore. The shoreward, wind-induced currents may have reinforced the wave-induced currents and thereby caused the wave variables, especially wave height, to become more influential in its effects on average mean grain size distribution. The influence of winds parallel to shore were possibly "masked" by the increased influence of wave height. The winds blowing onshore and offshore may generate currents normal to the wind direction. Such currents will be generally parallel to shore and would become interrelated with the tidal currents in the area. With the strong tidal currents occurring during the peak of the storm, it is believed that whatever effect the onshore and offshore winds exerted on distribution of grain size, such influence was masked by the dominant southerly flowing tidal currents.

The angle of wave approach had relatively minor influence on grain size distribution in the present analysis. During the storm the waves approached from the northeast, and after the storm the waves approached from the southeast. The basic difference in wave characteristics associated with the two directions of wave approach was wave height, and apparently most all of the influence exerted by the wave conditions was contained in that wave variable.

The sediment deposited during the maximum intensity of the storm contained sand grains smaller in average mean grain size than the grains found in the study area prior to the storm. This observation may be due, in part, to the transport of fine sand grains by seaward flowing rip currents and/or mid-depth return flows such as that observed by Miller and Zeigler (1958). Upon reaching the study area, where a breaker zone had developed during the storm, these seaward currents possibly dissipated and deposited the relatively finer sand grains upon the sediment bed. After the storm had passed and the oceanic and atmospheric conditions became relatively calm, the observed average mean grain size increased, covering a range larger than that present prior to the storm. This increase could have been expected since the still-water depth had decreased, thus placing the sand grains closer to the acting forces of passing waves. There were no rapid depth changes in the earlier analysis; consequently, little change occurred in average mean grain size due to the still-water depth. In the present study, rapid depth changes and seemingly related average mean grain size distributions occurred. The present analysis indicated that variation in still-water depth, indeed, was a very influential factor on average mean grain size distribution. It is realized that still-water depth is not an energy term in the environment, but it is important in mediating the application of energy terms.

Water viscosity has been found to have a significant effect on the dynamic properties of immersed sand grains at Virginia Beach (Harrison and Morales-Alamo, 1964). The water viscosity varies considerably over the seasons owing to temperature and salinity variations in the Chesapeake Bay runoff and in the local ocean water. Temperature and salinity fluctuations associated with tidal currents and heating and cooling during the day also affect the water viscosity. Storms, which may alter water temperature and salinity, will consequently have an effect on water viscosity as indicated by the observed sigma-t values in the present study. The net change of the sigma-t values in the study area caused by the observed storm was in the range of ten percent. Winds may indirectly affect water viscosity, especially the winds causing an offshore movement of surface water. Such winds, if sufficiently strong, cause a mild overturn along the coast, resulting in the shoreward movement of colder more-saline water in the summer months and slightly more-saline water in the winter months. Alterations in viscosity may affect fluid stress on the sand grains. With a significant decrease in water temperature and slight increase in salinity, as observed during and immediately following the storm period, water viscosity may increase thereby increasing fluid stress on the sediment surface. An increase in fluid stress entrains more sediment, causing an increase in sand grain distribution. An increase in grain size was observed with diminution of the storm. Results indicated that the increased viscosity of the water after the storm acting in less water depth under similar induced forces was influential in increasing average mean grain size distribution.

In the earlier analysis (Tables 3-7, non-storm data), the influence of viscosity was significant; however, the full effect was apparently suppressed owing to the dominance of the shoaling-wave zone slope variable. In a separate analysis of the earlier data (Harrison and Krumbein, 1964, Tables B52 - B56), slope was deleted and water viscosity became highly significant. Under storm conditions, when slope became a less influential variable, water viscosity was observed to be a rather dominant variable in affecting average mean grain size distribution.

As mentioned earlier, the tidal-current speeds during the storm were approximately fifty percent greater than those during the non-storm period. With currents of this magnitude, some of the smaller sand grains may be held in suspension and transported without the combined action of other environmental forces (Scheidegger, 1961, pp. 213-216). The usual direction of sand transport caused by reversing tidal currents alone would be parallel to the beach. It is reasonable to assume that storm wave-induced currents caused sand to be transported in an offshore direction. This interlocking relationship between wave-drift and tidal currents possibly explains the significant influence that each exerts on the average mean grain size distribution as indicated by the present study. In the earlier study (Tables 3-7, non-storm data) tidal currents also appeared influential. However, the accompanying wave-induced currents were insignificant, apparently caused by the masking effect of the shoaling-wave zone slope variable.

SUMMARY

Results of the present study indicated that sigma-t was the most dominant variable in affecting average mean grain size distribution when the independent variables were ranked individually by a simple regression procedure. This observation is in agreement with the earlier study (Harrison and Krumbein, 1964) in which sigma-t was among the more dominant variables when the independent variables were ranked individually. Other influential variables, when taken individually, observed in the present study were tidal currents, still-water depth, wave height, and wind speed parallel to shore. When the variables were analyzed in combinations of four variables at a time, the results suggested that the four strongest variables, considering all lag periods, were sigma-t, tidal currents, wave height, and still-water depth in that order. Wind speed parallel to shore became less influential in four-variable combinations, apparently due to the masking effect of wave height and tidal currents.

Whereas the most significant four-variable combinations for the non-storm conditions manifested 8-12 hours prior to the time of measurement of average mean grain size distribution; the most significant combinations for the combined weather conditions manifested 4-8 hours prior to the time of measurement of the dependent variable. Thus, the multiregression analyses indicated that average mean grain size distribution responded more readily to vigorous environmental conditions than to less vigorous environmental conditions; that is, the rate of change in the dependent variable varied directly with the magnitude of the applied forces. Results of the regression analysis suggested that, although the causal variables observed under non-storm conditions maintained considerable influence on average mean grain size distribution for at least twenty hours (Table 2), those observed under storm conditions exhibited their major influence within 4-8 hours after measurement (Table 2).

The significant interdependence between bottom slope and average mean grain size was reflected in the dominance of slope angle as a determinative variable in the regression analysis under non-storm conditions. Under storm conditions, bottom slope angle became a rather insignificant causal variable, and other forces (i.e., wave-drift currents and tidal currents), which may be strengthened by storms, became more influential in affecting the distribution of average mean grain size, according to the multi-regression analyses.

APPENDIX A

A print-out of the data used in this study and explanations of the data fields on the print-out.

APPENDIX A

The following pages contain a "print-out" of the data as prepared and fed into IBM 7090 and IBM 1620 computers used in this study. The system could handle only eighty spaces per line (or card); however, the data associated with one response required more than the available spaces, therefore an additional line (or card) was needed for each set of responses. As shown on the following several pages, each two print-out lines contain the values of the ten environmental variables, occurring at one specific time, as related to the given beach response observed at a specific time. This procedure was conducted through five lag periods.

A key to the code lettering over the individual "fields" is presented below.

KEY

First Line:

A - A field of six spaces containing the project number of the specific analysis.

B - A field of four spaces containing the control number which applies to a specific beach response through the five lag periods.

Y - A field of six spaces containing the beach response data (average mean grain size) in mm with the decimal point between the third and fourth digits in the field.

X_1 to X_8 - Each X has a field of six spaces containing the environmental variable data of bottom slope angle (X1) in degrees, wave period (X2) in seconds, wave height (X3) in feet, wind velocity onshore (X4) in mph, wind velocity offshore (X5) in mph, wind velocity parallel to shore (X6) in mph, angle of wave approach (X7) in degrees, and still-water depth (X8) in feet. The decimal point for each field is between the fourth and fifth digits.

C, D, and E - The blank fields of six, six, and three spaces respectively are for convenience.

LP - A field of one space containing the lag period numbers.

Second Line:

A' and B' - These fields correspond to A and B respectively in the first line.

X_9 and X_{10} - Each X has a field of six spaces containing the environmental variable data of the sigma-t anomaly (X9) and tidal-current speed (X10) in ft/s. In both fields the decimal point is between the fourth and fifth digits.

F and G - The blank fields of six and forty-nine spaces respectively are for convenience.

PN - A field of three spaces containing process numbers which is merely a way of designating the various lag periods for all beach response observations.

```
                PROJ A010 11 VARIABLES
        RUN NO 0001'MEAN SIZE    15 ST PIER VS
        MEAN SLOPE' WV T'WV HO'UON'UOFF' UPARALLEL
        ANG WV APP' WATER DEP'RHO' TID CURR VEL
        LAG PERIOD 1

   A    | B |  Y  |  X1  |  X2  |--C--| X3  |--D--| X4  | X5  | X6  | X7  | X8  |-E-|LP
HA0010000100084300006800090.0        0001.10      0003500000.000000. 0  40.00001260   1
   A'   | B'|--F--|  X9  | X10  |-------------------------G--------------------------|PN
HA00100001         001470000038                                                      6

HA0010000200060600008500080 0        000150       0008000000000000 0   3500001100    1
HA00100002         001580000000                                                     41
HA001000030007630000660008 00        000100       0004000000000000 0   4000001060    1
HA00100003         001590000026                                                     84
HA0010000500023400018600055 0        000130       000 00          65000300001070     1
HA00100005         001980000000                                                    504
HA0010000700025600021700040 0        000340       0024000000000000 0   2500001280    1
HA00100007         002200000025                                                    510
HA0010000900055200016800110 0        000150       000000001350000000003000001330     1
HA00100009         002500000038                                                    516
HA0010001000047400020500090 0        000130       000000001600000000003000001410     1
HA00100010         002260000068                                                    519
HA0010001100058800018300030 0        000050       000000001100000000003500001340     1
HA00100011         002220000048                                                    522
HA0010001200047400018400060 0        000150       000000001200000000003000001350     1
HA00100012         002190000054                                                    525
HA0010001300049700018700030 0        000050       000000001300000000003500001330     1
HA00100013         002030000044                                                    528
HA0010001500046800018500035 0        000100       000 0           12500020000 01410  1
HA00100015         001960000014                                                    534
HA0010001600041700017500035 0        000250       000 00          19000030000 01530  1
HA00100016         001960000000                                                    537
HA0010001700037000015100050 0        000160       0006000000000000 0   2000001400    1
HA00100017         001900000022                                                    540
HA0010001800038100013800035 0        000050       000 00          12000040000 01440  1
HA00100018         002280000030                                                    543
HAA010000100030700005400040 0        000200       0017000000000000 0   1500001090    1
HAA0100001         002060000042                                                      8
HAA010000200035900005600045 0        000200       0011500000000000 0   1500001100    1
HAA0100002         002050000050                                                    011
HAA010000300033900005900060 0        000210       00000000 650000000004000001120     1
HAA0100003         002080000025                                                    014
```

Lag Period 1, continued.

```
HAA0100004000243000116000500      000270      000 00         1700003000001160   1
HAA0100004          00209000034                                                  017
HAA0100005000237000084000500      000360      000 0          2400002500001170   1
HAA0100005          00206000025                                                  020
HAA0100006000307000084000600      000640      000 0          4200003000001180   1
HAA0100006          00204000075                                                  023
HAA0100007000384000087000900      000550      0000000034000000000005000001110   1
HAA0100007          00201000050                                                  026
HAA0100008000336000130001100      000330      0000000018000000000003000000970   1
HAA0100008          00203000008                                                  029
HAA0100009000326000145001100      000150      000 00          8000022500000960   1
HAA0100009          00214000017                                                  032
HAA0100011000343000127000350      000130      000 00         1550003250001020   1
HAA0100011          00226000017                                                  038
HAA0100012000333000133001000      000130      0008500000000000 0 05000000960    1
HAA0100012          00224000008                                                  041
HAA0100013000350000147000500      000110      000 00         1100003000000920   1
HAA0100013          00216000008                                                  044
HAA0100014000347000070000700      000140      000 00         1500003000000960   1
HAA0100014          00218000017                                                  047
HA00100004000695000050000800      000050      00000000 9000000000002000001200   1
HA00100004          00181000042                                                  149
HA00100006000246000233001000      000120      0009000000000000 0  2500001110    1
HA00100006          00215000012                                                  507
HA00100008000414000183001100      000360      0000000018500000000001000001330   1
HA00100008          00249000063                                                  513
HA00100014000516000182000300      000130      000 00         1500003000001440   1
HA00100014          00196000042                                                  531
HAA0100010000369000175000300      000110      000 00         1150004500000940   1
HAA0100010          00224000008                                                  035
```

```
          PROJ 0010 II VARIABLES
     RUN NO. 0001' MEAN SIZE  15 ST. PIER VS
     MEAN SLOPE' WV T'WV HO'UON'UOFF' UPARALLEL
     ANG WV APP' WATER DEP'RHO' TID CURR VEL
     LAG PERIOD 2


HA0010000100084300006600053O      000170      .000 000  650000000003000001420   2
HA00100001        001469000000                                                  5
HA0010000200060600008100080O      000150      0008000000000000 0  4000001320   2
HA00100002        001560000050                                                040
HA0010000300076300006300080O      000100      000 0000 5500000000004000001350   2
HA00100003        001620000030                                                083
HA0010000500023400017000060O      000250      000 00          120000300001380   2
HA00100005        001940000068                                                503
HA0010000700025600022200035O      000200      0014500000000000 00 2000001490   2
HA00100007        002140000030                                                509
HA0010000900055200017300110O      000200      0000000017000000000003000001510   2
HA00100009        002490000000                                                515
HA0010001000047400019300090O      000130      0000000012000000000003000001610   2
HA00100010        002360000000                                                518
HA0010001100058800019000030O      000170      0000000021500000000003500001450   2
HA00100011        002220000019                                                521
HA0010001200047400018400060O      000130      0000000016000000000003000001450   2
HA00100012        002210000028                                                524
HA0010001300049700018600040O      000050      0000000014000000000003000001330   2
HA00100013        002030000033                                                527
HA0010001500046800018400040O      000120      000 0           120000250000130O   2
HA00100015        001960000041                                                533
HA0010001600041700017800035O      000150      000 000         185000250000134O   2
HA00100016        001970000055                                                536
HA0010001700037000015900050O      000130      000 00          125000200000124O   2
HA00100017        001900000027                                                539
HA0010001800038100014300060O      000050      000 00          100000300000123O   2
HA00100018        002130000027                                                542
HAA010000100030700005000080O      000220      0013500000000000 0  150000096O   2
HAA0100001        002050000017                                                  7
HAA010000200035900007200050O      000250      0012500000000000 0  175000096O   2
HAA0100002        002050000008                                                010
HAA010000300033900005600100O      000180      000 00          100000300000097O   2
HAA0100003        002070000008                                                013
HAA010000400024300011500060O      000300      000 0           230000350000095O   2
HAA0100004        002100000058                                                016
```

Lag Period 2, continued.

```
HAA0100005000237000086000500      000320      000 00       1900003000000920    2
HAA0100005      002070000050                                                 019
HAA0100006000307000082000550      000500      000 0        2850003000001000    2
HAA0100006      002060000067                                                 022
HAA0100007000384000089000800      000500      00000000370000000004000000880    2
HAA0100007      002020000067                                                 025
HAA0100008000336000103001000      000320      00000000265000000003000000880    2
HAA0100008      001980000067                                                 028
HAA0100009000326000150000900      000130      00000000145000000002500000800    2
HAA0100009      002110000000                                                  31
HAA0100011000343000140000350      000100      000 0        1300003500000910    2
HAA0100011      002250000008                                                 037
HAA0100012000333000135000350      000050      00000000 70000000000500000900    2
HAA0100012      002270000008                                                 040
HAA0100013000350000145000600      000120      000 00       1050003500000890    2
HAA0100013      002180000017                                                 043
HAA0100014000347000097001000      000150      000 00       1650003500000900    2
HAA0100014      002150000000                                                  46
HA00100004000695000050000900      000080      00000000110000000006000001370    2
HA00100004      001740000018                                                 148
HA00100006000246000216001000      000150      000 00        900003000001350    2
HA00100006      002070000054                                                 506
HA00100008000414000194000900      000600      00000000160000000002000001590    2
HA00100008      002400000018                                                 512
HA00100014000516000183000800      000050      000 00       1150003500001350    2
HA00100014      001990000054                                                 530
HAA0100010000369000145001000      000110      000 000      1250004500000900    2
HAA0100010      002260000000                                                  34
```

```
           PROJ A010 11 VARIABLES
     RUN NO 0001'MEAN SIZE   15 ST PIER VS
     MEAN SLOPE' WV T'WV HO'UON'UOFF' UPARALLEL
     ANG WV APP' WATER DEP'RHO' TID CURR VEL
     LAG PERIOD 3


HA001000010008430000640006 40     000110      000 0             650002500001250   3
HA00100001        001468000040                                                  4
HA0010000200060600007700 0750     000150      000 00            700003500001370   3
HA00100002        001540000047                                                039
HA0010000300076300006000 0700     000080      00000000 450000000003500001180   3
HA00100003        001650000062                                                 82
HA0010000500023400015400 0450     000250      000000002000000000003000001400   3
HA00100005        001900000056                                                502
HA0010000700025600022700 1000     000200      0011000000000000 0   2000001350   3
HA00100007        002170000065                                                508
HA0010000900055200017800 1000     000170      000000001750000000002000001270   3
HA00100009        002490000043                                                514
HA0010001000047400018000 0900     000130      000000001100000000003000001420   3
HA00100010        002460000038                                                517
HA0010001100058800019700 0900     000100      000000002400000000003000001280   3
HA00100011        002210000011                                                520
HA0010001200047400018300 0600     000050      000000001150000000003500001250   3
HA00100012        002220000012                                                523
HA0010001300049700018500 0600     000050      000000001000000000003000001170   3
HA00100013        002130000000                                                526
HA0010001500046800018300 0350     000100      000 0            145000300001110   3
HA00100015        001950000025                                                532
HA0010001600041700018200 0300     000150      000 00           165000200001200   3
HA00100016        001970000024                                                535
HA0010001700037000016700 0400     000250      000 00           180000250001290   3
HA00100017        001940000048                                                538
HA0010001800038100014700 0600     000130      0006500000000000 0002500001260   3
HA00100018        001980000050                                                541
HAA010000100030700005000 0900     000240      0015500000000000 0001500001020   3
HAA0100001        002050000017                                                  6
HAA010000200035900006300 0400     000270      0014000000000000 0   1750000920   3
HAA0100002        002070000058                                                  9
```

Lag Period 3, continued.

```
HAA0100003000339000053001000      000210      000 00          800002000000890   3
HAA0100003      002060000008                                                  012
HAA0100004000243000076000700      000250      000 00         3200004000000940   3
HAA0100004      002100000042                                                  015
HAA0100005000237000089000500      000260      000 00         1800003500001010   3
HAA0100005      002080000017                                                  018
HAA0100006000307000084000500      000350      000 00         2200002500001015   3
HAA0100006      002060000025                                                  021
HAA0100007000384000091000700      000650      0000000040000000000003000001100   3
HAA0100007      002030000117                                                  024
HAA0100008000336000095000550      000400      0000000032000000000004000001110   3
HAA0100008      001990000025                                                  027
HAA0100009000326000155001100      000200      0000000015000000000002/50001030   3
HAA0100009      002080000025                                                  030
HAA0100011000343000152000700      000150      000 000        1250003750001030   3
HAA0100011      002240000000                                                   36
HAA0100012000333000130000350      000100      000 0          1350003250001090   3
HAA0100012      002270000017                                                  039
HAA0100013000350000143000600      000130      000 00         1100003000001030   3
HAA0100013      002200000050                                                  042
HAA0100014000347000137000600      000120      000 00         1050003000000970   3
HAA0100014      002140000034                                                  045
HA00100004000695000050000850      000100      000 0          1050005000001230   3
HA00100004      001665000034                                                  147
HA00100006000246000200000500      000190      0007500000000000 0   3000001330   3
HA00100006      002030000055                                                  505
HA00100008000414000106000700      000740      0022500000000000  0 02500001410   3
HA00100008      002300000054                                                  511
HA00100014000516000185000550      000050      00000000 9000000000003500001140   3
HA00100014      002020000009                                                  529
HAA0100010000369000122001200      000140      000 00          800003000001130   3
HAA0100010      002200000034                                                  033
```

```
          PROJ A010 11 VARIABLES
     RUN NO 0001'MEAN SIZE   15 ST PIER VS
     MEAN SLOPE' WV T'WV HO'UON'UOFF' UPARALLEL
     ANG WV APP' WATER DEP'RHO' TID CURR VEL
     LAG PERIOD 4


HA00100004000695000050000750      000110      000 0000 80000000000040000001160   4
HA00100004        0016000000044                                                146
HA0010000600024600018600055O      000130      000 00          650003000001070   4
HA00100006        0019800000000                                                504
HA0010000800041400021700040O      000340      002400000000000000 0  2500001280   4
HA00100008        0022000000025                                                510
HA0010001400051600018700030O      000050      00000000130000000000035000001330   4
HA00100014        0020300000044                                                528
HAA010001000036900014500110O      000150      000 00          800002250000960   4
HAA0100010        0021400000017                                                032
HA0010000100084300006200078O      000080      00165000000000000 0003000001240   4
HA00100001        0014670000041                                                  3
HA0010000200060600007300070O      000150      000600000000000000 0  2500001140   4
HA00100002        0015200000000                                                 38
HA0010000300076300005700080O      000100      00000000 40000000000035000001070   4
HA00100003        0016800000030                                                081
HA0010000500023400013800043O      000190      00000000245000000000030000001130   4
HA00100005        0018600000000                                                501
HA0010000700025600023300100O      000120      000900000000000000 0  2500001110   4
HA00100007        0022200000012                                                507
HA0010000900055200018300110O      000360      00000000185000000000010000001330   4
HA00100009        0024900000063                                                513
HA0010001000047400016800110O      000150      00000000135000000000030000001330   4
HA00100010        0025000000038                                                516
HA0010001100058800020500090O      000130      00000000160000000000030000001410   4
HA00100011        0022600000068                                                519
HA0010001200047400018300030O      000050      00000000110000000000035000001340   4
HA00100012        0022200000048                                                522
HA0010001300049700018400060O      000150      00000000120000000000030000001350   4
HA00100013        0021900000054                                                525
HA0010001500046800018200030O      000130      000 00          1500003000001440   4
HA00100015        0019600000042                                                531
HA0010001600041700018500035O      000100      000 0           1250002000001410   4
HA00100016        0019600000014                                                534
HA0010001700037000017500035O      000250      000 00          1900003000001530   4
HA00100017        0019600000000                                                537
```

Lag Period 4, continued.

```
HA00100018000381000151000500       000160      0006000000000000 0  2000001400   4
HA00100018         001900000022                                               540
HAA0100001000307000054001000       000250      0009500000000000 0 01500001140   4
HAA0100001         002060000017                                                 5
HAA0100002000359000054000400       000200      0017000000000000 0  1500001100   4
HAA0100002         002060000042                                                 8
HAA0100003000339000056000450       000200      0011500000000000 000150001100   4
HAA0100003         002050000050                                               011
HAA0100004000243000059000600       000210      0000000 650000000004000001120   4
HAA0100004         002080000025                                               014
HAA0100005000237000116000500       000270      000 00          1700003000001160   4
HAA0100005         002090000034                                               017
HAA0100006000307000084000500       000360      000 00          2400002500001170   4
HAA0100006         002060000025                                               020
HAA0100007000384000084000600       000640      000 00          4200003000001180   4
HAA0100007         002040000075                                               023
HAA0100008000336000087000900       000550      0000000034000000000005000001110   4
HAA0100008         002010000050                                               026
HAA0100009000326000130001100       000330      0000000018000000000003000000970   4
HAA0100009         002030000008                                               029
HAA0100011000343000175000300       000110      000 00*         1150004500000940   4
HAA0100011         002240000008                                               035
HAA0100012000333000127000350       000130      000 000         1550003250001020   4
HAA0100012         002260000017                                               038
HAA0100013000350000133001000       000130      0008500000000000 0005000000960   4
HAA0100013         002240000008                                               041
HAA0100014000347000147000500       000110      000 00          1100003000000920   4
HAA0100014         002160000008                                               044
```

```
          PROJ A010 11 VARIABLES
     RUN NO 0001'MEAN SIZE   15 ST PIER VS
     MEAN SLOPE' WV T'WV HO'UON'UOFF' UPARALLEL
     ANG WV APP' WATER DEP'RHO' TID CURR VEL

     LAG PERIOD 5


HA0010000100084300006000077O      000080      000 0            1250003500001400    5
HA00100001        001466000000                                                     2
HA0010000200060600006900070O      000120      0007500000000000 0 02000001270      5
HA00100002        001500000056                                                   037
HA0010000300076300005400080O      000080      000 00            550003000001330    5
HA00100003        001710000033                                                   080
HA0010000500023400012200040O      000250      000000002500000000003000001380      5
HA00100005        001820000063                                                   500
HA0010000700025600021600100O      000150      000 00            900003000001350    5
HA00100007        002100000054                                                   506
HA0010000900055200019400090O      000600      000000001600000000002000001590      5
HA00100009        002400000018                                                   512
HA00100Q1000047400017300110O      000200      000000001700000000003000001510      5
HA00100010        002490000000                                                   515
HA0010001100058800019300090O      000130      000000001200000000003000001610      5
HA00100011        002360000000                                                   518
HA0010001200047400019000030O      000170      000000002150000000003500001450      5
HA00100012        002220000019                                                   521
HA0010001300049700018400060O      000130      000000001600000000003000001450      5
HA00100013        002210000028                                                   524
HA0010001500046800018300080O      000050      000 00           1150003500001350    5
HA00100015        001990000054                                                   530
HA0010001600041700018400040O      000120      000 00           1200002500001300    5
HA00100016        001960000041                                                   533
HA0010001700037000017800035O      000150      000 000          1850002500001340    5
HA00100017        001970000055                                                   536
HA0010001800038100015900050O      000130      000 00           1250002000001240    5
HA00100018        001900000027                                                   539
HAA010000100030700006200090O      000250      0011500000000000 000150000960       5
HAA0100001        002070000050                                                     4
```

Lag Period 5, continued.

```
HAA0100002000359000050000800        000220       0013500000000000 0 01500000960   5
HAA0100002        002050000017                                                    7
HAA0100003000339000072000500        000250       0012500000000000 0001750000960   5
HAA0100003        002050000008                                                  010
HAA0100004000243000056001000        000180       000 00         1000003000000970   5
HAA0100004        002070000008                                                  013
HAA0100005000237000115000600        000300       000 0          2300003500000950   5
HAA0100005        002100000058                                                  016
HAA0100006000307000086000500        000320       000 00         1900003000000920   5
HAA0100006        002070000050                                                  019
HAA0100007000384000082000550        000500       000 00         2850003000001000   5
HAA0100007        002060000067                                                  022
HAA0100008000336000089000800        000500       0000000037000000000004000000880   5
HAA0100008        002020000067                                                  025
HAA0100009000326000103001000        000320       0000000026500000000003000000880   5
HAA0100009        001980000067                                                  028
HAA0100011000343000145001000        000110       000 000        1250004500000900   5
HAA0100011        002260000000                                                   34
HAA0100012000333000140000350        000100       000 0          1300003500000910   5
HAA0100012        002250000008                                                  037
HAA0100013000350000135000350        000050       00000000 7000000000005000000900   5
HAA0100013        002270000008                                                  040
HAA0100014000347000145000600        000120       000 000        1050003500000890   5
HAA0100014        002180000017                                                  043
HA00100004000695000050000650        000130       00000000 5500000000003000001380   5
HA00100004        001520000014                                                  145
HA00100006000246000170000600        000250       000 00         1200003000001380   5
HA00100006        001940000068                                                  503
HA00100008000414000222000350        000200       0014500000000000000002000001490   5
HA00100008        002140000030                                                  509
HA00100014000516000186000400        000050       0000000014000000000003000001330   5
HA00100014        002030000033                                                  527
HAA0100010000369000150000900        000130       0000000014500000000002500000800   5
HAA0100010        002110000000                                                   31
```

APPENDIX B

An explanation of the computer process
in a sequential multiregression analysis.

APPENDIX B

In the linear sequential regression analysis, all possible combinations of the ten major environmental variables were analyzed in determining the effect each variable or group of variables had on the average mean grain size in the area of investigation. As discussed in the text, a combination of four variables would suffice; the single most influential combination was found to be that containing wind velocity (offshore) (X5), still-water depth (X8), sigma-t anomaly (X9), and tidal current speed (X10). With the dependent variable of average mean grain size represented by Y, then the general linear model would be:

$$\beta_0 + \beta_5 X5 + \beta_8 X8 + \beta_9 X9 + \beta_{10} X10 = Y.$$

In a more concise form, the model would be:

$$\underline{S}\underline{\hat{\beta}} = \underline{g}$$

where $\underline{g}$ is a 5 X 1 vector of Y, $\underline{S}$ is a 5 X 5 matrix of squares and cross-products of the Xs, and $\underline{\hat{\beta}}$ is a 5 X 1 vector of the estimated βs. The expanded matrix equation would be:

$$\begin{bmatrix} N & \Sigma X5 & \Sigma X8 & \Sigma X9 & \Sigma X10 \\ \Sigma X5 & \Sigma X5^2 & \Sigma X5X8 & \Sigma X5X9 & \Sigma X5X10 \\ \Sigma X8 & \Sigma X5X8 & \Sigma X8^2 & \Sigma X8X9 & \Sigma X8X10 \\ \Sigma X9 & \Sigma X5X9 & \Sigma X8X9 & \Sigma X9^2 & \Sigma X9X10 \\ \Sigma X10 & \Sigma X5X10 & \Sigma X8X10 & \Sigma X9X10 & \Sigma X10^2 \end{bmatrix} \cdot \begin{bmatrix} \beta_0 \\ \beta_5 \\ \beta_8 \\ \beta_9 \\ \beta_{10} \end{bmatrix} = \begin{bmatrix} \Sigma Y \\ \Sigma X5Y \\ \Sigma X8Y \\ \Sigma X9Y \\ \Sigma X10Y \end{bmatrix}$$

The computer inverts the matrix and multiplies by $\underline{g}$ to obtain the coefficients ($\hat{\beta}$). The proportion of the total sum of squares of Y explained by the four variables is then computed and expressed as a percentage.

In examining the variables individually, the matrix for the first variable would simply be:

$$\begin{bmatrix} N & \Sigma X1 \\ \Sigma X1 & \Sigma X1^2 \end{bmatrix} \cdot \begin{bmatrix} \beta_0 \\ \beta_1 \end{bmatrix} = \begin{bmatrix} \Sigma Y \\ \Sigma X1Y \end{bmatrix}$$

For a pair of variables in combination, another row and column of the appropriate X values would be added to the matrix. From the base matrix given above, any reasonable number of X variables and subsequent combinations could be employed in the linear sequential regression analysis.

LITERATURE CITED

Arlman, J. J., P. Santema, and J. N. Svasek. 1958. Movement of bottom sediment in coastal waters by currents and waves; measurements with the help of radioactive tracers in the Netherlands. U. S. Army, Corps of Engineers, Beach Erosion Board, Tech. Memo. 105:51 p.

Bascom, W. N. 1951. The relationship between sand size and beach face slope. Trans. Amer. Geoph. Union 32:866-874.

Brunn, P. 1954. Coastal erosion and the development of beach profiles. U. S. Army, Corps of Engineers, Beach Erosion Board, Tech. Memo. 44:77 p.

Eagleson, P. S., B. Glenne, and J. A. Dracup. 1961. Equilibrium characteristics of sand beaches in the offshore zone. U. S. Army, Corps of Engineers, Beach Erosion Board, Tech. Memo. 126:63 p.

Harrison, W., and W. C. Krumbein. 1964. Interactions of the beach-ocean-atmosphere system at Virginia Beach, Virginia. U. S. Army Coastal Engineering Research Center, Tech. Memo. 7:52 p.

Harrison, W., and R. Morales-Alamo. 1964. Dynamic properties of immersed sand at Virginia Beach, Virginia. U. S. Army Coastal Engineering Research Center, Tech. Memo. 9:20 p.

Harrison, W., and K. A. Wagner. 1964. Beach changes at Virginia Beach, Virginia. U. S. Army Coastal Engineering Research Center, Misc. Paper 6-64:10 p.

Helle, J. R. 1958. Surf statistics for the coast of the United States. U. S. Army, Corps of Engineers, Beach Erosion Board, Tech. Memo. 108: 22 p.

Krumbein, W. C. 1959. The sorting out of geological variables illustrated by regression analysis of factors controlling beach firmness. J. Sed. Petrology 29: 575-587.

Krumbein, W. C. 1961. The analysis of observational data from natural beaches. U. S. Army, Corps of Engineers, Beach Erosion Board, Tech. Memo. 130: 50 p.

Krumbein, W. C., B. Benson, and W. B. Hempkins. 1964. Whirlpool, a computer program for sorting out independent variables by sequential multiple linear regression. ONR Tech. Rept. 14, ONR Task No. 389-135, Contract Nonr-1228 (26) Northwestern University, Dept. of Geology, 49 p.

Miller, R. L., and J. M. Zeigler. 1958. A model relating dynamics and sediment pattern in equilibrium in the region of shoaling waves, breaker zone, and foreshore. J. Geology 66: 417-441.

Pore, N. A. 1964. The relation of wind and pressure to extratropical storm surges at Atlantic City. J. Applied Meteor. 3: 155-163.

Scheidegger, A. E. 1961. Theoretical geomorphology. Prentice-Hall Inc., Englewood Cliffs, N. J. 333 p.

Shepard, F. P. 1950. Longshore bars and longshore troughs. U. S. Army, Corps of Engineers, Beach Erosion Board, Tech. Memo. 15: 30 p.

Shepard, F. P. 1963. Submarine geology. Harper and Row, New York. 487 p.

Shepard, F. P., and E. C. La Fond. 1940. Sand movements along the Scripps Institution pier. Amer. J. Sci. 238: 272-285.

Snedecar, G. W. 1956. Statistical methods. Iowa State University Press, Ames, Iowa. 523 p.

U. S. Congress. 1953. Virginia Beach, Virginia, beach erosion control study. 83rd Congress, 1st session, House Doc. 186: 45 p.

Zeigler, J. M., G. G. Whitney, and C. R. Hayes. 1960. Woods Hole rapid sediment analyzer. J. Sed. Petrology 30: 490-495.

VITA

D. Richard Tuck

Born in South Boston, Virginia, April 10, 1937. Graduated from Thomas Jefferson High School in Richmond, Virginia, June 1955, B. A. in Biology, Virginia Military Institute, 1959. M. A. in Marine Science, Virginia Institute of Marine Science, 1969.

In February 1966, the author became employed by the U. S. Naval Oceanographic Office as an oceanographer in the Oceanographic Surveys Department, Nearshore Surveys Division.